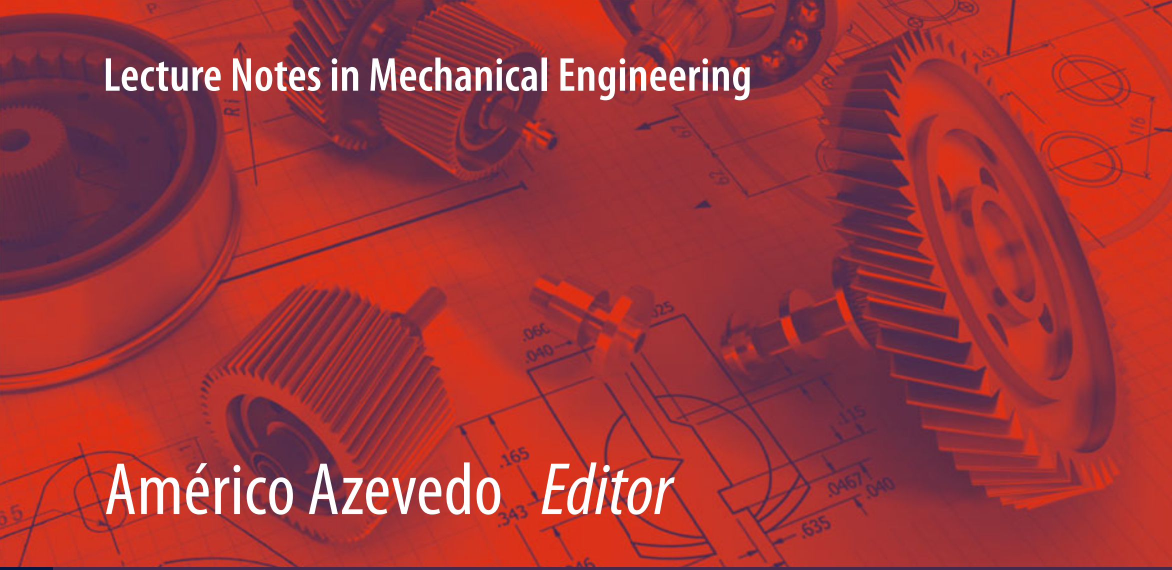

Lecture Notes in Mechanical Engineering

Américo Azevedo *Editor*

# Advances in Sustainable and Competitive Manufacturing Systems

## 23rd International Conference on Flexible Automation and Intelligent Manufacturing

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Editor

# Advances in Sustainable and Competitive Manufacturing Systems

## 23rd International Conference on Flexible Automation and Intelligent Manufacturing

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# Foreword

The design, development, implementation and use of *Flexible Automation and Intelligent Manufacturing Systems* require an ever-increasing knowledge on enabling technologies and business and operational practices. Moreover, the digital and networked world will surely trigger new business and operational practices in manufacturing. Therefore, this is an important and timely research issue to guarantee an effective and efficient performance. In this manufacturing context, sustainable and competitive development is emerging as the mandatory global strategic vision to be deployed so as to meet the economic, social, environmental and technological challenges that most societies are facing today.

Nowadays, manufacturing is being shaped by the paradigm shift from mass production to on-demand personalised, customer-driven and knowledge-based production. Furthermore, advanced manufacturing leads to an increasingly automated world that will continue to rely less on labor-intensive mechanical processes and more on sophisticated information-technology intensive processes that enable flexibility. Moreover, advanced manufacturing will become increasingly linked at global level, as automation and digital supply chain management become the norm across enterprise systems. This new production environment trend is an encouraging approach to significantly improve the competitiveness of the manufacturing industry. Manufacturing, as the heartbeat of growth and development, must become increasingly high-added value, competitive and sustainable, by building on competences and knowledge coming from higher education and R&D.

The FAIM 2013-Flexible Automation & Intelligent Manufacturing Conference, which was held in Porto, Portugal, was the 23rd event in a series of successful conferences. The global aim was to provide an international forum to exchange leading edge scientific knowledge and industrial experience on the development and integration of the various aspects of Flexible Automation and Intelligent Manufacturing Systems, covering the complete life cycle of companies' products, processes and manufacturing technologies.

The aim with this edition of the conference was to discuss ***The Challenge of Sustaining Global Competitive Manufacturing Systems*** covering current research, best practices and future trends within the areas of global competitiveness and rapidly advancing technologies in flexible automation, information management and intelligent manufacturing.

This volume includes the papers selected for this edition of the conference, providing a comprehensive overview of the recent advances in various manufacturing issues within the Conference aims.

This book is divided into the following parts:

- Product, Process and Factory Integrated Design
- Manufacturing Technology and Intelligent Systems
- Manufacturing Operations Management and Optimisation
- Manufacturing Organisation and Strategies
- Lean and Six Sigma Applications
- Energy Efficiency in Factory Life Cycle

Despite the significant efforts that are required in order to make progress in the domain of the FAIM conference, as a whole the papers in this book will prove to be a significant contribution to the already existing literature. We would like to acknowledge the authors for their excellent contributions.

We hope that the book contributes to a better understanding of the conference domain.

Américo Azevedo
INESC TEC and Faculdade de Engenharia
Universidade do Porto

# Acknowledgments

This book is the direct consequence of extensive teamwork, resulting from the generous collaboration of all the authors, who are members of the academia, research and industry, from the members of the Organising Committee and the members of the FAIM 2013 Program Committees who participated in the selection of articles, and from the valuable input which contributed to help authors in improving the quality of their work.

A special thank you goes to Mr. Luis Carneiro and Mr. António Almeida for their valuable and continuous help during the preparation of the book and to Ms. Grasiela Almeida for her continuous valuable help, availability and deep professionalism.

# Contents

## Part II Manufacturing Technologies and Intelligent Systems

# Part I
# Section One: Product, Process and Factory Integrated Design

# Impacts of Product Lifecycle and Production System Design on Competitive and Sustainable Production

**Hasse Nylund, Mikko Tapaninaho, Seppo Torvinen and Paul H. Andersson**

**Abstract** In this paper, the design and development of productions systems is discussed. The role of production system is investigated as a part of life cycle of products as well as one of the players, an evolving entity fulfilling the strategic goals of a company. These two are then combined to discuss on how they effect on design, development, and operation of production systems. The study focuses on the flow of material, i.e., the transformation of raw material to finished products as well as the flow of information related to the realization of the products. Simulation of production systems is discussed on how it can be used to enhance the daily operations and investigating the alternative future solutions. Finally, the issues discussed in this paper are explained on how they can be utilized in university level education in engineering.

## 1 Introduction

In this paper, the impacts of closed loop product life cycle as well as design and development of production systems are considered. The aim is to create a holistic view of the impacts to a production system, studying what the impacts are, and how they have an effect on the short- and long-term overall management of production systems. The flows of technical systems can be simplified to material, energy, and information [1]. The research discussed in this paper is limited on material flow from raw material into finished products, including only the related information flow necessary to produce the products. This study investigates the following:

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- What are the typical phases in a product life cycle, where production is one of the phases?
- What are the key areas of design and development of production systems?
- How the two aspects above affect on design and development production systems?
- How computer aided technologies and simulations can be used in developing production systems?
- How all the topics above can be included into the teaching of university students?

These views are aimed to be classified and categorized to create more explicit understanding toward formal inputs that can be utilized in digital production, such as computer aided technologies, modelling, and simulation, as well as product and production information and knowledge management. The expected benefits are more accurate understanding and knowledge that can support more efficient decision making. This study belongs to an ongoing national research project in the area of competitive and sustainable manufacturing (CSM). The aim of the project is to enhance the national know-how and understanding within the area of Sustainable Manufacturing as well as to support Finnish companies in realizing competitive and environment friendly products and production networks. The research project will build higher level static analysis tools and simulation supported dynamic Information and Communications Technologies (ICT) tools for the design, implementation, measurement, and development of production systems. The terms *manufacturing* and *production* are sometimes used differently in the publications of different research groups. In this research the term production is used as a top term. Production is therefore divided into part manufacturing as well as module and final assemblies.

## 2 Viewpoints on Production Systems

### *2.1 Closed-Loop Life Cycle of Products*

Figure 1 represents typical phases of product's life-cycle. Materials are mined from the environment and processed to raw material. In production the raw material is transformed to products, which are distributed to customers. The products are used for a certain time and are usually maintained and renovated to prolong the time the products can be used. For certain products, product take-back mechanisms exist, and the used products can be sustained for second-hand markets. On a traditional life cycle (the top part of Fig. 1 from left to right) of a product, after the use phase of a product, it is disposed as a waste to environment.

The Lowell Centre for Sustainable Production [2] defines sustainable production as "the creation of goods and services using processes and systems that are non-polluting, conserving of energy and natural resources, economically viable,

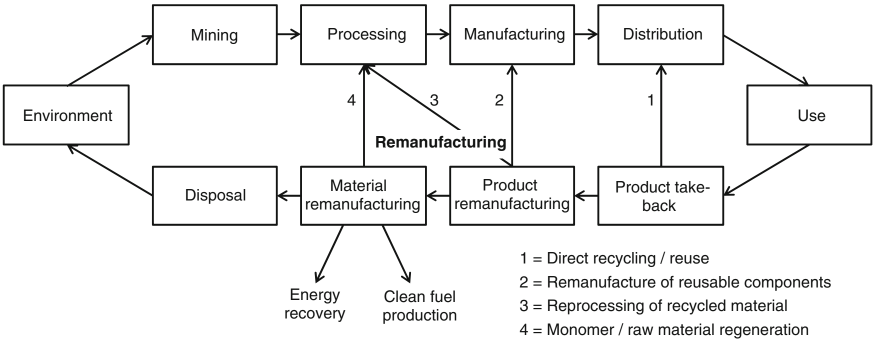


**Fig. 1** A representation of a product's life-cycle, adapted from [3]

safe, and healthful for employees, communities, consumers, and socially and creatively rewarding for all working people." These goals can be partially fulfilled by adding the product and material remanufacturing a phases to a life cycle of a product. It means that companies, rather than disposing used products, need to find solutions reuse the products or the material of the products in producing their new products.

The life-cycle of a product can also be presented by 6R concept, a recently developed concept of more efficient planning of the post use activities for a products, i.e,. Reuse, Reduce, Recycle, Recover, Redesign, and Remanufacture [4]. The 6R concept extends the traditional 3R concept (Reuse, Reduce, Recycle) by enabling operations and innovations in the end-of-life management of products [5]. The 6R's can be briefly explained as follows:

- *Reduce* aims at simplifying products to enhance the end-of-life management as well as decreasing the amount of required material and minimizing the needed energy and wastes during the life cycle of a product.
- *Reuse* means that the product can be directly reused without embedding further resources in the product or reusing parts of product or parts that can be reused [6].
- *Recycling* includes a number of activities such as separating, sorting, and processing recycled products into raw materials [7] reducing the emissions, saving energy, and serving as a supply of raw materials for the industry.
- *Recover* includes the collecting end-of-life products to enable the subsequent post-use activities as well as disassembling and dismantling of specific components from a product at the end of its life for reuse.
- *Redesign* is closely linked with reduce as it involves redesigning the product to be more simplified for future post-use processes. Design for Environment (DFE) is a central part of the redesign process since it takes environmental issues into account.

- *Remanufacturing* is similar to normal manufacturing. Remanufacturing can be applied to restore used products to same condition as the original product with lower cost.

## 2.2 Design and Development of Production Systems

Miltenburg [8] describes that company's business strategy states, "Among all the possible plans and actions, we will move in this direction, focus on these markets and customer needs, compete in this fashion, allocate our resources and energies in these ways, and rely on these particular business approaches." Therefore, strategy defines the direction and scope of an organization to meet the needs customers and stakeholders [9]. Figure 2 represents the main areas of production system design and development. It starts with business strategy, which sets the goals for the next steps, namely product and production analysis [10].

*Product Analysis* aims to clarify the features of a product, relevant to their production, as a base for production system design. These include product structure of modules and core components, material types and tolerances, production volumes and variation as well as customer demands. The amount of work required for product analysis can be reduced by selecting a set of products that present all the products in the portfolio in a sufficient manner. As an example, the size of a

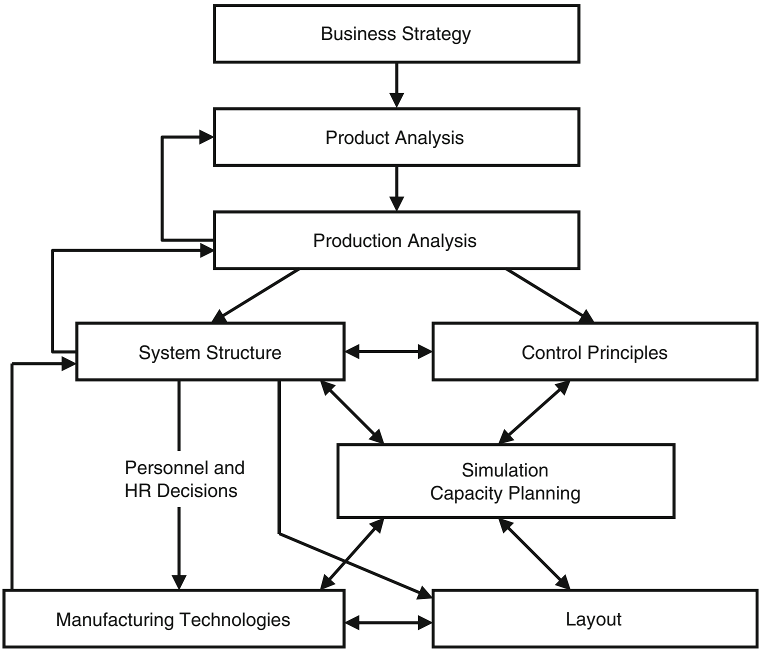


**Fig. 2** Production system design framework, adapted from [10]

product can be a factor for selecting the set. The portfolio can be classified into, e.g., small, medium, and large products.

*Production analysis* should answer to the question of what is required from the production system to produce the products. This requires the knowledge of what and how much should the production system be able to produce. The MPB-analysis (Make, Partnership, Buy) can be used to answer the question what should be able to produce. *Make* means that the products are done in company's own factories and require skilled workers as well as suitable machines and devices. *Partnership* involves other companies in the supply network and the issues involving the products require close collaboration. The alternative *Buy* usually refers to bulk products that are used in high volumes and are fairly easy to produce. These are typically ordered from the stocks of the product suppliers.

The product and production analyses serve a base for designing system structure and control principles. *System structure* defines the general level of the steps in the manufacturing phase of product's lifecycle, between material processing and distribution. Typical division follows the product structure and flow of products, i.e., (1) stock- and service-oriented material suppliers, (2) technology-oriented part manufacturing units, (3) product-oriented module assembly units, and (4) customer-oriented final assembly units [11]. All these units rarely exist in a same location and are usually distributed into several locations of a supply network either locally or globally.

*Control principles* of production intends to answer to questions of what is produced, where it is produced as well as when and how much is produced with the aim of right products are produced at right times. The strategy of a company and the system structure both have an impact on the selected control principles. Typical general examples of control principles are order-based and stock-based controls. *Manufacturing technologies* concentrates on the internal production processes of the parts of the system structure. Typical focus areas are manufacturing methods, selection of machines and tools, internal layout of manufacturing areas, transferring devices as well as material storage areas. For the capacity planning of a factory, it is important to measure or assess the durations of processes and transfers in the chain of processes. *Layout* explains how the needed manufacturing and storage areas as well as paths for material transferring will be located on a factory floor. Typical layout alternatives are cellular and functional areas as well as stages and lines. Most factories consist of combination of different layout alternatives.

## 3 Horizontal and Vertical Impacts on Production

When the aspects of life cycle and production system design framework are combined, a production system can be investigated both vertically and horizontally. Product life cycle represents the horizontal view, i.e., the flow of material in the closed loop life cycle. The production system design framework, starting from

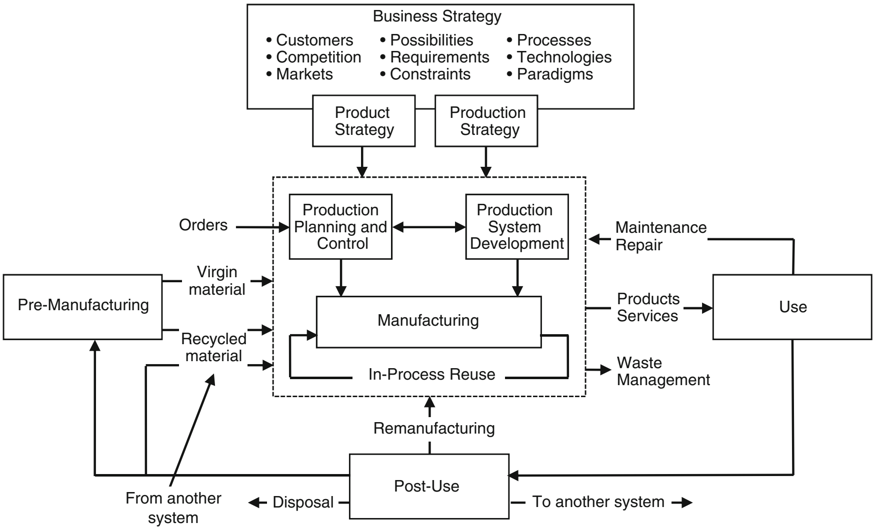


**Fig. 3** Horizontal and vertical inputs of production systems

business strategy adds the vertical view, i.e., change drivers deriving from, e.g., customer requirements and market situations. Figure 3 illustrates the combination of the two aspects. The vertical division is basically information that influences the production system. It can be divided into strategic, tactical, and operational levels. Examples of the elements of the strategic part are:

- Market view explains in what markets a company is operating. It includes the demands of the customers and offerings of the competitors.
- Innovation view seeks to find solutions to differ from competitors exploring new possibilities within the requirements and constraints deriving from, e.g., legislation or customer expectations.
- Technology view aims to increase production productivity by actively seeking new technologies and processes or even new production paradigms to reach more radical changes.

The product and production strategies as well as production system development can be seen as the tactical level. The responsibility is to find solutions on how the strategic goals can be realized at the operational level, i.e., the daily operations on a factory floor. These correspond with the simulation and capacity planning in the production system design framework, i.e., experiments on computer models. The experiments can be carried out parallel with the current system operations as they do not disturb the real manufacturing system. New production policies and operating procedures can be experimented with and evaluated in advance. Solution alternatives can be compared and possible problems can be solved before actions are taken in the real system [12].

Horizontal view, in addition to information flow, includes flow of material. The information flow, i.e., customer orders is the basis for all production activities. If no customer orders are placed, no material is required either. The material that is input for a production system is divided into virgin and recycled material as well as repair and maintenance activities during the use phase of a product. All these inputs, despite having different kind of characteristics, cause production activities that need to be planned and will use portions of the capacity of a production system.

Virgin material represents the traditional raw material used in production processes. Recycled material can come from several different sources. Material can be reused inside a production system, which is typical for molding. In some cases, leftover material can be used for some other purpose. Recycled material that comes from outside a production system can be reprocessed in pre-manufacturing, as full products or parts from disassembled products as well as come from some other product life cycle.

## 4 Typical Effects Deriving from the Impacts

Figure 4 represents a production system divided into digital, virtual, and real production systems. The real production system represents the physical transformation of material and components into finished products, i.e., the factory floor. The digital production system holds the production related information and knowledge. It can be divided into production planning and control as well as production system development. The former focuses on present time and aims at timely deliveries and efficient use of production capacity. The latter focuses more on future of the production system, e.g., changes in volume and variation of

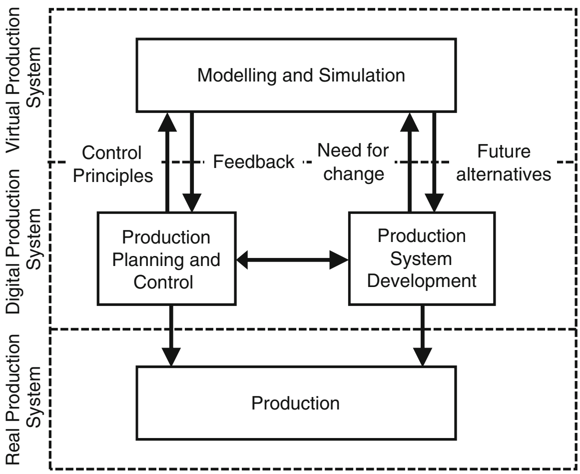


**Fig. 4** Digital, virtual, and real view of production systems, adapted from [13]

customer orders and more generally to any change drivers that can have an effect on the production system.

The virtual production system is a representation of the real production system as computer models. It can also be focused on both present and future production activities. When experiments are carried out in a virtual manufacturing system, i.e., utilizing the possibilities of computer-aided technologies such as computer-aided manufacturing (CAM) and factory simulation, the experiments can be done without disturbing the operational activities of the real production system.

The returning part (post-use) of product's life cycle is more new and challenging for the operation of production systems. Examples of challenges and business opportunities related to the production system design framework are briefly as follows:

- For a system structure, all different alternatives for reusing used products or parts of the products need facilities. This either requires changes to current facilities or adds new facilities to new locations.
- For production control, adding new players to be controlled makes the control more challenging. Raw material arriving from more locations than before adds more uncertainty to the delivery of raw material.
- For manufacturing technologies, new production resources and methods are most likely required to make the used products or their parts useable in producing new products.
- If remanufacturing is realized in same facilities as the traditional production processes, they have to be included in designing efficient factory layouts.

Utilizing the possibilities of modelling and simulation of production systems, numerous different issues can be experimented. Table 1 summarizes some of the most typical issues, related to the production system design framework that can be addressed by modelling and simulation.

Modelling and simulation should be carefully planned before building any simulation models. The goals that are aimed to be achieved define the level of details needed for modelling and simulation. Depending on the case for what modelling and simulation is used, the simulation experiments can be carried out with calculations or simulations on different level of details [14]:

- Calculation models built on, e.g., spreadsheets for rough level analysis. Many simulations do not need to be extensive and they can be designed to provide approximate estimates and to show general system.
- Rough level simulation focusing on the basic principles and structures of systems, e.g., layout planning.
- Detailed level simulation for controlling, planning and scheduling of production systems. It can be targeted into a specific subsystem of the environment and the rest of the environment is examined on more rough level.

**Table 1** Examples of issues that can be addressed by modelling and simulation of production systems

| Area of production system design | Goals for simulation |
|---|---|
| Product strategy | Requirements for new or modified products |
| | Product modules and configurations |
| | Material properties, virgin versus recycled material |
| | Volumes and variation |
| Production strategy | Tact and throughput times |
| | Core competences |
| | Capacity needs |
| | Make, partnership, buy-analysis |
| System structure | Number of products in a delivery batch |
| | Duration and tact time of a delivery batch |
| | Delivery reliability |
| Control principles | Comparison of different production control alternatives |
| | Bottleneck analysis |
| | Procurement alternatives |
| Manufacturing technologies | Number of different machines and devices |
| | Number of parallel machines and devices |
| | Failures and repair times |
| | Number of personnel |
| | Worker skills and absences |
| Layout | Sizes and locations of machines and devices |
| | Sizes and lengths of transferring devices and pathways |
| | Sizes and locations of storage areas and buffers |

## 5 Educational Aspects of the Research

The issues discussed in this paper belong to a university course *Production Concepts and Systems* at the Department of Production Engineering in Tampere University of Technology. The course consists of normal and visiting lectures, class room and computer exercises, an industrial visit, written course work, and oral presentations, as well as a final written exam.

The exercises include short introduction to the problems the students are solving, leaving most of the time for interactive working within groups of students guided by the teachers. As the authors are mostly carrying out research, it is connected to the course via lectures that, not only introduce well known theories and practices, but also give insight to basic and applied research in the area of the course topics. These activities are flavored with pre- and post-tasks that form a bonus point system. The bonus point system, with a possibility to raise the grade a student gets from the course, was realized to encourage the students to participate in the learning activities. Part of the research presented in this paper will be executed in small group exercises in the following way:

- The students will be given sub-problems and related reading material to be familiarized with before an exercise.
- Students with same sub-problem will be grouped to discuss on their findings.
- The groups will prepare short presentation of their subject followed by discussion with other groups and teachers.
- Everybody makes individual notes, especially from the sub-problems of other groups.
- Everybody makes a short written presentation on the whole subject and the work will be graded.
- After the submission deadline, a summary lecture on the topic will be given by the teachers.

The authors believe that an interactive learning by doing beats traditional lectures as a learning experience, and inspire the students to active participation. As in all activities, the authors are continuously improving the course based on feedback from the students, needs from industry, and topics from research for technology and development.

## 6 Summary

This paper discussed on production systems, horizontally as part of product's lifecycle and vertically from the viewpoint of production system design. These aspects were integrated to present the material and information inputs and outputs of a production system. The inputs from the reverse part of a closed loop supply chain were emphasized over the more traditional supply chain. These issues were then further discussed in the context of simulation of production systems, how simulation can be applied and what can be achieved by using simulation. Finally, the research topics presented in this paper, was discussed on how they can be applied in education of university students.

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## References

1. Hubka V, Eder E (1988) Theory of technical systems. Springer, Berlin, Germany
2. Veleva V, Ellenbecker M (2001) Indicators of sustainable production: framework and methodology. J Clean Prod 9(6):519–549
3. Bras B (1997) Incorporating environmental issues in product design and realization. Ind Environ 20:1–19 (Special Issue on Product Design and the Environment)
4. Jaafar IH, Venkatachalam A, Joshi K, Ungureanu C, De Silva N, Rouch KE, Dillon OW Jr, Jawahir IS (2007) Product design for sustainability: a new assessment methodology and case studies. In: Kutz M (ed) Environmentally conscious mechanical design. Wiley, New York

5. Joshi K, Venkatachalam A, Jaafar IH, Jawahir IS (2006) A new methodology for transforming 3R concept into 6R concept for improved product sustainability. In: Proceedings of global conference on sustainable manufacturing, Sao Paolo, Brazil
6. The University of Bolton (2013) Online postgraduate courses for the electronics industry, life-cycle thinking. http://www.ami.ac.uk/. Accessed 9 Mar 2013
7. http://www.epa.gov/epaoswer/nonhw/muncpl/recycle.htm. Accessed 9 Mar 2013
8. Miltenburg J (2005) Manufacturing strategy: how to formulate and implement a winning plan. Productivity Press, Portland, p 435
9. Johnson G, Scholes K, Whittingon R (2010) Exploring corporate strategy, 8th edn. Pearson Education, Essex, UK, p 625
10. Lapinleimu I, Kauppinen V, Torvinen S (1997) Kone- ja metalliteollisuuden tuotantojärjestelmät. Tammer-paino, Porvoo, Finland (in Finnish)
11. Lapinleimu I (2001) Ideal factory theory of factory planning, produceability and ideality. Doctoral thesis, Tampere University of Technology, Publications 328, p 195
12. Nylund H, Salminen K, Andersson PH (2009) An approach to the integrated design and development of manufacturing systems. In: Proceedings of the 19th CIRP design conference, competitive design, Cranfield, UK, pp 428–435
13. Nylund H, Andersson PH (2010) Digital manufacturing supporting integrated improvement of products and production systems. In: Proceedings of 17th CIRP international conference on life cycle engineering, LCE 2010, Hefei, China, pp 156–161
14. Nylund H, Koho M, Torvinen S (2010) Framework and toolset for developing and realizing competitive and sustainable production systems. In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing, Oakland, CA, USA, pp 294–301

# A Framework for Optimizing Product Performance Through Using Field Experience of In-Service Products to Improve the Design and Manufacture Stages of the Product Lifecycle

**Joel E. Igba, Kazem Alemzadeh, Paul M. Gibbons and John Friis**

**Abstract** For many component sub-systems which make up the individual elements of a larger product system, the optimization of their performance in the system becomes more difficult through design modifications and/or manufacturing process improvements alone. The authors argue this can be improved if adequate field performance data has been fed back to the early stages of the product lifecycle. This paper presents a framework for an inclusive lifecycle approach to optimizing product performance through the effective use of field experience and knowledge to improve the design and manufacturing of sub-systems. The problem is presented alongside a taxonomic and captious review of literature of relevant subject areas, followed by a case study using wind turbine sub-system components as a basis to support the investigation. A framework is then developed through the combination of systems thinking and continuous improvement tools, applied to the conventional product lifecycle. The findings of the investigation indicate that subsystem performance can be improved through the accumulation of knowledge fed back to the design and manufacture stages of the product lifecycle using information from in-service product performance. The approach would be useful to practitioners and academics with an interest in applying an inclusive and holistic approach to product lifecycle management. This framework is particularly useful for companies that produce and/or operate systems whose sub-systems are manufactured by different suppliers.

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## 1 Introduction

Engineering product development has moved away from the traditional linear steps to a more integrated product life cycle development process [1]. This has led manufacturers to change their principles from designing and learning from failures and errors during the production stage of the life cycle to a more integrated approach to design and manufacturing. Well-known concepts such as Integrated CAD/CAM, design for reliability and maintainability, design for manufacture, concurrent engineering, etc. have led to more integrated, optimized and advanced product development techniques saving costs and reducing the lead time to make a product [1]. For complex systems which consist of several major sub-systems, there is a greater chance for one or several sub-systems to be designed and/or manufactured by different original equipment suppliers (OEMs). Once such a system is in service, it is expected to perform according to its design requirements and if there is a sign of deviation from the requirements, it can be put back to its running state through good operations and maintenance. This typically would be the case for most products until they reach their end of life or fail. However, in practice, companies who operate large systems and OEMs find it difficult to collect, feedback, and re-use field in-service knowledge for design improvements [2, 3].

Traditionally, manufacturers get most of their product usage and performance information through warranty and spare parts data, customer complaints, and information from service personnel [3]. Access to complete in-service data is rare because traditionally, in-service information is often collected by the customers who usually are unwilling to share such information [2]. Many supplying and designing companies are shifting to a product-service system (PSS) which Goh and McMahon [2] described as an integrated solution that fulfills functions and provides services to end-users without necessarily transferring the ownership of the product to them. In this case the traditional product offering companies offer more and more service packages comprising of installation, maintenance contracts, overhaul and repair, upgrades and training. This allows such companies to use insights gained from use and in-service to adapt their on-going support activities (through continuous improvement) and also to feed-forward the knowledge gained to new design projects [2]. Goh and McMahon [2] also gave examples of some high profile companies which have adopted PSS in diverse applications, including: Xerox, IBM, Canon, and Rolls-Royce. Unlike companies that are able to adopt PSS, other companies involved in designing, manufacturing and/or delivering part of a large system which is been put to service by a different company, do not have this luxury and ease of accumulating and feeding back in-service knowledge for product improvement. This paper presents a framework for a more integrated approach toward aligning, capturing, and the feedback of in-service knowledge for the purpose of optimizing product performance by improving the design and manufacturing stages of the life cycle.

# 2 Related Work

## *2.1 Life Cycle Models and In-Service Feedback*

The concept of life cycle popularly used to describe the stages a living organism covers a period from the time of birth until death. Any engineering artifact goes through a similar "lifelike" analogy to a living organism: Conception-Birth-Growth-Adulthood-Death [4]. In general there is a life cycle that describes the stage of a product from its conception/design through its use up to its disposal. For the purpose of this research, several relevant literature themes which the authors have seen to be relevant to their argument are explored indicating different perspectives to the life cycle stages. Life cycle models, in engineering, are abstract functional models that represent the conceptualization of a need for the system, its realization, utilization, evolution, and disposal [4]. Typically, the generic life cycle model has the following stages as represented in Fig. 1.

In Fig. 1, the iterative feedback loops indicate that for an ideal product life cycle, it is possible to improve upon the early stages of product development, by feeding back acquired knowledge and experience from the later stages hence optimizing the performance of the product through the entire life cycle. This iterative feedback is easy to implement and manage if a single enterprise is responsible for delivering the majority or all of the life cycle stages. If on the other hand, one or several stages of the life cycle are delivered by different enterprises, it becomes more difficult to fully implement and manage this knowledge feedback process; it becomes even more complicated when a product consists of subsystems that are designed and/or manufactured by several enterprises. Figure 2 shows an example of some of the different perspectives of a product/system life cycle. From Fig. 2 it can be seen that in most cases, the life cycle of the commercial manufacturer may repeat several cycles for every one cycle of a large integrated system when both life cycle perspectives are compared. The logic behind this is that the life cycle stages of most systems integrators run for a longer period especially for systems with a design life of several decades.

However for the high tech manufacturer, the time span is shorter with most of its life cycle stages coming before the operations phase of the systems integrator. Manufacturers are mainly involved in the early stages of design and production and only provide support during the operation stage. In some cases new subcomponents of the system may have to be re-developed or provided as spares or design upgrades in order to keep the system running; hence repeating the

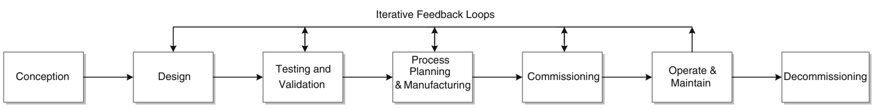


**Fig. 1** Generic life cycle stages as described in [5]

Typical High-Tech Commercial Systems Integrator

| Study Period | | | | Implementation Period | | | Operations Period | | |
|---|---|---|---|---|---|---|---|---|---|
| User Requirements Definition Phase | Concept Definition Phase | System Specification Phase | Acq Prep Phase | Source Select. Phase | Development Phase | Verification Phase | Deployment Phase | Operations and Maintenance Phase | Deactivation Phase |

Typical High-Tech Commercial Manufacturer

| Study Period | | | Implementation Period | | | Operations Period | | |
|---|---|---|---|---|---|---|---|---|
| Product Requirements Phase | Product Definition Phase | Product Development Phase | Engr Model Phase | Internal Test Phase | External Test Phase | Full-Scale Production Phase | Manufacturing, Sales, and Support Phase | Deactivation Phase |

ISO/IEC 15288

| | | | | |
|---|---|---|---|---|
| Concept Stage | Development Stage | Production Stage | Utilization Stage | Retirement Stage |
| | | | Support Stage | |

**Fig. 2** Various perspectives of the life cycle stages [6]

production cycle several times before disposal of the system. In order for both the high-tech manufacturer and the systems integrator to fully optimize through-life product performance, they both have to understand how their respective life cycle stages interact. Understanding and managing life cycles is a key ingredient toward achieving optimization. There are several concepts by the help of which engineers and project managers oversee the entire life cycle of a product/system. Westkämper et al. [7] described the term "Life Cycle Management" (LCM) as a means of considering the product life cycle as a whole, by optimizing the interaction of product design, manufacturing and life cycle activities. This is also popularly known as product life cycle management (PLM). There is a huge focus by manufacturers on integrating and optimizing their design and production processes. This is discussed further in the next subsection.

## *2.2 Integrated Design and Manufacturing Systems*

The process of developing and introducing a new product into the market has radically evolved, with the last five decades in particular seeing new manufacturing and management strategies beginning to surface, reflecting the dynamic nature of improvements in manufacturing applications [8]. Some noteworthy examples include Lean Manufacturing (LM), Just-In-Time (JIT), Concurrent Engineering (CE), Cellular Manufacturing (CM), agile manufacturing, responsive manufacturing, holonic manufacturing, distributed manufacturing, and collaborative manufacturing. Nagalingam and Lin [8] suggest that even though these new approaches were being developed every few years in the past decades, the concept of computer integrated manufacturing (CIM) is a far broader approach. Nagalingam and Lin [8] argued further that CIM is still able to embrace all these new approaches and provide the required features offered by these concepts or strategies.

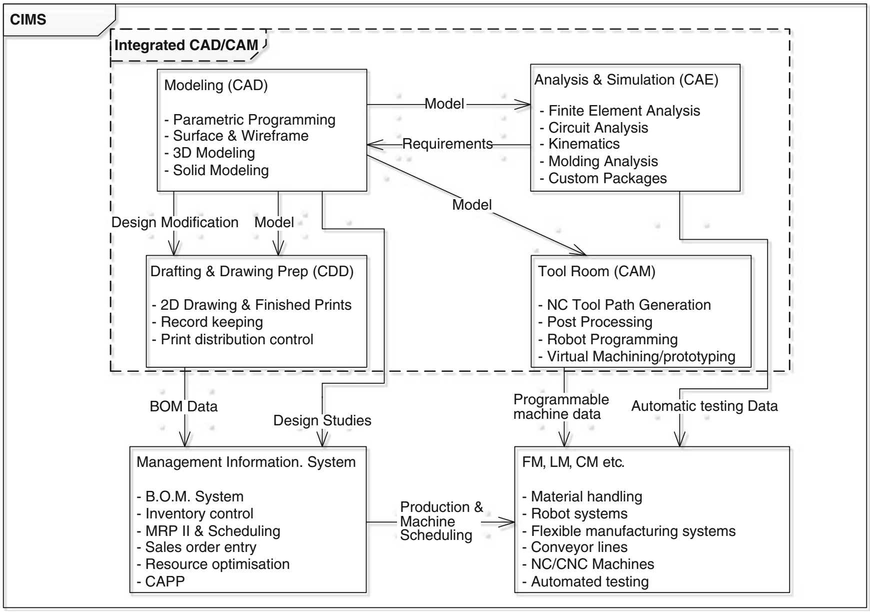


**Fig. 3** The concept of a computer integrated manufacturing system CIMS

The concept of CIM, which was initially proposed by Dr. Joseph Harrington in 1973 in a book published by the name “Computer Integrated Manufacturing” [9] but the acronym became well known in the 1980s [8]. CIM is the integration of the total manufacturing enterprise by using integrated information technology (IT) systems and data communication coupled with managerial philosophies that improve the efficiency of a manufacturing enterprise and its personnel. Another directly related concept is computer integrated manufacturing system (CIMS), which was described by Rzevski [10] as a system whose aim is to add value to manufacturing business by employing IT with a view to achieving an effective integration of all planning and control activities within an organization. This is achieved by integrating advanced technologies in various functional units to achieve corporate objectives [8]. Hence, having a CIMS as a manufacturing organization will help to drive other key manufacturing strategies (such as: CE, LM, FM etc.) that are vital to a business’ competitive advantage. Figure 3 shows the authors’ interpretation of CIMS from relevant literature, including Nagaligam and Lin [8], Rzevski [10], Beeby [11] and Harrington [9], in the area of integrated design and manufacturing. This consists of the integrated computer-aided design, manufacture and engineering (CAD/CAM/CAE) as well as additional managerial, planning and control activities.

## 2.3 Feedback and Re-Use of In-Service Data

Antecedent research by Markeset and Kumar [3], Goh and McMahon [2], and Hallquist and Schick [12] has also argued that the feedback of field experience data is necessary for product improvement. Markeset and Kumar [3] stated in their paper that this feedback is the key to improved products, product design and related work processes; while Goh and McMahon [2] argued that it is important to capture in-service knowledge, manage it, and make it available, from the product, system and people perspective, so as to improve new design projects. Markeset and Kumar [3] went even further by arguing that a product's reliability, availability, maintainability, and safety (RAMS) characteristics are an important part of product quality since these characteristics determine if the product performs according to specifications. This implies that product reliability is closely related to both product quality and the quality of the processes involved in delivering the product, hence agreeing with Madu [13]. However, in-service data does not include only RAMS data; it includes other forms of informal information such as customer satisfaction indices and communication between designers and service engineers. Recent work [14] by the authors of this paper proposed a framework for holistic life cycle approach for reliability centered maintenance (RCM) of in-service assets. Figure 4a depicts the proposed framework that summaries the findings from the paper, which emphasizes the importance of integrating RCM with other stages of the product life cycle. In the paper, Igba et. al. [14] argued that the integration can be achieved through design input to maintenance planning and feedback of in-service data to design through a product life cycle management (PLM) database. This can be achieved by a continuous knowledge accumulation cycle which follows the product life cycle framework from birth through to the disposal of systems. The vital steps in the learning process begin with in-service feedback through updating the PLM database with operational data. After this, the new designs are updated through redesign prompted by field knowledge and

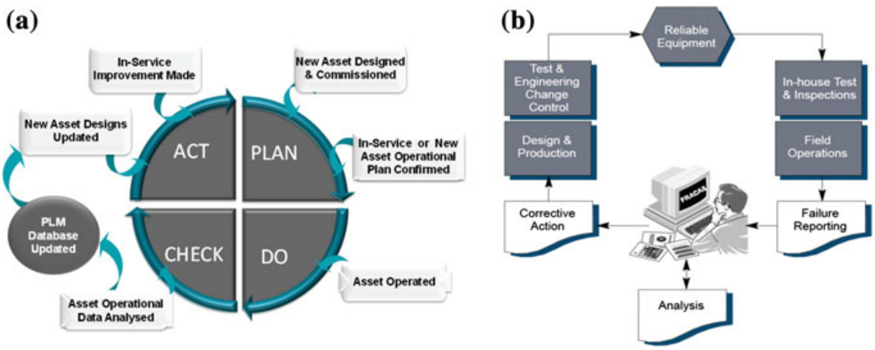


**Fig. 4** **a** Framework for holistic life cycle approach to RCM for assets [14], **b** high level FRACAS process [15]

experience and finally the design changes are implemented in the field either as upgrades or in an entirely new system.

Of relevance to this continuous knowledge accumulation is the process of feeding back in-service data, which Goh and McMahon [2] suggest can be achieved via two different means. The first being the personalization approach which is essentially concerned with the development of communities of practice and socio-technical models for enhancing company performance; while the second approach, codification, is concerned with an explicit form of knowledge through its capture and formal representation which allows it to be reused. This paper focuses on the codification approach to in-service feedback since they allow knowledge gained to be codified into suitable representation, stored and organized so that the information can be used at a later stage [2]. Figure 4b presents one key example of a structured and systematic way of documenting and utilizing field failure data. This technique is called “Failure Reporting and Corrective Action System” (FRACAS) and it is widely used in industry especially in military applications. FRACAS is a closed-loop process for in-service feedback and is commonly known as the closed-loop analysis and corrective action tool. Hallquist and Schick [12] identified three common issues surrounding the implementation of FRACAS in an organization—lack of prioritized goals, complex organizational interaction, and poor data traceability—and presented an eight step process as best practices for implementing FRACAS. The authors agree with Goh and McMahon [2], Hallquist and Schick [12], and Markeset and Kumar [3] who have all emphasized the importance of in-service feedback and have all outlined several issues surrounding the feedback process in their papers. Consequently, the authors will now attempt to take the findings from literature explored in this section further by proposing a framework for through-life optimization of large integrated systems.

## 3 An Integrated Framework for Through-Life Optimization

Optimizing a certain design variable during manufacturing can play a tremendous role in improving product performance during in-service operation. Considering an example where this may occur, in the manufacture of gearboxes for wind turbines, which are subjected to heavy contact loading, increasing the case-hardening depth of the gears can have a significant improvement in the number of load cycles the gearbox can withstand. The hardening depth specification is only as accurate as the specified design load which in most cases includes a safety factor. In a situation where failure of a gear during operation is linked with the case hardening depth, questions can be raised about the design load specification and the gearbox manufacturing process. In some cases, the design loads might have been underestimated leading to a lower hardening depth, while in other cases, this could reveal a potential flaw in the manufacturing process such as the heat treatment process or the gear teeth grinding, which led to the hardening depth being out of specification. Furthermore, the flaw might not be in the entire manufacturing process but in a certain batch which perhaps had some quality issues (perhaps due to wrong ambient conditions). Hence, being able to link field failures to a certain batch of the manufacturing process will not only help to improve quality control but also help to proactively monitor or replace the affected items while in the field preventing potential failure. In a situation where the design load has been overestimated, and where several years of field knowledge about operation conditions have been accumulated, proactive decisions can be taken to reduce the case hardening depth if it is known that the operating loads are well within the design loads and thus a smaller hardening depth is required. Reducing this depth implies savings in lead time and costs during the manufacturing process without affecting product performance.

Although the example above can be easily related to several engineering disciplines, it is however difficult to implement some of the changes in design and manufacture if adequate knowledge from the field operation is not fed back. The dilemma many companies face is how to capture, feedback, and re-use this knowledge when their sub-systems are manufactured by several suppliers. The following subsection presents a framework that will help manufacturers and system integrators understand how to feedback in-service data for life cycle optimization.

## *3.1 Integrating Multi-Perspective Systems with an Architecture Model Framework*

The proposed framework for integrated life cycle optimization has been modelled by combining a high-level SysML[1] use case diagram with the data flow model diagram[2] concept so as to capture both the flow of data and the interaction of the key stakeholders that are involved in the different stages of the lifecycle. Figure 5 shows the framework for setting up in-service data feedback in a formal and systematic way through integrating the already existing computerized maintenance management system (CMMS) of the customer with the CIMS of the manufactures through a central and shared engineering database. The framework also suggests some generic inputs and outputs for data flow and stakeholder communication and gives a high level overview of where ownership limits to the databases are for both the customer and manufacturers. This framework has been simplified and represented on the highest level and only serves as a guide toward capturing the whole picture. The key interactions that may exist between several departments within each enterprise (e.g., management, finance, and engineering) will depend on the

[1] SysML means Systems Modeling Language. For more visit http://www.omgsysml.org/.

[2] http://en.wikipedia.org/wiki/Data_flow_diagram.

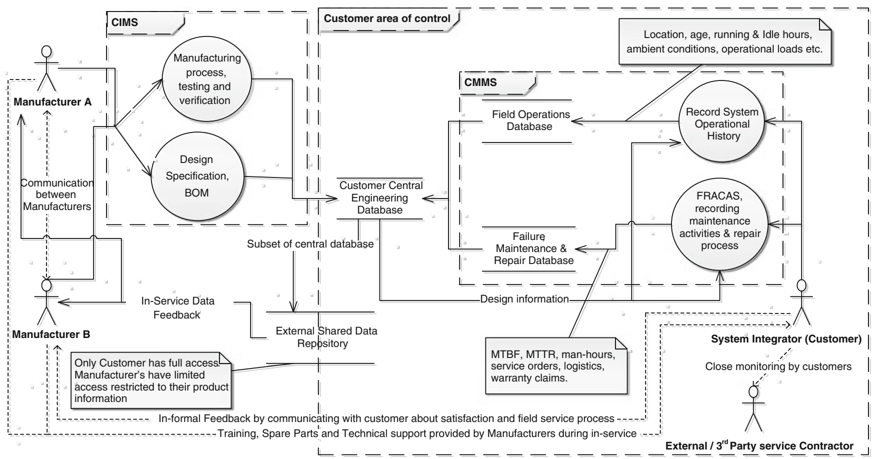


**Fig. 5** Framework for in-service knowledge feedback

organizational structure and culture in each enterprise. Furthermore the type and direction of the arrows indicate the type and direction of data flow respectively. The solid arrows represent the formal and codified data while the dotted arrows represent the more in-formal communication between the stakeholders. In-formal in this context implies that there is no formal and detailed documentation process (e.g., FRACAS) for such data flow, e.g., manufacturers may offer training and support to the service teams but may not fully document the entire process, however there will be an inherent flow of knowledge in both directions.

# 4 Discussion

## *4.1 Enablers for In-Service Data Feedback*

The first and most critical enabler is having the infrastructure for in-service data collection, feedback, and utilization. With the degree of complexity and large size of data, computer-aided tools have to be used for data collection. During service, a useful tool for feedback is a CMMS which consists of the daily RAMS records and also several operating data such as the ambient conditions, operational loads, temperatures, and running hours. Some industries have a separate system for condition monitoring which has a unique database that is linked to the central database. The ability to integrate a CMMS to the CIMS of manufacturers will accelerate the feedback of in-service data and this can be achieved by having one central engineering database which contains the CMMS and CIMS data as subsets and serves as a knowledge repository; hence making it possible to transfer data through the life cycle. Another critical enabler is the process of collecting, analyzing, and utilizing in-service data. The authors have argued that FRACAS is a useful method for reporting, analyzing, and utilizing operational data. However, FRACAS cannot be a stand-alone process and should be integrated with other processes such as RCM.

Also important as an enabler for this framework is the issue of governance with regards to ownership, accessibility, and interoperability of large integrated databases. This perhaps is the most important, especially when it comes to the willingness of customers to give manufacturers access to their data. Manufacturers should be willing to make their database structure compatible with their customers for better interoperability. Creating a shared database between the system integrator and key OEMs with different levels of access can be of great advantage. In a case where there are issues of accessing rights to a customer's database, data can be exchanged through an external source but in a unified format which can be easily uploaded to the manufacturer's database. Otherwise a web based portal access to selected data for each manufacturer can be created by the customer. For such a shared system to work, stakeholders must be willing to share the costs for setting up and maintaining the database or web portal. In a situation where the customer contracts a third party for the service of part or the entire system, service information and knowledge can still be captured by the designers through a similar online platform. However, the third party company may not necessarily have access to view critical design data since they are not explicitly involved in the design. This can be aided by specifying the need for mandatory data reporting as a key requirement before the third party service agreements are reached. The final enabler revolves around how to incentivize service engineers and technicians to document and report maintenance procedures and service information. Service engineers are concerned with resolving issues and bringing back a system to its running conditions as soon as possible, often being under time pressure [2]. This makes it more difficult for them to document service procedures given that their main definition of success is a system which is always running. Incentivizing the service engineers for data collection is a huge task and is worthy of separate research, perhaps building on the concepts presented in this paper. However, several methods such as those proposed by Hallquist and Schick [12] can be employed to enable good quality data collection. One way to address this issue is to establish other key performance indicators (KPIs) which would additionally measure the performance of service teams with respect data collection and help to motivate them. Equally important, companies must be willing to provide service engineers with the necessary tools and gadgets for making the process easy and quicker.

## *4.2 Utilizing Information and Knowledge Feedback*

Data has no value if it is not used for a purpose [3] and information re-use occurs when information is assimilated and used in new applications, yielding useful insights and knowledge [2]. In their paper, Goh and McMahon [2] discussed two key techniques that aid the re-use of in-service data. These are the information classification technique, and statistical analysis and data mining. The former uses taxonomy or classification to structure and organize in-service information making it easy to retrieve data. The use of similar terminologies between the manufacturers and customers is also a key for easy retrieval so that the manufacturers do not need to worry about translating vocabularies before analyzing in-service data and also it is easy to copy from one database to another if similar terms are used. Traceability of data is another key to data re-use. Markeset and Kumar [3] suggest that if data is time stamped and it has a well-defined context and background, it helps in understanding the process. Having time stamps and also linking records to individuals or teams can help track data quality to ensure that the source of poor or incorrect data is known. It can also help link operational data to service and maintenance records which can be used to identify trends and other attributes that can aid decision making toward continuous improvement and proper data analysis.

Although understanding the key enablers for data re-use can be vital to the feedback process, there are however, some pitfalls which if not identified or tackled will reduce the potential of data re-use through either poor data quality or poor interpretation. These pitfalls have been identified in literature as the existence of ineffective maintenance data management and a lack of knowledge in data processing techniques [2]. Companies should provide their employees with the necessary skills to be competent in each aspect of data feedback if not all the processes and enablers would have been put in place with no benefit.

## *4.3 Through-Life Optimization of Integrated Systems*

The preceding section presented a framework with key enablers for the collection, feedback, and re-use of in-service knowledge. Developing this further, the authors of this paper propose a model of a more holistic approach to through-life optimization of integrated systems. From the reliability point of view, the life of a component is described by the bathtub curve which relates the failure rate of the component to its age. This helps engineers to predict how long the component has until its useful life ends.

The system engineering domain adopts a unique life cycle model for designing and delivering integrated engineering systems called the “Vee model” Fig. 6a. The Vee model is widely used in the systems and software engineering field for designing and delivering complex integrated systems starting with the high level system requirements and system design through the detailed design and production of each sub-system/component. The left hand side of the Vee can also be seen to be the stages of defining/designing while on the right hand side are the stages of delivery. The authors have found the Vee model to be very useful in delivering the whole life of large systems. However, it is difficult to know the right time to commission a system and the right time to begin the redesign for upgrades or new

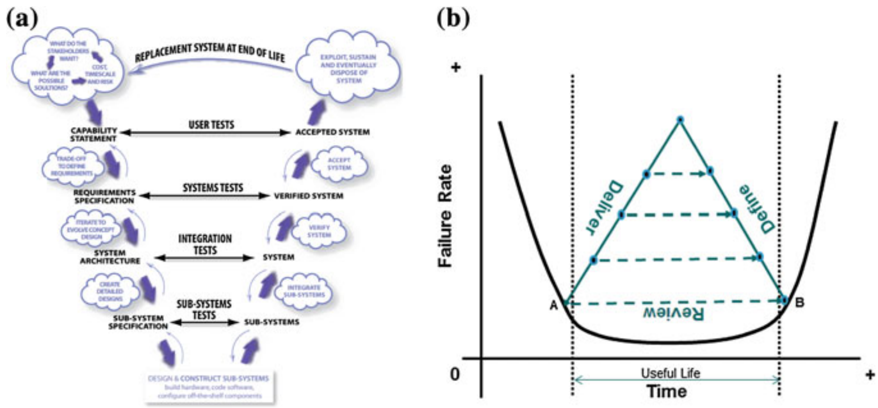


**Fig. 6** **a** The original "Vee" model [16]; **b** combined Vee and bathtub curve needed to support the proposed framework

systems, hence not fully utilizing the potential of the Vee model. Figure 6b shows an inverted Vee combined with the bathtub curve which the authors have chosen to illustrate the ideal through-life continuous optimization of engineering systems. In the bathtub curve, the best time to commission a system is just before its useful life phase (point A), where the burning-in failures have all been known and designed out. Here, the failure rate is within the constant and acceptable zone. This implies that the right end "deliver" of the original Vee model should end just before the beginning of the useful life. Furthermore, the best time to start redesign or new system design is when the useful life is about to end (just before wear out begins, Point B). This implies that the left end "design" of the original Vee model should begin just before the useful life ends. This aligns the time at which a new system is delivered to the time the old one is decommissioned saving costs and time. This also applies to sub-system redesign. This model can be used for life extension plans where critical sub-systems can be redesigned at the end of the useful life to keep extending the life time of the system by shifting the bathtub curve more to the right.

## 5 Conclusion

This paper has presented a framework for the through-life performance optimization of a system through the feedback and use of in-service data for design and manufacturing continuous improvements. The paper has presented and discussed relevant literature in the context of in-service feedback and life cycle optimization and also highlighted the key challenges many manufacturing enterprises and system integrators face in collecting and using in-service data for design improvements. The framework is proposed as a guide in decision making toward setting up a link between the formal and informal in-service data sources and integrating them to already existing integrated manufacturing, maintenance, and management systems. Future research should look to operationalize the concepts presented in this paper, perhaps through a case study to better understand the detailed process of the proposed framework's implementation and application.

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## References

1. Poeth DF (1990) Concurrent engineering—key to cost-effective product reliability, maintainability and manufacturability. R&M CAE in concurrent engineering workshop
2. Goh YM, McMahon C (2009) Improving reuse of in-service information capture and feedback. J Manuf Technol Manag 20(5):626–639
3. Markeset T, Kumar U (2003) Integration of RAMS information in design process—a case study. In: Proceedings of reliability and maintainability symposium, 2003
4. ISO/IEC (2008) ISO/IEC 15228: systems and software engineering—system life cycle processes, 2008
5. Thimm G, Lee SG, Ma Y-S (2006) Towards unified modelling of product life-cycles. Comput Ind 57:331–341
6. INCOSE (2007) INCOSE systems engineering handbook version 3. In: Proceedings of international council on systems engineering, 2007
7. Westkämper E, Alting L, Arndt G (2000) Life cycle management and assessment: approaches and visions towards sustainable manufacturing (Keynote Paper). CIRP Ann Manuf Technol 49(2):501–526
8. Nagalingam SV, Lin GC (2008) CIM—still the solution for manufacturing industry. Robot Comput Integr Manuf 24:332–344
9. Harrington J Jr (1973) Computer integrated manufacturing. Industrial Press Inc., New York
10. Rzevski G (1987) The concept of computer integrated manufacturing system architecture. In: Proceedings of 4th European conference on automated manufacturing, Bedford, 1987
11. Beeby W (1982) The future of integrated CAD/CAM systems: the Boeing perspective. IEEE Comput Graphics Appl 2:51, 52, 54–56
12. Hallquist EJ, Schick T (2004) Best practices for a FRACAS implementation. In: Proceedings of reliability and maintainability annual symposium, 2004
13. Madu CN (1999) Reliability and quality interface. Int J Qual Reliab Manage 16(7):691–698
14. Igba J, Alemzadeh K, Anyanwu-Ebo I, Gibbons PM, Friis J (2013) A systems approach towards reliability-centred maintenance (RCM) of wind turbines. In: Conference on systems engineering research, Atlanta, Georgia, 2013
15. Villacourt M, Govil P (1994) Failure reporting and corrective action system. In: Proceedings of SEMATECH, 1994
16. RAEng (2007) Creating systems that work: principles of engineering systems for the 21st century. In: Proceedings of Royal Academy of Engineering, 2007

# Advanced Product and Process Design Through Methodological Analysis and Forecasting of Energy Consumption in Manufacturing

**Tim Spiering, Stephan Kohlitz and Harald Sundmaeker**

**Abstract** Energy and resource efficiency is becoming an important factor in manufacturing, helping to avoid bottleneck situations in times of sparse resources. Sustainable products are promising new improvements and are attracting customers more than ever. In the automotive industry, the assessment of the environmental impact of a product in use phase is already common practice. In contrast, the manufacturing phase often lacks detailed data. Product and process designers can benefit from reference data serving assessments, whether improvements were achieved compared to theoretical average values. This is most relevant for complex manufacturing processes like injection molding with non-linear relationships toward the degree of optimality. The paper presents a systematic approach for realizing and using a knowledge base facilitating advanced product/process design decisions. This knowledge base can be used to verify energy related hypothesis, enabling to create design rules and identifying weak points in processes. With an increasing database, energy consumption of similar new/planned products can be forecasted. The approach facilitates to assess decisions and investments in efficiency measures from an ecological and economical point of view, also serving as basis for detailed internal and external reports. It was applied and validated for production of plastic parts in the automotive industry.

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# 1 Introduction

Politics promote energy and resource efficiency as a main driver to create an environmentally less harmful economy [1]. Besides the EU proposals for reducing $CO_2$ emissions in use-phase, the automotive industry for example is aiming at ECO-innovations of engine, powertrain, and part related technology. Companies become more and more aware that a market segment significantly favoring environmentally friendly products is fast growing. Ideally an environmentally friendly product should not only consider the use-phase but also the manufacturing phase. Currently, there is a lack of information regarding energy efficiency of many production processes. Especially in times of withering resources, consequent analysis of production processes also in terms of energy efficiency is a vital basis for making improvements. The reduction of energy and resource consumption during manufacturing is a key opportunity to lower costs. In the past, especially the input factor energy was mostly seen and treated as an invisible resource and overhead costs. The resulting deficit in transparency toward energy consumption in production processes is one major reason for a phenomenon called efficiency gap. The efficiency gap describes the difference between actual efficiency level in production and the technically postulated efficiency level [2]. Instruments and methods are needed to allow a monitoring of resource consumption for specific products or processes. Best practice examples need to be identified and measures to foster efficiency have to be economically and ecologically evaluated. To promote a sustainable change, such methods or instruments need to be efficient themselves and thus not increasing overall costs.

In this paper, we are presenting an approach to significantly increase the knowledge about energy consumption with respect to production of plastic parts in the automotive industry. The approach is based on demand driven monitoring of energy consumption on unit process and therewith very technical level. It is reflecting the restrictions of productive environments, especially avoiding interferences and taking into account the process-time relation. A knowledge base serves as a baseline for a method to assess and estimate energy consumption for specific products. The approach enables manufacturers to benchmark process designs and identify products with a leading impact on energy consumption. This facilitates the development of economically and ecologically sustainable strategies.

# 2 Theoretical Background

## *2.1 Energy Efficient Production of Plastic Parts*

To achieve a more environmentally friendly production, there are basically two options available: Technology and/or processes can be optimized. While the first option mainly aims at reducing the average consumption of energy or material, the second approach usually focuses on reducing the "time for value"-creation. In injection molding, which is the most relevant manufacturing process for automotive plastic parts, electric energy is the most important source of energy. It can be easily provided and allows fast production cycles. The main drivers for energy consumption in injection molding are the injection molding machine, cooling system, material dryer, and take-out-system (e.g., robot or handling system), see Fig. 5. Other sources of energy, e.g., pressurized air for take-out systems, can in most cases be traced back to electrical energy. Therefore, it is reasonable to focus on electrical energy as a parameter for energy efficiency. A good key performance indicator (KPI) for energy efficiency of an injection molding processes is the "energy used per ok-part." It is important to emphasize the "ok-part." Especially when looking at processes demanding high quality, the scrap-rate must not be neglected. Scrap usually means that energy and resources get lost (including pre-processes), it is a main driver for energy consumption. The scrap related energy consumption should therefore be added proportionately when calculating the energy used per "ok-part." So the KPI is comparing the wanted outcome of the value-creation with the full amount of energy used.

One possibility to reduce energy consumption is therefore to reduce material usage. Since production part weight is defined by product design, material usage can only be influenced at production level by minimizing scrap rates. One example is using hot-runner-systems for injection to minimize material usage for gates as well as cold-runners and—if possible for the plastic material used—reuse scrap material. Obviously, the technological level of the injection molding machine used for production can have a strong impact on the performance and energy efficiency [5, 6]. The injection mold also can have huge influence on energy efficiency, as it is directly linked with production speed (especially cooling time) and scrap rate. Besides technological aspects, the machine operator remains as a key factor for efficient molding processes. The operator's goal is to set up stable and efficient processes for a specific combination of mold and machine. Considering machines and molds as existing equipment, the key to energy efficient production processes is combining the machines and molds in a way that minimizes the target function "energy use for production program."

## *2.2 Energy Monitoring and Benchmarking*

Industrial environments incorporate a wide range of stakeholders who can benefit from or demand energy related data. While the maintenance department can enhance their services, a growing group of customers demand accountability for the environmental impact of their product choice. Energy related data in industrial environments can be structured to three different levels which are factory level, department level, or unit process level [3]. The highest level of detail can be found on unit process level. Data on this level is usually structured according to the value-creation in contrast to the organizational structured other levels. Concerning technical improvements, energy related data on unit process level offers highest benefit. Bunse et al. notice that only few studies engaged energy related indicators for process level so far. They also found out that especially ICT tools and standardization can be major drivers for the improvement and measurement of energy efficiency in production processes [4]. Currently, the main goal in production is to maximize output without compromising quality. Saving energy as a new additional goal is sometimes perceived as being in conflict to quality or maximizing output [5]. For instance, measurements or the implementation of energy efficiency measures will most probably cause interferences in production. Resources will in most cases only be granted by decision-makers if energy related activities can justify their expenses by economic and ecologic improvements. A useful KPI to compare the energy efficiency of processes is the specific energy consumption (SEC), which in case of injection molding is commonly defined as the relation between energy consumption and material mass processed. Qureshi et al. performed energy measurements on an injection molding process and evaluated the SEC where they continuously varied process parameters. They determined main parameters with influence on the energy consumption by using the SEC. Furthermore, by comparing SEC to throughput, they were able to build an energy consumption prediction model based on process parameters [7].

Focusing on the implementation of efficiency measures and the precise calculation of their economic and ecologic advantages, Thiede, Spiering, and Kohlitz developed a dynamic production process simulation. They specifically used the key figure energy consumption per sub-phase of a process to identify process inefficiencies and possible points of action. They furthermore combined energy related data with maintenance data, which is already collected in most companies, to create a combined model serving to identify measures which in parallel increase energy efficiency and productivity [8]. To estimate the entire environmental impact of industrial processes or products, the method Life Cycle Assessment (LCA) has been developed to determine the entire environmental impact of products. Beyond consumption of electric energy it integrates every kind of emission "from cradle to grave" into an assessment. A very important stage, when performing a LCA, is the "inventory stage" and it is also currently the weakest point of the entire method [9]. Some LCA models for injection molding try to allocate the energy intensity of processes based on specific energy consumption (SEC) [6]. Information about part weight and productivity and average energy consumption in exemplary processes is needed in this case. However, depending on the quality of the reference data, a high generalization level due to vast differences in machine and also part characteristics might produce wrong outcomes initiating wrong actions. Weissmann et al. therefore propose a LCA model which includes more parameters available in CAD design [9]. The higher quality has the trade-off of higher complexity concerning deployment in a productive environment.

## 2.3 Knowledge Base for Energy Efficient Product and Process Design

Product and process design in manufacturing cannot be considered as pure sequential workflows. Usually, the designs of products, related tools as well as production processes represent concurrent engineering tasks. Engineering change orders (ECOs) in one area can have a significant impact on other design workflows. At the same time, maintenance and production shall provide data that can be used to assess the energy efficiency of specific design choices. Diverse ICT tools like CAD, CAE, or CAM are in place. Service based approaches can help to work in such environments and the elaboration of a knowledge base can satisfy the needs for an energy efficiency analysis. The compatibility to existing data models facilitates setting up such knowledge bases. Data import and export is required, which needs to be simplified as far as possible to avoid laborious adjustments of systems and infrastructures. A standardized interchange format, based on a related data model needs to be developed. There are different examples available that structure manufacturing data based on grouping of objects and putting elements in a defined relationship for reusable ontologies [10]. As outlined by [11] the association of object models with engineering models facilitates conceptual communication about the engineering models between domain experts and knowledge engineers.

As defined in the scope of architectures for enterprise integration by [12], life cycles apply to the enterprise itself and to its products at the same time. Similarly, this principle applies to the product, tools, and machines. Therefore, a knowledge base has to be as generic as possible to be compatible with different life cycle views. At the same time it needs to be specific enough by incorporating relationships of objects and detailing the object's attributes. Efforts for setting up a knowledge base can be reduced by reuse of basic data models extended with attributes for the specific application. This basic preparatory work was accomplished in coordination with the monitoring and benchmarking approach. On top of that, a tool supported methodological approach enabling to set-up collaborative working environments with stakeholders from design, maintenance, and production was elaborated. This paper is specifically outlining the methodological approach for analysis and forecasting. Further work was realized by developing a software tool that directly enables the stakeholders to dynamically access and generate knowledge relevant for design, maintenance, and production. It is currently under finalization and will be published soon.

# 3 Concept Development for Knowledge Base Approach

## *3.1 Objective, Approach and Research Demand*

The approach is specifically taking into account the evaluation of energy efficiency in process and product assessments. In comparison to other approaches [6–9], the work is focusing on current process related needs and considers boundary conditions in productive environments. Therefore, the key objective was to enable an easy integration into daily practice as well as in the available ICT infrastructure. Decision makers in the manufacturing organization are directly supported by providing an economically reasonable level of transparency with respect to energy consumption. Cost-centers are able to assess and report their energy and resource efficiency improvements for different time periods. Beyond the structuring and reuse of ontologies and architectures as recommended by [11, 12], additional principles were developed for acquiring and accessing the relevant data considering different life-cycle phases. Considering the reference data model, as also developed for other processes like in [10], an ICT support enabling product and process engineers to analyze energy efficiency related data was realized. Flexible analysis functionalities and intuitive usability at the same time require no specific ICT skills to interact with a large knowledge base. Different types of reports can be made available and KPIs can be accessed based on individual product or process analysis. The approach allows assessing and comparing any measure to reduce the energy consumption and can therefore be used for long term investment planning.

## *3.2 Conceptual Framework*

The underlying idea is to elaborate a supporting control system for design of products and processes in manufacturing industry. Especially human operators (HO)—designers as well as maintenance and production staff—shall be intelligently supported in improving designs, measurements, and decisions on improvements. To realize such an approach, Stokic, Kirchhoff, and Sundmaeker elaborated a reference architecture for Ambient Intelligence systems that is structuring the main components for realizing control systems [13]. Main element is to provide the appropriate information to the HO based on the context in relation to the ambience, the process, and the organizational environment (e.g., plant). Key prerequisite is the definition of the required (observable) knowledge that serves as input of control related features. There is a need for knowledge about HOs, the process and the context to provide explicit input to HOs [13, 14].

Based on this reference model, a conceptual framework was elaborated to develop and use a knowledge base for methodological analysis and forecasting of energy consumption in manufacturing environments. From a system functionality perspective, a software component was realized that provides a collaborative environment for HOs and is principally based on a kind of plan-do-check-act cycle. Designers can communicate their need for knowledge that would facilitate the design of products or processes. Maintenance is put in the role as recipient of requests and is supported to plan, optimize and carry out measurements. From the energy related data collected, KPIs for other stakeholders are derived. The functionality is quite generic and first evaluations showed its applicability in different manufacturing domains with minor adaptations. The baseline to realize this supporting system was the availability of an appropriate data model that could represent the different types of knowledge required for an intelligent support of HOs. As outlined in Sect. 2.3, different types of manufacturing domains and life cycle perspectives need to be supported. A detailed ontology was elaborated. The collaborating team was enabled to adapt the more generic model and create a common data model. It is used for the tool supported generation of Java classes and the object/relational mapping. This enabled an easy reconfiguration of the common data model, thereby reducing the effort for changes. Key factor for the success was the early and continuous integration of users into the development process.

## 4 Continuous Process Improvement Using Energy Related Data

As stated above, transparency about energy consumption is of crucial importance. To achieve this, measurements on energy consumption in production need to be performed. The approach is based on energy measurements according to the monitoring procedure for unit process level described by Bogdanski, Spiering, and Li [15]. Single energy measurements with mobile devices on older machines or results from continuous measurements from integrated energy measurement devices in newer machines are used. If equal consumers of electric energy are included in the measurement the following analysis of the data is not affected by how the data was collected. Measurement results are analyzed in a standardized procedure to derive the key figures SEC versus throughput, $SEC_{product\ weight}$ versus. product weight, energy intensity (total energy consumption per part) and energy intensity per standardized process sub-phase. Thereby, the key figure $SEC_{product\ weight}$ is defined as the relation between energy consumption during one cycle and product mass in one cycle instead of the mass processed used to calculate SEC. Using these key figures, processes can be benchmarked and weaknesses can be identified.

## 4.1 Considered Use-Case

The approach was applied in a large production facility, manufacturing various plastic parts for the automotive industry. The observed machine park consisted of 93 different injection molding machines with significant differences in technological level and year of manufacture, ranging from 500 kN clamping force to 27,000 kN clamping force. The observed product portfolio consisted of about 500 different products for the interior as well as exterior of automobiles. Consequently, processes have different requirements toward visual and mechanical quality. Over 50 different plastic materials are used for this portfolio. For some injection molded parts, two paint shops and three small assembly workshops complete the manufacturing process chain in the production plant. On management level, the goal to improve energy efficiency by 25 % during the next upcoming 6 years was set. Measures to achieve this goal had already been implemented and energy savings had been achieved. However, the increase in energy efficiency could not be reported, assessed, and planned since the total energy consumption so far could not be put into relation to a reasonable allocation base, describing the varying value-creation respectively output of the factory. Such an allocation base has to respect the vast differences in energy efficiency of injection molding processes between e.g., small parts made of Polycarbonate processed at temperatures around 290 °C and large parts made of Polypropylene processed at temperatures around 230 °C. Otherwise, the efficiency level reported is depending on market demand. If, e.g., the amount of material processed would be used as an allocation base to measure the efficiency, the reported energy efficiency would be plummeting in case the production plant would be forced to mainly produce very small parts in small molds, since the SEC of larger parts is usually smaller [6].

## 4.2 Product Related Forecasting of Energy Consumption

As described in Sect. 2, the relation between SEC and throughput found in empirical measurements is significant enough to be modelled mathematically. In the considered use-case, 43 measurements of the consumption of electric energy in different injection molding processes have been conducted and analyzed according to the procedure described in [8, 15]. For a single measurement, process data (used material, cycle times) and energy measurement data are analyzed and put into a relation in a standardized procedure. Due to the standardization, the results can be consolidated in the knowledge base described in Sect. 2.3, allowing comprehensive analysis over all measurements. In Fig. 1 this possibility was used to look at the relation between material throughput and SEC. Measured processes can be compared in terms of energy efficiency by determining their position in relation to the curve modelling the relation between SEC and throughput. Also, the expected energy consumption of new processes can be determined. However, certain

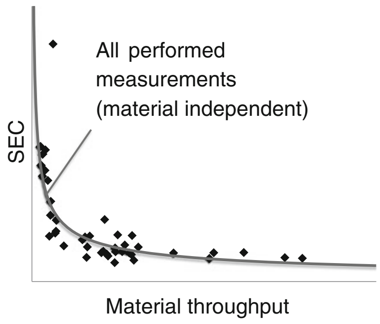


**Fig. 1** Relation between material throughput and SEC for 43 injection molding processes

problems arise: Although the technological level toward energy efficiency is quite equal between the machines in the use-case, the process efficiency and corresponding energy efficiency is always determined by the unique combination of machine, mold product design, peripheries, and process parameters. This is the reason for the statistical spread in Fig. 1, characterized by a coefficient of determination of about 70 %. Also, looking solely at the material throughput (without considering different material groups) as an input to forecast and compare energy efficiency might obscure effects of efficiency measures and produce misleading results. High throughput should be pursued in production; core competence of a production line is to manufacture products at desired quality with low scrap rates. Using cold runners for example increases the throughput, but looking at the entire process and its outcome, hot runners are often more energy efficient [16]. Also, it is complicated to get a correct assumption for material throughput at design stage since cycle time often cannot be forecasted precisely enough.

Therefore, material throughput was replaced by “total product material used per one cycle” as input parameter. This parameter is usually constant during the product life cycle and can be calculated by multiplying product weight with the number of cavities in a mold. It is easy to obtain in practice, as the product weight can be well estimated even at design stage. Taking the product material used in one cycle as a parameter instead of throughput, the effect of energy efficiency measures can be validated more easily at an early stage. The relation between entire product mass in a cycle and $SEC_{product\ weight}$ related to the product weight could be modelled with an exponential function for the measured processes. As expected, the coefficient of determination was below the correlation between SEC and throughput, but with 57 % quite low.

Referring to Sect. 2.1, energy consumption in injection molding is significantly influenced by the used material. Specific requirements like very high stability or piano lacquer optic is often attained by using a specific material. The used material (at least the material class) is—like the product weight—an easily accessible parameter. We therefore grouped the measurements according to material classes. The relation between product weight and material-specific $SEC_{product\ weight}$ has been analyzed, exemplary results for three groups are shown in Fig. 2. Mathematical functions could be derived which describe the relation between product

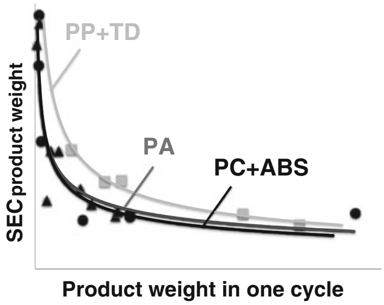


**Fig. 2** Relation between product weight in one production cycle and $SEC_{product\ weight}$, differentiated in material groups

weight and $SEC_{product\ weight}$ with coefficients of determination ranging from 64 to 97 % maximum over all established material groups to comprise the entire product portfolio. Energy efficiency curves have been deduced to describe the expected energy consumption of a random injection molding process depending on material group and product weight processed in one cycle (assuming the technological level will be utilized which was present at the time the energy measurements have been conducted). Due to the focus on product weight it is possible to reliably assess and report improvements in energy efficiency without influence of externally induced changes to the product portfolio as described in the following.

## *4.3 Product Related Energy Efficiency Assessment for Single Processes*

Given the material group based relations between product weight in one cycle and $SEC_{product\ weight}$, it is possible to establish a process assessment and benchmarking. For example, a new process for the production of a new product using a blend of Polypropylene and talc with a product weight of 100 g, produced on a mold with two cavities, shall be evaluated. Using the mathematical model from Sect. 4.2, for the current technological level an energy consumption of 8 MJ/kg can be expected as pictured in Fig. 3. After establishing the real process in production, the actual efficiency of the process can be evaluated via measurements and its positive or negative deviation toward set efficiency goals can be evaluated.

If the process is as efficient as expected and therewith positioned on the curve as shown in Fig. 3, the three approaches described in Sect. 2.1 are available to decrease the energy consumption. Any kind of effective efficiency measure, independent from how savings are achieved, leads to a shifting on the y-axis as shown in Fig. 4. If an efficiency goal is set for the portfolio, its fulfillment can be controlled for each single process. Consequently, more efficient processes placed below the curve can be analyzed in detail and be compared with less efficient processes to gain process or product design knowledge and rules.

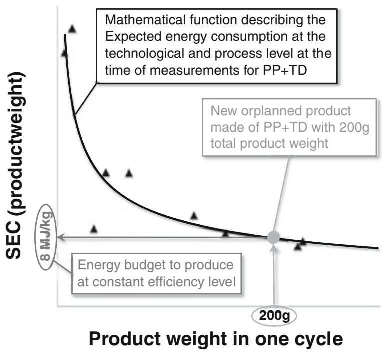


**Fig. 3** Expected energy consumption for a new process

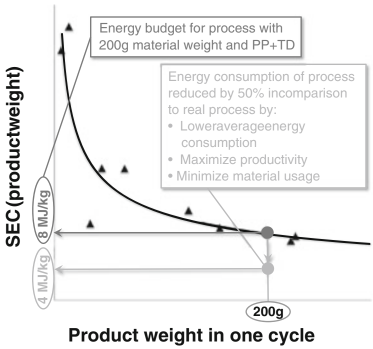


**Fig. 4** Identifying more efficient processes

## *4.4 Product Related Energy Efficiency Assessment of Cost-Centers*

So far, we are only looking at the energy consumption arising in the system *injection molding machine and direct periphery* in production state. Energy consumption due to machine idle states or centralized energy consumers like cooling water or compressed air supply are so far not assessed. It would be possible to additionally monitor all these sub-processes, this however would become costly. Therefore, a new key performance indicator (KPI) is established to monitor the energy efficiency in an entire facility related to the value-creation in production with minimized effort. Energy efficiency means to achieve a pursued benefit with minimum energy input [17]. For an injection molding facility or cost-center, the benefit is equal to the products produced at desired quality. The energy input on factory level is corresponding to the entire energy consumption in the entire facility, integrating even the consumption in office areas. In contrast to the individual processes, this figure is commonly well monitored since it's the basis for the monthly energy cost bill. As explained in 4.1, energy KPI's to report energy efficiency must not be driven by market demand. By calculating the amount of material processed during an assessment period, a so called energy budget for the production of a certain amount of certain products can be calculated. The sum of all products' individual energy budgets represents the facilities energy budget for the direct value-creation. The energy budget versus. the entire energy consumption of the facility is a KPI which measures the current energy efficiency level of an entire cost-center as shown in Eq. 1. With this KPI, the energy efficiency level of an entire injection molding cost-center can be determined independent from factors mainly determined by the customer. It is however still possible for the manufacturer to determine which materials and products are more efficient, as shown in Sect. 4.3.

$$EE_{cc} = \text{Energy Efficiency}_{\text{cost-center}} = \frac{\text{Energy Budget}_{\text{cost-center}}}{\text{Total Energy consumption}_{\text{cost-center}}} \tag{1}$$

Improvements in the direct and indirect productive environment become visible using this KPI. Measures influencing the energy efficiency of the direct production processes decrease the denominator by reduced energy intensity; measures influencing the indirect energy consumption like lowered idle-consumption during setup times likewise decrease the denominator. Both times, the energy efficiency coefficient is increased. So far, reducing the energy consumption by decreasing the amount of scrap does not become visible in the KPI. The reduction of scrap is a major lever to reduce the environmental impact of production. At least the energy lost during manufacturing in the own cost-center should be considered. When calculating the energy budget of the cost center, the scrap rate can be integrated as an additional factor like shown in Eq. 2. The modified KPI still accounts an efficiency level, which is independent from external factors. The KPI is applicable for external reports, especially if improvement goals are set. It is also applicable for internal reports, assessments, and benchmarking since it is based on a procedure which allows a precise assessment of every production process.

$$EE_{cc} = \frac{\sum_{i=0}^{all\,products} SEC_{product\,weight,\,i}^{expected} \cdot products\,produced_i \cdot product\,weight_i \cdot number\,of\,cavities_i \cdot (1 - scrap\,rate_i)}{\text{Total energy consumption}_{\text{cost-center}}} \tag{2}$$

*Example* If a cost-center would produce 125,000 shots in 1 cavity of a product weighing 1,000 g with an average $SEC_{\text{product weight}}$ of 0.8 MJ/kg and a scrap rate of 5 %, the term in the enumerator would be 95,000 MJ, reflecting the expected energy consumption. In case, the measured energy consumption of the cost-center was 100,000 MJ, the EEcc would be 0.95. By regularly reporting on EEcc, improvements in energy efficiency can be made visible compared to the technological level for which $SEC_{\text{product weight}}$ curves were determined.

# 5 Application and Conclusion

## *5.1 Forecasting the Direct Energy Consumption Due to Value-Creation*

Before the approach was applied, it was validated that the curves derived from the energy measurements realistically reflect the direct energy consumption of the production plant. Two comparable injection molding cost-centers with installed energy measurement devices to monitor the energy consumption of indirect consumers could be used as a reference for this purpose. We used these values to obtain good appraisal values for the energy consumption of lighting, cooling device, centralized material dryers, assembly places, and office areas for our use case. To get an appraisal value for the energy consumption due to machines in idle or stand-by state, we carried out additional measurements and combined this data with information about machine states from operating data logging. The remaining energy consumers in the considered cost-center, ventilation and a small paint shop were measured directly. We added all these values to obtain the expected total energy consumption of the cost-center for an already completed business year. In comparison to the measured value from this year, the deviance was below 1 % as shown in Fig. 5. Therewith, it is proven that the approach is able to obtain a quite precise estimate for the direct energy consumption due to a specific production portfolio, basing on the process and technology level present during our measurements. In the upcoming 6 years, it is now possible for the cost center to assess its improvements regarding energy efficiency by monitoring the development of the EEcc indicator, which can also be reported to the management board. In comparison to the base year, this indicator should be lowered by at least 25 % to fulfill the company goals.

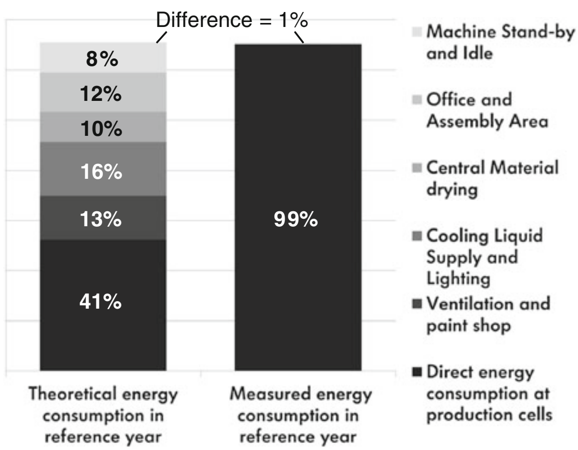


**Fig. 5** Accuracy of predicted energy consumption in comparison to measured energy consumption

## 6 Identifying Process Weaknesses and Efficiency Measures

The approach also enables to identify more efficient processes and therewith facilitates energy efficient product and process design. First of all, the approach enables to benchmark the achievements regarding energy efficiency of the cost center with others to identify best practice efficiency measures. Additionally, single processes can be compared to each other. In Fig. 6, injection molding processes for parts made of Polypropylene and blends of Polypropylene with glass-fibers are displayed. Here, processes are highlighted, which are comparable to each other but differ regarding energy efficiency. In Fig. 6, cost saving potentials of newer machine generations, having more expensive but more energy efficient actuation could be evaluated. Furthermore, it became visible that running molds with less than the maximum number of cavities leads to very low energy efficiency in production. These results can be directly transferred into knowledge for buying new machines or designing new molds. An extended solution on how to use such energy analyses to derive and evaluate efficiency measures is shown in [8].

## 7 Outlook and Acknowledgements

Future work will focus on further enhancing the measurement database which will allow detailing the assessed material groups in terms of product use. We will thereby further integrate the automatized energy measurement on newer machines and the measurement of the consumption of other media like cooling liquid or compressed air. The approach is working for the production of plastic parts; future work should test the application on other product portfolios.

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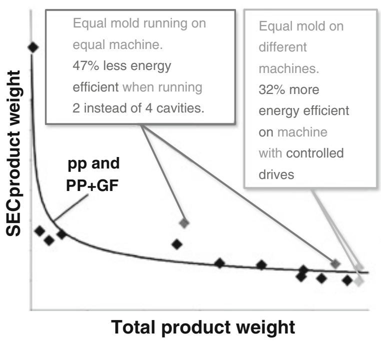


**Fig. 6** Identifying process weaknesses and energy efficient solutions

## References


1. European Commission (2010) Communication from the commission Europe 2020. In: Proceedings of COM 2020 final, 2010
2. Schmid C (2004) Energieeffizienz in Unternehmen—Eine wissensbasierte Analyse von Einflussfaktoren und Instrumenten. vdf Hochschulverlag AG an der ETH Zürich, Zürich, pp 16–17
3. Kara S, Bogdanski G, Li W (2011) Electricity metering and monitoring in manufacturing systems. In: Proceedings of the 18th CIRP LCE, Braunschweig, Germany, pp 01–10, 2011
4. Bunse K, Vodicka M, Schönsleben P, Brülhart M, Ernst FO (2011) Integrating energy efficiency performance in production management. Clean Prod 19:667–679
5. Pamminger R, Wimmer W, Winkler R (2010) Entwicklung von Kriterien zur Kommunikation der Energieeffizienz von Kunststoff verarbeitenden Maschinen. BMVIT, Wien, Austria
6. Thierez A, Gutowski T (2006) An environmental analysis of injection moulding. In: Proceedings of the 2006 IEEE international symposium on electronics and the environment, Scottsdale, AZ, USA, pp 195–200, 2006
7. Qureshi F, Li W, Kara S, Herrmann C (2012) Unit process energy consumption models for material addition processes: a case of the injection molding process. In: Proceedings of the 19th CIRP LCE 2012, Berkeley, pp 269–274, 2012
8. Thiede S, Spiering T, Kohlitz S, Herrmann C, Kara S (2012) Dynamic total cost of ownership (TCO) calculation of injection moulding machines. In: Proceedings of the 19th CIRP LCE 2012, Berkeley, USA, pp 275–280, 2012
9. Weissmann A, Ananthanarayanan A, Gupta SK, Sriram RD (2010) A systematic methodology for accurate design-stage estimation of energy consumption for injection molded parts. In: Proceedings of the ASMA 2010, Canada, 2010
10. Sundmaeker H et al (2004) Integration of concurrent engineering business processes and information systems in the virtual enterprise, EMISA 2004—information systems in e-business and e-government. Luxembourg, pp 187–198, 2004
11. Lin LF, Zhang WY, Lou YC, Chu CY, Cai M (2011) Developing manufacturing ontologies for knowledge reuse in distributed manufacturing environment. Int J Prod Res 49(2):343–359
12. Williams TJ (1999) The Purdue enterprise reference architecture and methodology (PERA). In: Proceedings of handbook of life cycle engineering: concepts, models and technologies, Springer, pp 289–331, 1999
13. Stokic D, Kirchhoff U, Sundmaeker H (2006) Ambient intelligence in manufacturing industry: control system point of view. In: Proceedings of the eighth IASTED CA 2006; Montreal, Canada, pp 63–68, 2006
14. Scholze S, Sundmaeker H, Kirchhoff U (2008) Ambient intelligence technologies for industrial working environments in manufacturing SMEs. In: Proceedings of 14th international conference on concurrent enterprising, Lisboa, Portugal, pp 71–78, 2008
15. Bogdanski G, Spiering T, Li W, Herrmann C, Kara S (2012) Energy monitoring in manufacturing companies—generating energy awareness through feedback. In: Proceedings of the 19th CIRP LCE, Berkeley, USA; pp 539–544, 2012
16. Wortberg J, Michels R, Neumann M (1997) Energieeinsparpotentiale in der kunststoffverarbeitenden Industrie. Energie und Management, 1997
17. Müller E, Engelmann J, Löffler T, Strauch J (2009) Energieeffiziente Fabriken planen und betreiben, Springer, 2009

# Cost-Based Evaluation for Product Selective Disassemblability

**Qingjin Peng, Yongtao Luo and Peihua Gu**

**Abstract** Disassembly is required for product repairing, component reusing, and material recycling in the product lifecycle. Existing research in the area mainly focus on the complete disassembly for process planning algorithms, operation evaluations, and guidelines of product design. This paper introduces the evaluation of product selective disassembly planning. Cost measures are introduced in the evaluation of product disassemblability. Operating tools and tool changes are included in the analysis. A hybrid product representation is proposed to improve the existing method for the product selective disassembly analysis. The proposed method is verified using a case study.

## 1 Introduction

Product disassembly analysis at the early design stage will benefit the product with lower cost of product maintenance and end-of-life recycling operations. As the importance of product disassemblability in product repairing, component reusing, and material recycling [1], product disassembly has been investigated intensively [2]. Product disassembly can be classified into complete disassembly and selective disassembly. The complete disassembly separates an entire product into components, which can be processed as a reverse processing of the assembly. The selective disassembly takes some components from a product for the purpose of the product repair or the part replacement [3]. To replace failed parts from a

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product requires a process of the selective disassembly. There is no preplanned sequence available for the selective disassembly as the part failure is uncertainty in the product operation. The selective disassembly depends on the product status and operation conditions.

Product disassemblability is mainly decided in the product design stage. Existing research in the area mainly focuses on the complete disassembly in process planning algorithms, operation evaluations, and guidelines of design for disassembly. However, as the selective disassembly is planned based on the part selected for replacement or recycling, the plan has to be made based on the selected part, which cannot be planned in advance as in the case of completed disassembly in the design stage. The special attention has to be paid to product representation for selective disassembly planning. A well designed representation scheme can support the easy implementation of disassembly planning. An optimal disassembly plan needs the shortest operation to access the selected part with the least effort [4]. As the difference from the completed disassembly, selective disassembly plan has been challenges for the product representation and optimal sequence planning [5].

There are different methods for the generation and evaluation of disassembly plan such as optimization methods, design tools, or physical prototypes [6]. These methods provide different disassembly solutions with different measures for the optimal plan, such measures as shorter time used and fewer components moved. These different measures can be converted into the cost measure for the disassembly evaluation. Product disassembly cost includes the operation cost, tool cost, labor cost, and waiting for processing cost. Slavila and Decreuse used a fuzzy function as 'criteria weight' to evaluate the maintainability in product design [7]. Dong reviewed existing research and methods in disassembly modelling [8]. Desai surveyed disassembly algorithms and disassembly guidelines in product design [9]. However, there is a lack of effective methods in design analysis for selective disassembly with the consideration of operation constraints such as tools used and the tool operation. It is suggested that a systematic method should incorporate disassembly planning in product design for the quantitative evaluation. It is necessary to have an effective method to evaluate product selective disassemblability.

This research evaluates product disassembly based on the cost estimation. A cost-based method is developed to measure the product selective disassembly plan. The method uses a new hybrid product representation scheme, which simplifies product modelling to improve efficiency of disassembly planning. Operation and tool costs are included in the evaluation. Cost related to product structure constraints and tool changes in the operation is also considered. The analysis uses a combination of the automated process and user interactive process. A hybrid method simplifies the AND/OR graph to improve the matrix representation in the generation of disassembly plans. The disassembly plans are generated automatically based on the product representation. The plans are then used for the cost estimation to evaluate the product disassembly. In remaining parts of the paper, the research, and methods in the product disassembly planning and evaluation are introduced in Sect. 2. A cost-based method is proposed in Sect. 3 for the selective disassembly analysis and evaluation. The proposed system structure and implementation are discussed in Sect. 4. A case study is used to verify effectiveness of the proposed method in Sect. 5, followed by conclusions and further work discussed in Sect. 6.

## 2 Related Research

A feasible disassembly plan has to be generated before any evaluation of product disassemblability can be performed. The proposed method consists of product representation-based selective disassembly planning, and the cost-based evaluation for the product disassemblability. This section reviews the existing research and methods in these two areas.

### *2.1 Product Representation and Disassembly Planning*

Product representation decides the method and efficiency of product disassembly planning and optimization. The existing product representation methods mainly include graph representation, matrix representation, state representation, and Petri Net presentation.

*Graph representation for disassembly planning* AND/OR graph is a commonly used graph in the product disassembly analysis. It seems a natural way using AND/OR graph to represent the relation of product disassembly. Nodes in the graph denote components or subassemblies, hyperarcs represent product disassembly tasks. Two components or subassemblies are joined to yield an assembly. Each node in the AND/OR graph may have k ($k > 1$) disassemblies to form an OR-relation. If a process splits a node into sub-nodes, parts, or subassemblies, there will be m hyperarcs linking the node to its sub-nodes, which forms an AND-relation [10]. An AND/OR graph contains all possible disassembly options. Using AND/OR graphs, all sequences of a product disassembly can be generated with a complete search of the graph.

AND/OR graphs provide detailed relations of a product structure for the search of disassembly plans. It is advised that designers consider disassemblability from beginning of the product design using AND/OR graphs. Since a disassembly often happens after the product is made, the design stage normally only considers the product assembly. Some disassembly sequences may not exist in the corresponding AND/OR assembly graph. AND/OR graphs usually include unnecessary search space for the disassembly, which leads to the increasing computation in disassembly optimization. In addition, using AND/OR graphs, the disassembly precedence relationships are limited to simple AND and OR relationships. A product may contain complex AND/OR relationships. Therefore, there is much research to improve AND/OR graphs for the optimal disassembly planning [11].

Li suggested a hybrid graph that contains both undirected and directed edges to connect nodes [12]. This hybrid graph is called disassembly constraint graph. In the hybrid graph, nodes denote components or subassemblies, undirected edges represent geometrical relations or contact constraints between two components. The directed edges describe the precedence information for the priority of a part disassembly or non-contact constraint. The hybrid graph includes a reasoning mechanism to simplify the search space. The representation can represent both geometrical and precedence constraints for a product disassembly. It is usually a sub-graph of the AND/OR graph, which has a small search space for the disassembly planning.

*Matrix representation for disassembly planning* The matrix-based representation is the most commonly used method to explicitly describe information of products for the disassembly analysis. Matrices can represent constraints, process precedence and structure information of a product. Graph-based representation schemes are often converted into a matrix representation [13]. Different matrices have been defined to represent product information, such as part positions, connections, fasteners, and interferences [14]. Matrix-based representations can use decimal or binary values.

Decimal representation matrices often include logic, constraint, and precedence relationships of components without direction relationships of components. A relationship matrix can be derived from a directed graph for both component connections and precedence information [20]. It can separate fasteners and functional elements in a product. It is also necessary to know the physical link and layout interference of the functional elements. The physical link is the way of component connections. The layout interference reflects the precedence among functional components. Binary representation matrices often incorporate the direction information into one matrix. Other matrices can also use the binary representation such as interference matrix, connection matrix, disassembly sequence matrix, and contact matrix.

*State representation for disassembly planning* Using state representation, product disassembly relations are represented using a single disassembly graph based on the product connective state with binary variables. A true state indicates an established corresponding connection. Actions are transitions between states [15]. From the state representation, a large number of possible sequences may be derived. The selection of sequences is based on heuristic rules. As all possible disassembly sequences have to be searched to evaluate disassembly plans, the state representation method is not efficiency for the evaluation of product disassembly.

*Petri Net representation for disassembly planning* Petri Net provides a tool for discrete systems modelling [8]. A Petri Net-based disassembly model is regarded as a special case or variant of AND/OR graphs [12]. Using Petri Net method in product disassembly planning includes the development of disassembly precedence matrix, generation of disassembly Petri Net, and near-optimal search for disassembly plans. Petri Net representation schemes provide visual tools for showing processes of the product disassembly.

### 2.2 Cost-Based Evaluation of the Disassembly Plan

Cost is a common measure of product evaluation in product design, manufacturing, assembly, sale, product using, recycling, and disposal. The cost-based evaluation can be used to select an optimal plan from different disassembly solutions. Different methods have been proposed for using cost in the performance evaluation of disassembly plans, including intuitive evaluations, parametric techniques, variant-based models, and generative cost estimations [16]. The cost estimation can also use a bottom-up approach from a starting point of the least cost component aggregating to the total product cost [17]. Cost items included in evaluation models have the impact on efficiency and feasibility of the evaluation methods. The disassembly related time is a major part of the repair time. The statistical data can be used to form the cumulative distribution function based on available data for the cost calculation.

There are different methods for disassembly planning based on product representations [18, 19]. Operational research approaches are easy to be implemented based on the product representation. Other methods such as GA and ant colony are suitable to the disassembly sequences optimization from multi-sequences, or optimal disassembly sequence selections. We propose a heuristic rule-based recursive process with the cost measure for a feasibly selective disassembly plan optimized from alternatives of disassembly sequences.

## 3 Proposed Methods

A hybrid method is proposed in this research to generate selective disassembly plans using a simplified graph and improved matrix representation. The plans are then used for the cost estimation to evaluate the product disassemblability. In the simplified graph, product disassemblies are represented by only left components after a disassembly. Disassembly sequences are established using levels of product tree structures. Nodes in the tree represent components remaining after disassemblies. The improved matrix is used to indicate the information of part constraints for the disassembly operation. In the matrix, operation constraints are limited into x, y, z directions of positive and negative linear motions. The cost estimation method is built based on the disassembly operation and tool costs.

### 3.1 Framework

There are two major functions in the proposed method: selective disassembly planning and cost-based evaluation. The disassembly planning determines operation sequences of a chosen part in a product for disassembly. The cost is used as a measure of the optimal disassembly, which is then simulated in a 3D virtual environment to verify the solution. Product graph and representation matrix are formed based on the product structure. For a certain operation of the chosen part, the disassembly cost is assumed as known data. In following discussion, we use the module to represent a subassembly. A module can be operated as a part or a group of parts in a disassembly. The cost is related to the operation time, and time for using tool and the tool changes. Therefore, the disassembly efficiency depends on parts' constraints and operations. The operation cost is decided by both parts' and tools' operations.

## 3.2 Details

*Product representation* Product structure is represented using a simplified tree graph and improved matrix. The simplified AND/OR tree graph only keeps the remaining parts in the product after each disassembly. The improved matrix contains both part relationships and constraints. The part relationship is from the existing product design. The constraint here is the spacial limit from surrounding parts for disassembled part moving. A constraint is the restriction of part's operation in the disassembly. The restriction limits a disassembly or increases the operation cost. Constraints may also decrease the complexity of an AND/OR tree graph and help to find disassembly sequences. For example, considering the example of parts' connections in Fig. 1a, there are four disassembly sequences shown in AND/OR tree graph of Fig. 1b, ABCD->ABC-D, ABCD->ABD-C, ABCD->ACD-B, and ABCD->BCD-A. However, based on the product structure, we can ignore the sequence ABCD->ABC-D and ABCD->ABD-C because parts C and D cannot be moved firstly as part C is blocked by parts A and B, and part D is blocked by part C. We use a matrix to represent these constraints shown in Fig. 1c. Numbers on the matrix diagonal are defined as 'N,' as there is no self-constraint applied for any part. Part A or B does not have any restriction from other parts; its state is thus set as 0 including B-A or A-B, D-A, and D-B. Using the linear motion assumption of the part operation, constraint values between parts can be set to be 1 and $-1$, which stands for constraints at positive and negative moving directions, respectively. The sum of values in each column of the constraint matrix is defined as 'constraint' of the selected part for disassembly to indicate its total number of constraints from other parts. For a part with three linear motion freedoms, the maximum constraint value will be 6 in both positive and negative

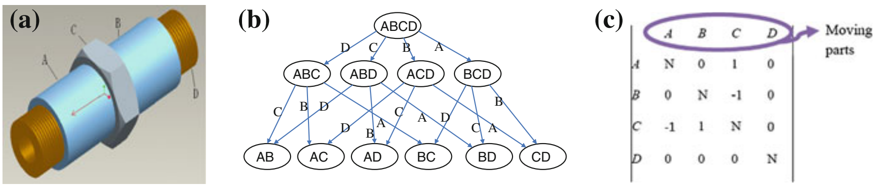


**Fig. 1** **a** Product example, **b** simplified AND/OR graph, **c** constraint matrix

directions. For the sample shown in Fig. 1a, there is only one linear motion freedom. The movement from part C to A is assumed in the positive direction. Thus, the states of C-A and C–B are set as 1 and −1, respectively. Therefore, the constraint value of part C in Fig. 1c is 2. Once a constraint is removed, the chosen part in this direction will be free to move. This is a dynamic processing based on the moving part and remaining parts. For example, when part A or B is moved, part C can be moved in positive or negative direction. The constraint value of part C will be decreased by 1 accordingly.

*Constraint detection and disassembly sequence generation* The operation direction decision finds part's degree of freedom (DOF) to decide movable directions of the selected part for disassembly. It is to find constraints for each part to be moved. For a selected part, the sum of values of its column in the matrix is the total constraints in movable directions. To build the matrix, the value is set for each part's movable direction between the selected part and its connected parts as 1 or −1. The values in matrix diagonal are set as 'N'. The matrix is used for the input information of the disassembly sequence generation. The matrix is updated along with the disassembly process. For example, for the structure shown in Fig. 1a, when part A is removed, the constraint of C-A becomes 0. Therefore, its value in the matrix will be updated to 0 accordingly. The total constraints of part C will be 1 in the updated constraint matrix. A counter is used to calculate the current constraint of a moving part.

*Assumptions for cost calculation and disassembly operation* Product disassembly time consists of operation preparation time, disassembly time, and post-processing time. Direct time of moving parts and related cost are only considered in this research. The cost is calculated based on the unit time cost. Therefore, the total cost of a part disassembly operation is defined as the sum of part's moving cost and constraint release cost. The moving cost depends on paths of the moving part. The product constraint matrix is used to generate possible moving paths for a part disassembly operation. If the chosen part is required moving only in one direction, the operation is assumed to take 1 unit time and its movement cost is set as 1 unit dollar. Otherwise, the movement time will be timed by n, and the related cost will be \$n when there are n moving directions required. The constraint cost is the current constraint value of a selected movable part. For example, the moving time of part C shown in Fig. 2a is 1 unit time, and constraint release time of part C is also 1 as part B will limit the operation of part C in one direction. We therefore

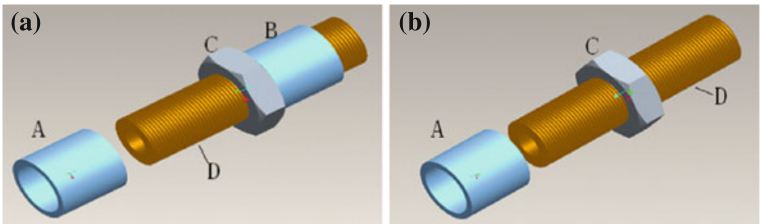


**Fig. 2** Different part moving conditions

assign the total operation time of the disassembly of part C as 2, which results from its constraint release time 1 plus its movement time 1. For the position of part C shown in Fig. 2b, the total movement time is only 1 as there is no constraint for part C to move. The cost estimation of a part disassembly is mainly based on the operation constraint. However, the tool used for disassembly operations may be different for different parts. Using different tools will affect the disassembly time. For example, an adjustable spanner is more flexible than a fix-sized handle tool, but it will take more time to adjust if different sized parts to be operated. The analysis will thus include both tool change and operation time for final disassembly cost estimation. When the tool is changed in an operation, there will be an extra cost added. The tool change time is assumed as 1 unit time, and its cost is 1 unit dollar for each change in the operation. That is, if there is a tool change required in a disassembly operation, the total cost will be added by 1 unit dollar. Therefore, the operation cost related to a disassembly is calculated using following equation: C = (Wp × Tpart moving + Wr × Trelease constraint + Wt × Ttool operation + Wc × Tchange), where Wi is the cost of each item in each unit time. The criteria in the cost-based evaluation include part constraints and tool operations in the disassembly. The weight and items can be adjusted based on the data collected in the real applications.

## 4 Implementation

Proposed methods include the product representation, disassembly sequence planning and cost evaluation. The connection of different steps in a disassembly plan is represented using '->.' Once a part is disassembled, the part's number will be deleted from the next sequencing process.

The selective disassembly analysis consists of three processes. The first process is the operation analysis to decide moving paths of the chosen part for disassembly. The disassembly operation is simulated in a 3D visual interface. The second process is the cost calculation of the generated disassembly sequences. The third process is the optimization of disassembly sequences based on the cost measure. For example, for the disassembly sequence generation of a selected part A as shown in Fig. 3, the process will start searching the part constraint information to generate the sequence by releasing the constraint for the part removing step by step until Part A is approached. If part A is a father node, all parts under part A are processed as a subassembly in a module which will be disassembled together with part A.

For the completion of a disassembly sequence, if a subassembly with more than one part is disassembled, the parts in the disassembly model will be stored in a temporary data set for the following process. It is an iterative process to check the part state in the process. The alternative disassembly sequences are evaluated based on the cost measure. An optimal solution will be a disassembly with the minimum cost.

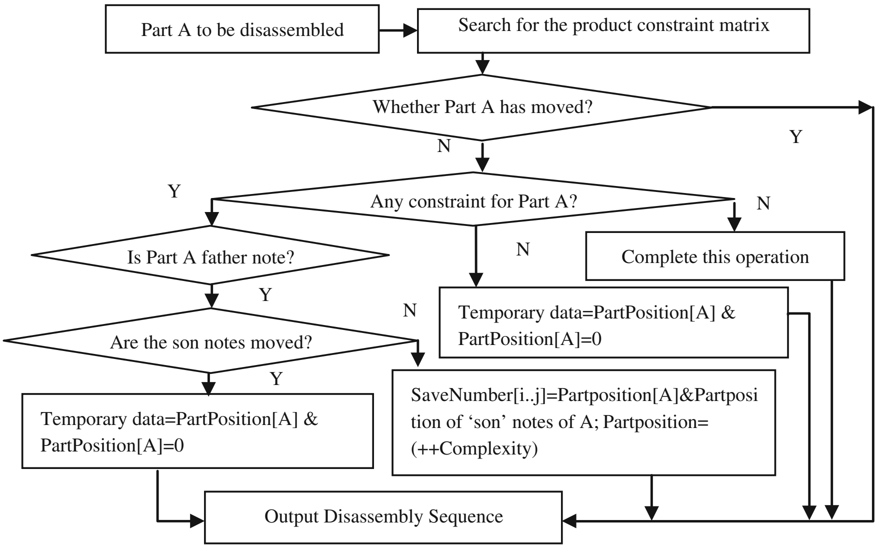


**Fig. 3** Flowchart of the selective disassembly sequence generation

# 5 Case Study

A product shown in Fig. 4 is used for the case study to verify the proposed method. The product model is built using Solidworks. The disassembly planning and cost analysis are integrated in a 3D virtual environment, EON Studio [20]. Numbers are used as labels for different parts for coding convenience. If a part number is greater than ten, brackets are used to indicate its sequence in a disassembly plan. For example, the part number 12 will be indicated as (12) for the difference from parts 1 and 2. The product is a wrist of a painting robot. The wrist product consists of a base and three joints, each joint contains many parts. Figure 4 shows the product model and its main parts.

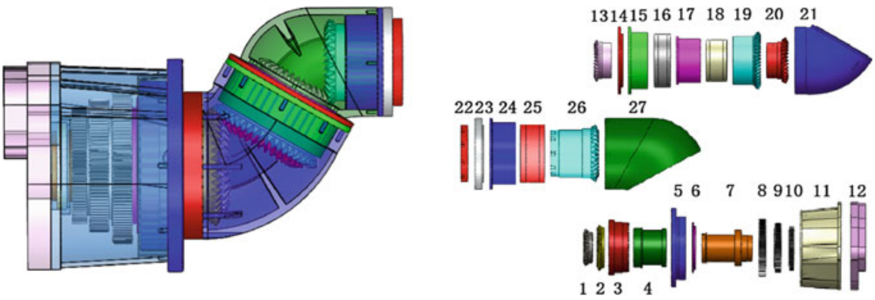


**Fig. 4** Product and its components

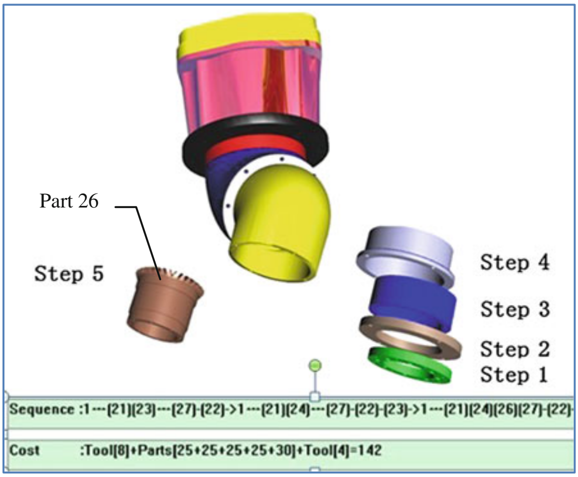


**Fig. 5** Disassembly simulation of part 26 (operation 1)

Using the proposed method based on product's structure, alternative disassembly sequences are generated for a selected component to be removed for replacement. Normally, there exists more than one of feasible operation sequences for a selected part. For example, if Part 26 is selected to be disassembled. For the disassembly sequence: 1… (27)->1…(21)(23)…(27)-(22)->1…(21)(24)…(27)-(22)-(23)->1…(21)(24)(26)(27)-(22)-(23)-(25)->1(21)(26)(27)-(22)-(23)-(25)-(24)->1 …(21)(27)-(22)-(23)-(25)-(24)-(26), part 26 can be removed after parts (22)(23)(25)(24). But for the sequence 1…(27)->1…(21)-(22)…(27)->1…(21)-(22)…(26)-(27)->1…(21)-(22)…(25)-(27)-(26), Part 26 moves with all the parts of Joint 3 together, then it can be disassembled after the removal of Part 27. Obviously, the time spent for these two operations are different.

Simulation is used to show disassembly operations for the solution verification. A user interface is developed for visualizing the disassembly process and for users to select part to be removed. A part can be interactively chosen for the disassembly. If there is no constraint for the selected part, the part can be disassembled directly. Otherwise, the part constraints will be released one by one until the selected part is reached based on the constraint matrix. The cost of operations is calculated based on the operation time and time for tools change. Figures 5 and 6 show different operations for the disassembly of Part 26. An optional sequence is selected based on the minimum operation cost. The cost calculation is programmed using Java script language embedded in EON Studio. A 'check sequence' selection is designed for users to compare the cost of a current operation with other disassembly sequence cost if there are different operation solutions. The compared results are used for the disassembly sequence evaluation and the optimal selection.

For the product disassembly in this case study, two types of screwdrivers are used for different types of screws as shown in Fig. 7. It is assumed that the screwdriver operation will need one unit time. For the disassembly of Joint 3, there are four screws to be disassembled. The flange has eight screws and the cover have four screws to be removed. As shown in Fig. 8, in order to disassemble Part 19,

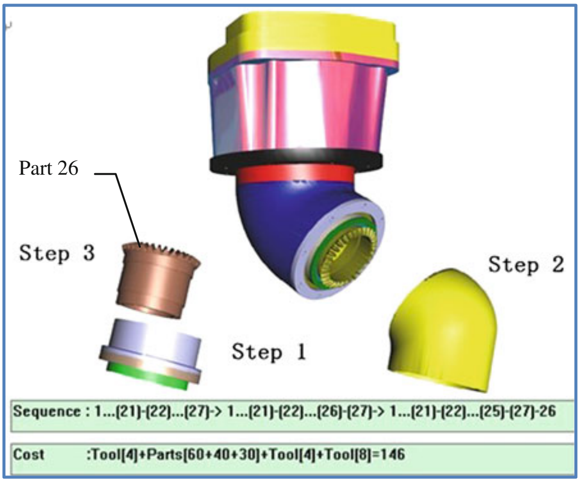


**Fig. 6** Disassembly simulation of part 26 (operation 2)

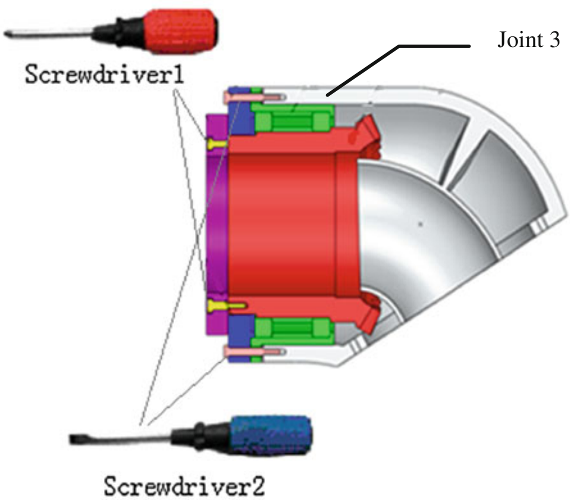


**Fig. 7** Tools used in the disassembly

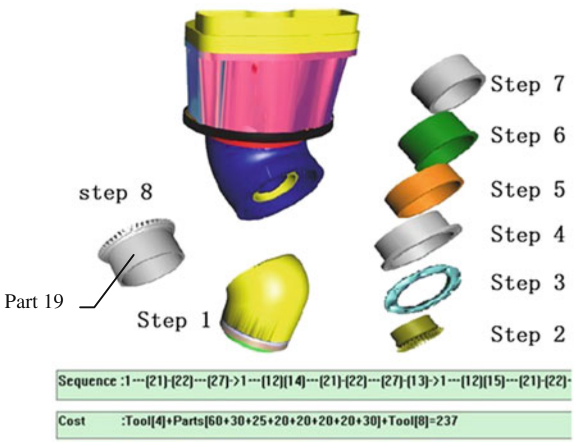


**Fig. 8** The analysis with the tool change cost

**Table 1** Disassembly cost for part 19 with tool changes (unit dollar)

| Sequence | Time cost | Tool cost | Total cost |
|---|---|---|---|
| (22)…(27)-(13)-(14)-(16)-(15)-(18)-(17)-(19) | 225 | 13 | 238 |
| (22)…(27)-(13)-(14)-(18)-(17)-(16)-(15)-(19) | 225 | 13 | 238 |
| (22)…(27)-(13)-(14)-(18)-(16)-(17)-(15)-(19) | 225 | 13 | 238 |
| (22)…(27)-(13)-(14)-(18)-(16)-(15)-(17)-(19) | 225 | 13 | 238 |
| 1…(12)-(21)-(20)-(19) | 180 | 5 | 185 |

total eight operation steps are required. The time used is then converted into cost based on the cost per unit time. The tool cost is 4 unit dollars for the first step while tool costs in rest several steps are 8 unit dollars. Table 1 shows disassembly sequences costs with the tool change cost included. It can be observed that different sequences may have the same cost based on the existing measures used which will need the human interaction to select the final operation sequence. Additional measures, such as operation environments and part handling information, can be introduced to limit the same cost generated in the optional search.

This case study shows use of the cost-based method to evaluate disassembly sequences. The cost calculation considers the operation complexity and tool changes. As the uncertainty of parts to be repaired or replaced in a product lifecycle, the product structure should be carefully planned in the design stage to make parts easy disassembly with less constraint and interaction in the geometric connection. For selective disassembly planning, the disassembly sequence will affect the operation cost. The fasteners used in a product should be easily operated using the same tool for less operation time.

## 6 Conclusions

Effective sequence planning of product disassembly is essential to reduce the cost of product disassembly. This paper introduces the analysis of product selective disassembly and the related cost. The proposed method measures the product disassemblability with a quantitative method. A simplified AND/OR graph and improved constraint matrix are introduced for product selective disassembly planning. The cost-based disassembly evaluation and a 3D visualization system are integrated for the solution verification. The case study shows the effectiveness of the proposal method to provide a quantities measure for the product disassembly, which improves the existing methods of design for disassembly.

Further work will develop methods for the automatic generation of the product representation from the product CAD model. Human factors will be included in the operation analysis of disassembly. Other factors, such as the product shape, size, and weight, and operation environments, will also be considered in the time estimation. Time spent for different product structures and tool using details will also be collected for the analysis to support the accurate time calculation. The method will also be evaluated using more examples.

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## References

1. Meier H, Roy R, Seliger G (2010) Industrial product-service systems—IPS$^2$. CIRP Ann Manuf Technol 59(2):607–627
2. Chung C, Peng Q (2009) Tool selection-embedded optimal assembly planning in a dynamic manufacturing environment. Comput Aided Des 41(7):501–512
3. Chung C, Peng Q (2006) A hybrid approach to selective-disassembly sequence planning for de-manufacturing and its implementation on the internet. Int J Adv Manuf Technol 30:521–529
4. Lambert A (2007) Optimizing disassembly processes subjected to sequence-dependent cost. Comput Oper Res 34(2):536–551
5. Smith S, Chen WH (2012) Multiple-target selective disassembly sequence planning with disassembly sequence structure graphs. In: Proceedings of the ASME IDETC/CIE 2012, DETC2012-70154, Chicago, IL, USA, Aug 12–15 2012
6. Berg L, Behdad S, Vance J, Thurston D (2012) Disassembly sequence evaluation using graph visualization and immersive computing technologies. In: Proceedings of the ASME IDETC/CIE 2012, DETC2012-70388, Chicago, IL, USA, Aug 12–15 2012
7. Slavila C, Decreuse C, Ferney M (2007) Fuzzy approach for maintainability evaluation in the design process. Concurrent Eng Res Appl 13(4):291–300
8. Dong J, Arndt G (2003) A review of current research on disassembly sequence generation and computer aided design for disassembly. Proc Inst Mech Eng Part B: J Eng Manuf 217(3):299–312
9. Desai A, Mital A (2003) Review of literature on disassembly algorithms and design for disassembly guidelines for product design. Int J Ind Eng 10(3):244–255
10. Lambert A (2003) Disassembly sequencing: a survey. Int J Prod Res 41(16):3721–3759
11. Lambert A (2007) Optimizing disassembly processes subjected to sequence-dependent cost. Comput Oper Res 34(2):536–551
12. Li JR, Khoo LP, Tor SB (2002) A novel representation scheme for disassembly sequence planning. Int J Adv Manuf Technol 20:621–630
13. Tang Y, Zhou M, Zussman E, Caudill R (2000) Disassembly modeling, planning, and application: a review. In: Proceedings of IEEE international conference on robotics and automation, San Francisco, CA, 2000
14. Chung C, Peng Q (2006) Evolutionary sequence planning for selective disassembly in de-manufacturing. Int J Comput Integr Manuf 19(3):278–286
15. Kang J, Xirouchakis P (2006) Disassembly sequencing for maintenance: a survey. Proc Inst Mech Eng Part B: J Eng Manuf 220(100):1697–1716
16. Fredrik E, Mikael C (2008) Cost-based producibility assessment: analysis and synthesis approaches through design automation. J Eng Des 19(2):113–130
17. Newnes LB, Mileham AR, Cheung WM, Marsh R, Lanham JD, Saravi ME, Bradbery RW (2008) Predicting the whole-life cost of a product at the conceptual design stage. J Eng Des 19(2):99–112
18. Yu J, Li Y (2006) The structure representation for the concurrent analysis of product assembly and disassembly. In: Proceedings of the 9th international conference on computer supported cooperative work in design proceedings, pp 893–898, 2006
19. Galantucci LM, Percoco G, Spina R (2004) Assembly and disassembly planning by using fuzzy logic and genetic algorithms. Int J Adv Rob Syst 1(2):67–74
20. EON Reality, Inc. (2011) EON studio 5.2 user guide, 2011

# Risk Management Methodology Covering the Entire Product Lifecycle

**Jan Machac and Frantisek Steiner**

**Abstract** This paper deals with a new risk management methodology covering the entire product lifecycle. Since, no complex and lucid methodology involving all product lifecycle phases has ever occurred. Currently, not all phases are covered or different risk management methods are used for single phases. The proposed methodology copes with two types of risks which may occur during the life-cycle. Predictive risk are the first type and incident investigation the second. At the beginning of an each phase, all possible risks entering the process are considered. These risks are taken into consideration during the entire cycle. Nevertheless, some risk may stay undiscovered and impact. Then incident investigation starts in order to identify risks. The identified risks are treated and considered. Generally, it can be said the methodology makes a closed and never-ending circle of risk management. It is a part of universal process improvement.

## 1 Introduction

Currently, risk management is an integral part of every state-of-art production enterprise because running enterprises always goes with various kinds of risks. Therefore, it is necessary to develop and improve ways of implementation of a risk control system into enterprise processes. Risks are supposed to be controlled across all levels of organization and considered in terms of finance, environment and occupational safety. As far as production enterprises are concerned, it is also necessary to transfer the risk management to produced products. Every product has its product lifecycle where it is needful to consider various influences which enter the product lifecycle and manage risks here. The product lifecycle and its

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managing have become a present standard and a part of the information structure of modern enterprises. Due to comprehensibility and definiteness, it consists of several phases. This helps to make risk management easier because it is feasible to manage risks for each phase separately. Unfortunately, no complex methodology managing the entire product lifecycle has been developed by this time. Some methodologies attempt to combine several known methods but it is ambiguous in most cases. There is a need of a complex method which would cover all possible risk during the entire product lifecycle.

## 2 Product Lifecycle Management

The product lifecycle is based on the principle of a biological cycle, i.e. the process from birth to death. This theory is the same for a product and it can also be understood as a process which is one of the other enterprise processes. In risk management, all participating subjects must understand the relation between project management processes and the other enterprise processes. The project lifecycle is the natural framework for investigation of relations and processes in the field of project management.

In industry, product life cycle or PLM (Product Lifecycle Management) is a control process from conception through design and production to service and disposal. PLM includes people, data, processes, business systems and provides the main information flow for companies. Simultaneously, PLM systems help organizations in copying with an increasing complexity and engineering tasks of new products development for global competitive markets [1].

The life cycle is described as a means of defining of the beginning and end of a project and its phases. The form of life cycle definitions varies by industry areas but it is also various within the same industry for different organizations and businesses. In project management, the risk approach changes in various stages. This depends on how much information is available and what the extent of the project progress is.

Product lifecycle management is one of the four cornerstones of an enterprise's information technology structure. All companies need to manage communications and information with their customers (CRM—Customer Relationship Management), their suppliers (SCM—Supply Chain Management), their resources within the enterprise (ERP—Enterprise Resource Planning), and their planning (SDLC—Systems Development Life Cycle) [1]. In addition, manufacturing engineering companies must also develop, describe, manage, and communicate information about their products [2].


**Fig. 1** Elementary phases of the entire product lifecycle

## *2.1 PLM Division According to Single Phases*

The substance of product lifecycle is in making and managing of a centralization of all used product data and technologies which enables an easy access to information and knowledge. The product lifecycle is a discipline developed from tools as CAD, CAM, and PDM. It may be seen as a means of integration of these tools with methods, people, and processes during all phases of the product lifecycle. However, it is not only about software technologies, it is also about a business strategy [3]. For simplification, single phases are displayed in the traditional sequential engineering workflow. The exact order of events and operations may vary in dependence on a product or a type of industrial area. Main events are most the same as it can be seen in Fig. 1.

The meaning of phases consists in the fact that phases enable a better control of the continuance of the entire cycle. After ending a single phase, it is possible to reconsider a consequent project continuance. Further, usage of phases makes possible to control the main project indicators and risks formulation. Phases are connected to each other and a successful closing of a phase is usually necessary for a following phase initiation. These may be in a mutual overlap. Thus the mutual relationship must be defined.

## *2.2 Risk Aspects of Product Lifecycle*

The entire product lifecycle is inherently connected with risks and it is necessary to realize these risks and consider its occurrence in each phase of the product lifecycle. As it is shown in Fig. 2, most of nonconformities come into existence in the section between conception and production. The most significant increase is the section of design and preparation of the production process. On the other hand, revelation of these nonconformities is usually in the phase of control and usage. Then, consequent revelation and remedy in the production or at the customer is considerably more costly.

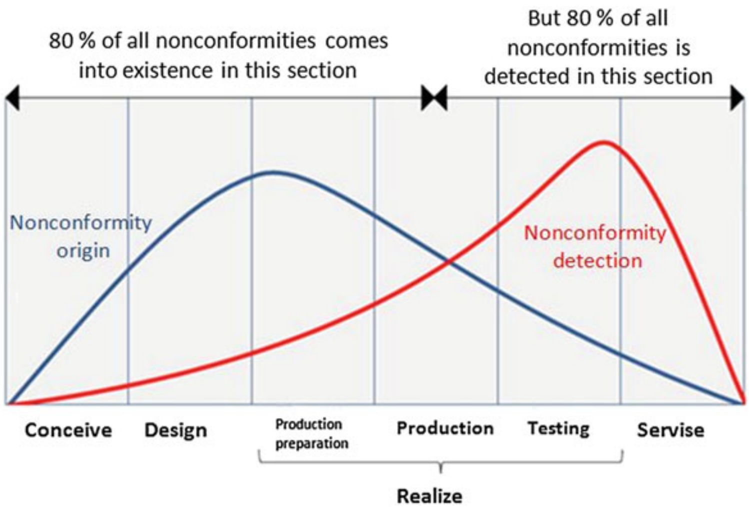


**Fig. 2** Estimated portion of the origin and detection of nonconformities [4]

## 3 Risk Management

Proper risk management process focuses on the identification and treatment of risks. The aim of risk management is to add the highest permanent value to all company activities. It contributes to better understanding of all possible advantages and disadvantages of all factors affecting the organization. It increases the likelihood of success and decreases the likelihood of failure as well as uncertainty in achieving of general objectives of organizations. The final output of the risk management process should be a decision about whether and how to manage risks. For an unacceptable level of risk, it may be required to stop the current process and accept countermeasures in order to reduce the risk level. If the risk is acceptable and the potential is considerable, development of a plan of preventive measures for its reduction usually follows. Residual risks which cannot be effectively decreased by countermeasures may be processed by using crisis plans [5].

Risk management should be a continuous and ever-improving process integrated into the organization's strategy and its enforcement. It must encourage responsibility, measurement, performance and contributes to higher efficiency at all levels of the organization. Programs or plans should be naturally proactive and future aimed. This is a gradual, recurrent improvement process. Preferably, it is integrated into existing practices or other production and design processes.

## 4 Framework for a New Methodology

The important milestone in the lifecycle of a product is the transition between single phases. These transitions are connected with risk aspects most often. Therefore, particular attention should be paid to them. Failure of significant risk factors detection from previous phases can significantly complicate the process of subsequent phases. As it can be seen in Fig. 3, risk factors passing from a previous phase to a next phase are always identified and considered simultaneously with new risk factors of a next phase. Furthermore, the feedback concerning identified risk factors of an actual phase is provided back to previous phases. Then, treatment of these risks is carried out in previous phases if it is possible. These risks can be based on the results of incident investigation and may be quantifiable.

The first phase of the product lifecycle (conceive) brings certain risk factors and influences. Consequently, these risk factors and effects must be considered in the second phase (design) where the risks of the second phase are also added. Thus, the risks from conceive phase are the input for the design phase. Then, both groups of risks become the input for the realize phase. To these risk factors, risks originated in the realize phase are added and considered. Risks of the fourth phase consist of all risks identified in previous phases and factors influencing the fourth phase only. It should be noted that mentioned risks identified in all phases are only predicted, therefore, it is not possible to determine their probabilities.

All identified risks of the fourth phase are the feedback for the third, second and first phase of the lifecycle. It is the same for the third phase, where the risks are identified if it is possible and treated in the previous phases, in the first and second. The feedback from the second phase is sent only to the first phase. It is also concerned with the risks which were not predicted and then later found in incident investigation. For each phase, different methods of risk analysis may be used but

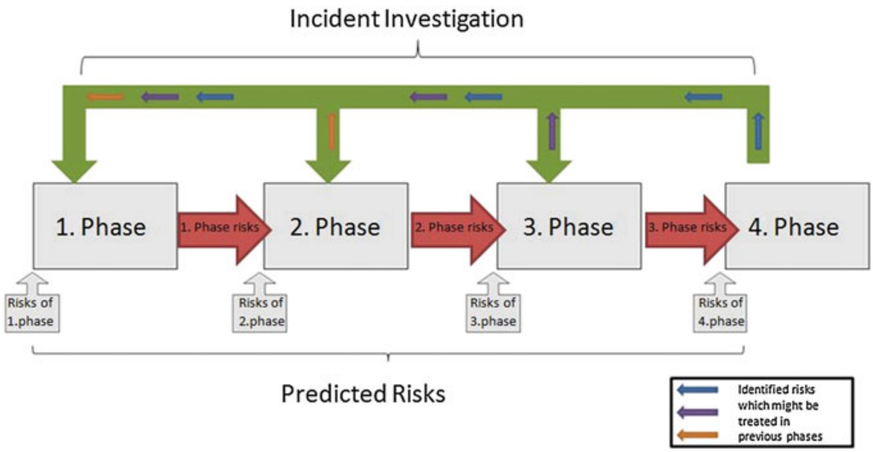


**Fig. 3** Framework for the new methodology

all of them should be interconnected and make a complex methodology. Selection of proper risk analyses or it parts and their right usage for PLM phases is under development. Generally, it is possible to claim that the methodology makes a closed, endless circle of risk management and it is a part of universal process improvement.

## 5 Summary

Ever-increasing financial, time and qualitative demands force current companies and project teams to consider all possible risks and their consequences which might have fatal impacts. Right awareness, considering and consequent risk management at the beginning of the project can mean a multiple saving at its progression or end. Risk management throughout the entire product lifecycle is slowly becoming a standard practice, but appropriate methods and procedures are not always used. Since the product and process risks should be managed throughout its entire lifecycle therefore a large number of different methods and procedures are required to manage risks. Absence of a comprehensive risk management methodology through which risks of the entire product lifecycle could be managed is obvious.

Implementation of the risk management system into the project or other procedural actions is becoming more commonplace. Risk management in all phases of the lifecycle provides a help in deciding which is usually carried out in each phase of the lifecycle. Identified risks can be used for a decision whether to continue the production of a product or make significant changes. Performing such an analysis can result in mitigation of property, health, or the environment losses.

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## References

1. Saaksvuori A, Immonen A (2008) Product lifecycle management. Springer, Berlin‘ ISBN 978-3-540-78173-8
2. Karnie A, Reich Y (2011) Managing the dynamic of new product development processes a new product lifecycle management. Springer, London. ISBN 978-85729-569-9
3. Zou W, Lin L (2010) The analysis and estimation on risk factors in engineering project lifecycle. In: 2010 international conference on management and service science (MASS), Wuhanm, pp 1–3. doi: 10.1109/ICMSS.2010.5578612
4. http://katedry.fmmi.vsb.cz/639/qmag/mj15-cz.htm. Accessed 12 Apr 2012
5. A risk management standard. London: AIRMIC, 2002. 14 s

# An Approach for the Selection of Process Plans Based on Part Family Changes

**S. M. Hasan and A. Baqai**

**Abstract** In recent times, in the field of manufacturing, due to the continuously changing market demand, the concept of reconfigurable manufacturing systems emerged. This requires a process plan along with the machinery (kinematic configuration) to produce the part. When the product is changed, consequently the process plans and the kinematic configurations change accordingly as well. The change in the basic machinery seriously affects the overall profit of the industry. This paper presents an approach to minimize this cost while still providing a suitable process plan for the associated kinematic configuration. The algorithm to implement this approach is also the part of this paper. A sample part is taken as an example to illustrate the use of this approach. The results are compared with the existing data for the part. The applicability, uses and future trends have been discussed in conclusion.

## 1 Introduction

Reconfigurable manufacturing system (RMS) due to less lead time and the ability to adapt to changing market trends is an effective and successful manufacturing system of the current era, where tough competition and unanticipated customer requirements is a regularity. RMS can convert its production methodology from a low volume single batch production to the high volume line production without many issues, thus its usefulness is obvious. RMS is basically for automated industries, therefore it has two levels of configuration; the system level and the machine level, i.e., tooling and tool positioning. Therefore, there is a two level control of RMS as well: software control at the system level and a G&M code (CNC) control at the hardware or machine level.

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The main purpose of this paper is to introduce an approach which can select from the generated process plans the most feasible process plan (in terms of time as well cost of production) for the current available machinery, to reduce the overall initial cost of production. To achieve this, initially the developed process plans are required and to develop those, it is important to understand the manufacturing system. The conventional approaches use computer aided process planning systems (CAPP) in which, the machine components are considered static and only one process plan is developed for the system (Dedicated Manufacturing System). On the other hand, recently most of the research is been carried out to develop multiple process plans and a system to implement them. The CAPP for RMS, known also as Reconfigurable process planning (RPP) allows much freedom in this regard and therefore multiple process plans can be developed and multiple machine configurations can be deducted from those process plans. This concept is illustrated in Fig. 1.

A considerable amount of work has been done on the machine structure reduction [1]. The approach used was machine structure configuration approach. Also, there have been various attempts to develop and improve the operational sequences to achieve the maximum production that can be achieved [2, 3]. But; in general, it has been directed toward the development and the selection of the most optimum process plan based on cost of production, the production rate, and so on. The research work in this regard is shown in Table 1.

The set of operations which are achieved in RMS if compared with the rigid DMS sequences, enable us to reconfigure the sequences on different machines as per our requirement [4], as well as quickly reconfiguring process plans [5] and developing new ones as well [6]. Nonlinearity plays a serious role in the development of part programs and has been utilized by developing the concept of Network Part Program (NetPP) [7]. This was implemented by machine tool builders (e.g., by MCM S.P.A.). A number of studies throughout the world are focused on developing the part programs which develop the machine sequences. These studies are mostly focused on identifying similarity between new or evolved

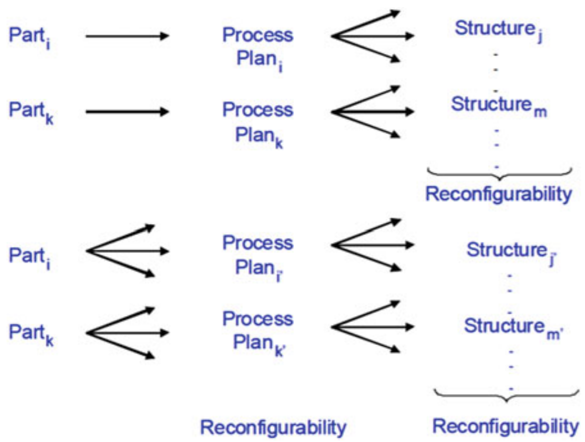


**Fig. 1** Enhancement of the domain of reconfigurability

**Table 1** Relevant research in RMS

| References | Issues addressed |
|---|---|
| Kruth , Detand [2] | CAPP for non-linear systems |
| Kim [3] | Geometry based precedence development |
| Gologlu [4] | Machine capability and fixturing constraints |
| Colosimo [5] | CAPP for non-linear systems |
| Azab [7] | Mathematical modeling for RMS |
| Shabaka [16] | Machine configuration generation |
| Tolio [11] | Introducing and developing an overall standard for co-evolution of process, product, and production systems |

products and existing ones as well as on algorithms for optimizing the process precedence charts. A generic constraint-based model for CAPP was proposed [8] along with some appropriate solution methods and applied to different industrial domains [9, 10]. Another step further would be an approach which (a) minimizes part handling and re-fixturing time and (b) minimizes the cost of changes in the evolved process plans referring to setups, tools, re-programming costs [7]. In addition, evolving process plans have an impact on device configuration, especially in reconfigurable manufacturing systems. On the basis of this and some other issues/limitations associated with reconfigurable manufacturing systems, the concept of co-evolution emerged [11]. This concept introduces the development of product, processes, and structures simultaneously instead of developing one with reference to the other (process dependent on structure etc.).

From this, it can be inferred that the issue of manufacturing systems' recurring and initial cost has been discussed many times since the first introduction of RMS in 1999. But, the concept of reducing them by co-relating the existing and the new parts' process plan, is a new one. Even the concept of co-evolution does not cater for these costs. These costs, when reduced, can boost the profits of the machining wing of the manufacturing setup. To address this issue, the methodology is discussed in Sect. 2.

## 2 Methodology

Machine Adaptive Retainability Approach (MARA) is presented in this paper. The flow chart of the algorithm is shown in Fig. 2. The assumptions made during this approach are presented later on. The inputs of the approach include: the dimensions of the work-piece, the tool approach directions, the previously employed process plans and the feasible process plans for the new part. The approach consists of a comparison stage, after that the decision making and finally the selection of the process plan. The output is: the proposed machine configuration in case the current configuration is not sufficient, the candidate operation sequences and their tool approach directions. If it is sufficient however, then the same plan is maintained.

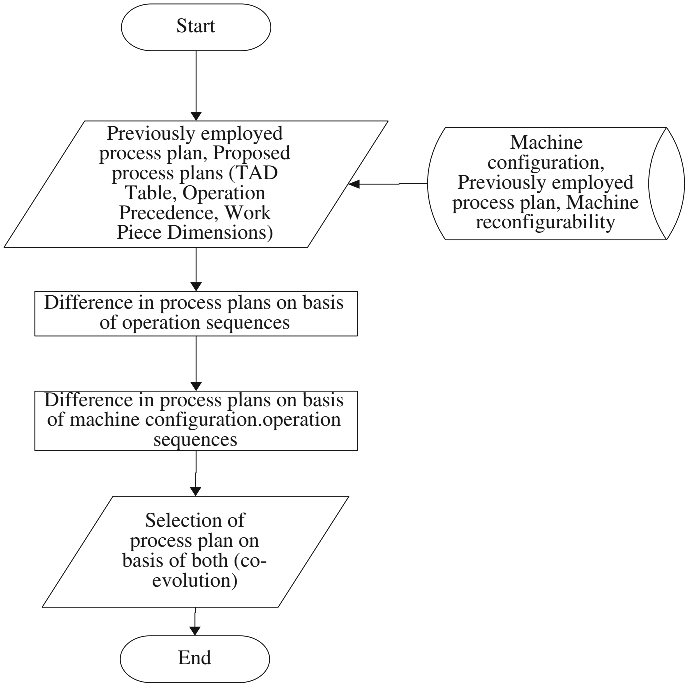


**Fig. 2** Machine adaptive retainability approach

## 2.1 Assumptions

- All the machines are reconfigurable.
- All machine structures have the basic three translations, i.e., x, y, and z axis.
- Since the basic translations are present, therefore the rest of the combinations which can be produced are ignored. And only the two possible rotations are considered.

The inputs required for this approach are as follows:

## 2.2 Tool Approach Directions

The direction from which the tool can approach to perform the specified task, is called the tool approach direction. The tool approach direction for some common tasks is shown in Fig. 3. The method by which they can be represented in a table is shown in Table 2. Further details can be found in [7, 12].

- 1 represents the possible TAD for the respective operation.
- 0 represents that TAD which cannot be used for the corresponding operation.

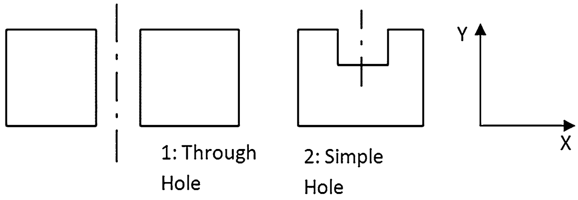


**Fig. 3** Sample operations

**Table 2** TAD table

| Op. no | Tool approach direction | | | | | |
|---|---|---|---|---|---|---|
| | +x | −x | +y | −y | +z | −z |
| 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| 2 | 0 | 0 | 0 | 1 | 0 | |

## *2.3 Previously Employed Process Plan*

The data required is the tool approach directions, the operation sequences, the tools used, and the machinery utilized. This approach using the previously employed process plans for any specified part, selects from the new feasible process plans for the new part the one which is nearest (with conditions explained later in this paper) to the previously employed process plans to reduce costs in machinery.

## *2.4 Feasible Process Plans*

Developing all the feasible process plans has been accomplished by many authors (El Maraghy 2007, T. Tolio 2002 etc.). Therefore, this is not a part of this research. Whatever means may have been adapted to develop the process plans, the feasible process plans for the part are taken as an input for the approach.

The algorithm for the approach is presented in Fig. 4. The abbreviations and the terminologies used in the flow chart are as follows:

| | |
|---|---|
| Tad | Tool approach direction |
| PEPP | Previously employed process plans |
| PPP | Proposed process plan |
| L, j, k, I | Variables initialized as 0 |
| Reftadop | TAD of the operation of the reference or previously employed process plan |
| Tadop | TAD of the operation of the proposed process plan. It should be noted that the operation should have the same serial wise location as the corresponding Reftadop |
| CPP | Counter for the difference in PPP and PEPP's operations |
| CKC | Counter for the overall kinematic configuration difference between PPP and PEPP |

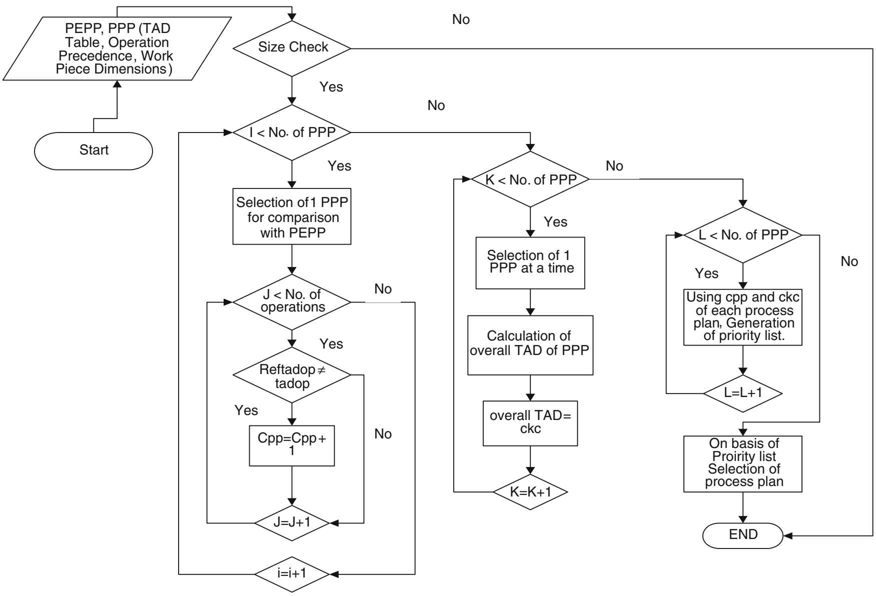


**Fig. 4** Algorithm of machine adaptive retainability approach

The algorithm starts off with the inputs (previously employed process plan, proposed process plans, and work piece dimensions) and then moves on to the size check. If the machine workspace is not sufficient for the work piece then the algorithm stops then and there. After this step the algorithm moves into the first loop. Here, it compares the first operation of the first feasible process plan with the previously employed process plan. In the second iteration of the loop, the second operation is compared and after that, the third, and so on. If the operation has the same tool approach direction as that of the subsequent operation of the old process plan then the algorithm moves on to the next operation. In case they are different, a counter counts the change. When all of the operations have been compared; the changes in the process plan as a whole are saved.

Next, the algorithm moves on to the second proposed process plans, comparing it again with the previously employed process plan. The result may be a different number of changes. Later, the algorithm moves on to the third proposed process plan, and then to the fourth up to the final proposed process plan. It should be noted that if the number of operations is different for the previously employed and the proposed process plans then the excess operations will automatically have a counter change of 1, each. For example; if the new process has 10 operations as compared to the previously employed plan with 5 operations then the counter will have the value of the difference 5 stored in it due to this difference. The next step in the algorithm is the comparison of the overall tool approach directions of the proposed process plans with the overall tad of the PEPP. The algorithm first calculates the overall tool approach directions of the previously employed process plan. Then, it moves on to the first proposed process plan, then to the second, after that to the third continuing up to the final proposed process plan. A stepwise check of the process plans is made moving from one operation to the next. Initially, the TAD of the first operation of the process plan is saved into memory then it is compared with the TAD of the second operation. If both are the same then the counter remains 1. If not; then the counter counts 2 and the TAD of the 2nd operation is saved as well.

Later, in the algorithm, both these TADs are compared with the TAD of the third operation; which, if different, is again saved in the memory and in case of being same as either of the operations, is ignored. In this way the algorithm compares all the operations of the process plan and finally the overall TAD of each process plan is now stored in the memory. The algorithm has now stored the TAD of each operation as well as the overall TAD of the operational sequences. An overall TAD comparison is made between the proposed and the previously employed process plan. In case there is no difference between the previously employed and the proposed process plan, the algorithm saves the difference as 0; if there is a single change the algorithm stores it as 1, and so on. The further explanation of the complete algorithm is made in the section ‘case study’. The final stage in the algorithm is the utilization of the data stored. For each proposed sequence, there are currently two sets of information (1) the difference in the proposed and the previously employed sequence and (2) the overall TAD difference. The plan having an overall TAD change of 0 is the most preferred process plan for that particular RMS machine. If the number of plans having 0 overall TAD change is more than 1, then, the difference in the sequence separates them. The plan having least differences in the sequence will be selected.

## 3 Case Study

MARA is implemented on parts ANC-090 and ANC-101. For the case study, it is assumed that a certain industry has been producing the part ANC-090 and now it intends to switch to the production of part ANC-101. The parts are shown in Fig. 5

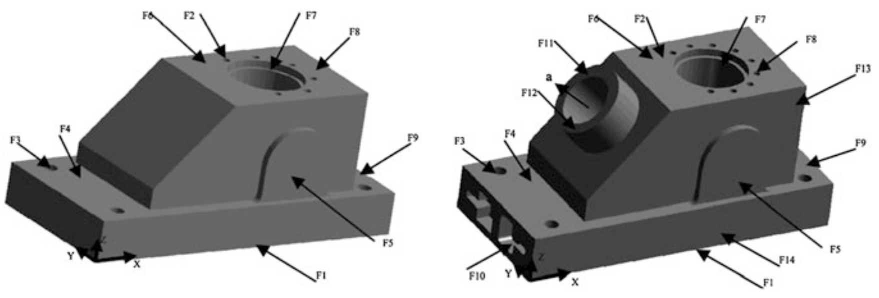


**Fig. 5** Parts ANC-090 and ANC-101

and **Error! Reference source not found**. A considerable amount of similarity exists between the two parts. The operation sequence along with the TAD of the operation for part ANC-090 which the company has been using is presented in Table 3. The proposed process plan is shown in Table 4. A comparison is made between these two in the following text to convert the differences into a numeric and thus, a calculable form. This numeric form can then be used to gauge the level and the cost that will be incurred by the new process plan.

**Table 3** Applied sequence for ANC-090

| Sr.no. | Op.id. | TAD | Description | Operation |
|---|---|---|---|---|
| 1 | 1 | +z | Planar surface | M |
| 2 | 2 | −z | Planar surface | M |
| 3 | 3 | −z | Four holes arranged as a replicated feature | D |
| 4 | 4 | −z | A step | M |
| 5 | 5 | −z | A protrusion (rib) | M |
| 6 | 6 | −z | A protrusion | M |
| 7 | 7 | −z | A compound hole (drill) | D |
| 8 | 8 | −z | Boring | B |
| 9 | 9 | −z | Reaming | R |
| 10 | 10 | −z | Six holes arranged in a replicated feature | D |
| 11 | 11 | −z | | D |
| 12 | 12 | −z | A step | M |

**Table 4** Proposed sequence for ANC-101

| Sr.no. | Op.id. | TAD | Description | Operation |
|---|---|---|---|---|
| 1 | 1 | +z | Planar surface | M |
| 2 | 2 | −z | Planar surface | M |
| 3 | 3 | −z | Four holes arranged as a replicated feature | D |
| 4 | 4 | −z | A step | M |
| 5 | 5 | −z | A protrusion (rib) | M |
| 6 | 6 | −z | A protrusion | M |
| 7 | 7 | −z | A compound hole | D |
| 8 | 8 | −z | Boring | B |
| 9 | 9 | −z | Reaming | R |
| 10 | 10 | −z | Nine holes arranged as a replicated feature | D |
| 11 | 11 | −z | | D |
| 12 | 12 | −z | A step | M |
| 13 | 13 | +x | Two pockets arranged as a replicated feature | M |
| 14 | 14 | −a | A boss | M |
| 15 | 15 | −a | A compound hole | D |
| 16 | 16 | −a | Boring | B |
| 17 | 17 | −a | Reaming | R |
| 18 | 18 | −x | A pocket | M |
| 19 | 19 | +z | A compound hole | D |
| 20 | 20 | +z | Reaming | R |

To explain the algorithm's working, it is implemented on the case study: Initially, a comparison is made between the first operation of the first proposed process plan and the first operation of the previously employed process plan. Form Tables 3 (Row 2) and 4 (Row 2), it can be seen that both of these have the same tool approach direction, i.e., +z. Therefore there is no addition to the value of CPP (initially 0). Then, it compares the second operation in the sequence. These too have the same TAD as well. Therefore, the algorithm moves on to the third and then the fourth and so on up to the twelfth operation all of which have the same TAD (−z). After this operation, the PEPP ends and for the comparison with the new process plan, the rest of the operations of the new process plan are compared with a 0 TAD. Therefore, all of these provide an increase in CPP. For example, operation 13 has TAD +x and in PEPP there is no operation 13 therefore it is compared with TAD: 0 and the CPP automatically increases by 1. The same is repeated for operation 14, 15 up to operation 20 increasing the CPP to 8. Therefore the total CPP for this sequence is 8.

Now, the 'overall TAD' of the PEPP and the new process plan is compared. The overall TAD is used to identify the machines capable of performing all the operations of a certain process plan. For example, if the overall TAD is 1 (−z), then a 3-axis machine is sufficient to perform all the operations of the process plan, if it is 2 (−z and +z), then a rotation will also be required and the minimum requirement will be a 4-axis machine. In this case however, the PEPP has an overall TAD of 3, (x, y axis are for positioning of the tool on the surface and −z for the TAD). While the Overall TAD of the new process plan is 4, (x and y are for positioning of the tool while −z and +x are the TAD. The –a direction is the new axis of motion for the angular hole). To achieve all of this a 4-axis machine at least with one axis of rotation is required. Hence, this concludes that the CKC is 1 for this process plan because a new axis is required as well. (CKC remains 0 if the previous and the new machines require same axis machines).

## 4 Results and Discussion

The results and the priority analysis is this approach is carried out only when there are at least 2 proposed process plans. The priority of one over the other through the MARA can then be developed. Hence, two of the PPP's for the new part is shown in Tables 5 and 6.

The 2nd and the 3rd proposed process plans have different operation sequences as compared to the 1st (Table 4). In the 2nd PPP, the angular hole and its features have precedence over other operations. Thus, they moved up to the 2nd, 3rd, 4th, and 5th operation in the operation sequence. These are the operations numbered form 14 to 17. Now, in this situation, when the each operation is sequentially compared with the operations of PEPP, the case is considerably different. In this case when the 2nd operation in the sequence is compared with the same in Table 3, the CPP is increased by 1. It is further increased when the 3rd, 4th, and 5th

**Table 5** Proposed sequence #2 for ANC-101

| No. | Op. | TAD | Description | Operation |
|---|---|---|---|---|
| 1 | 1 | +z | Planar surface | M |
| 2 | 14 | −a | A boss | M |
| 3 | 15 | −a | A compound hole | D |
| 4 | 16 | −a | Boring | B |
| 5 | 17 | −a | Reaming | R |
| 6 | 2 | −z | Planar surface | M |
| 7 | 3 | −z | Four holes arranged as a replicated feature | D |
| 8 | 4 | −z | A step | M |
| 9 | 5 | −z | A protrusion (rib) | M |
| 10 | 6 | −z | A protrusion | M |
| 11 | 7 | −z | A compound hole | D |
| 12 | 8 | −z | Boring | B |
| 13 | 9 | −z | Reaming | R |
| 14 | 10 | −z | Nine holes arranged as a replicated feature | D |
| 15 | 11 | −z | | D |
| 16 | 12 | −z | A step | M |
| 17 | 13 | +x | Two pockets arranged as a replicated feature | M |
| 18 | 18 | −x | A pocket | M |
| 19 | 19 | +z | A compound hole | D |
| 20 | 20 | +z | Reaming | R |

**Table 6** Proposed sequence #3 for ANC-101

| No. | TAD | Description | Operation |
|---|---|---|---|
| 1 | +z | Planar surface | M |
| 2 | −z | Planar surface | M |
| 5 | −z | A protrusion (rib) | M |
| 6 | −z | A protrusion | M |
| 4 | −z | A step | M |
| 7 | −z | A compound hole | D |
| 8 | −z | Boring | B |
| 9 | −z | Reaming | R |
| 10 | −z | Nine holes arranged as a replicated feature | D |
| 11 | −z | | D |
| 14 | −a | A boss | M |
| 15 | −a | A compound hole | D |
| 16 | −a | Boring | B |
| 17 | −a | Reaming | R |
| 12 | −z | A step | D |
| 3 | −z | Four holes arranged as a replicated feature | D |
| 18 | −x | A pocket | M |
| 19 | +z | A compound hole | D |
| 20 | +z | Reaming | R |
| 13 | +x | Two pockets arranged as a replicated feature | M |

**Table 7** Analysis of the PPP's for ANC-101

| Sr.No. | PPP | CPP | CKC |
|---|---|---|---|
| 1 | PPP #1 | 8 | 1 |
| 2 | PPP #2 | 12 | 1 |
| 3 | PPP #3 | 10 | 1 |

operations are compared. Hence, this PPP has a considerably higher CPP in comparison with the first PPP. The overall TAD of this PPP is same (Overall TAD = 4) as that of the first PPP. The result is that this will also require a rotation axis (not some different axis) for the operations to be performed. In this regard both these PPP's remain the same. The results drawn from the case study with different PPP's are shown in Table 7. It can be seen that the PPP#1 has less CPP as compared with the other PPP's while the CKC remains the same. Therefore the PPP#1 should be preferred over the other process plans.

## 5 Conclusion

A number of techniques are available for the problems associated with RMS, but are generally focused on either the development of the process plans for a certain machine configuration or try to find the most candidate configuration for a certain process plan. The issue which is generally not considered is the cost of changing the configuration as well as the process plan for new part. The concept of co-evolution which does consider this, was presented only recently. The major issue which co-evolution does not consider is the initial cost of production for any new part. MARA following the concepts presented in machine structure configuration approach was presented in the paper. It introduced the concept of developing the new part's process plans and kinematic configurations using the previous part's information. The kinematic configuration includes the machine's capability and the reconfigurable machine tools required to develop the part. The complete part information plus the previous part's knowledge is used as an input to initially develop a comparison between the currently employed process plan and the proposed process plans. This generated a deciding factor for the proposed process plans and concluded whether any one of these is a suitable candidate for the new part basing upon the current scheme. The required machine capabilities were then generated, helping in understanding the machine structures required for the subsequent process plans, thus prioritizing the most suitable one. The approach is more suitable if the both the previous and the new part to be produced belong to the same part family.

Finally, utilizing this information and including the previous data in the analysis, a suitable process plan along with the machine structure is proposed. This should not only help in the selection of the process plans but also significantly reduce the cost of the new machine structure which may have been required in case the previous information is ignored. This approach will help in automating and improving the process of machine as well as the process plan selection in commercial computer aided manufacturing (CAM) systems. It should be noted however, that this approach may be applied after some sort of sorting is done to select only the best few proposed process plans, if that is not the case, the approach will become tedious and redundant. In the current CAM systems the current machines and their configurations, plans are completely ignored when a new part is presented for manufacturing. This can be an important step in further developing the artificial intelligence (AI) of the current automated RMS. In the future this work will be taken further to develop the complete generation of suitable process plan for certain configurations.

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## References

1. Shabaka AI, ElMaraghi HA (2007) Generation of machine configurations based on product features. Int J Comput Integr Manuf 20(4):355–369
2. Kruth J, Detand J (1992) A CAPP system for nonlinear process plans. CIRP Ann Manufact Technol 41(1):489–492
3. Kim YS, Wang E, Rho HM (2001) Geometry-based machining precedence reasoning for feature-based process planning. Int J Product 2001 Res 39(10):2077–2103
4. Gologlu C (2004) Machine capability and fixturing constraints-imposed automatic machining set-ups generation. J Mater Process Technol 148(1):83–92
5. Colosimo BM, Semerar Q, Tolio T (2004) Rule based system for nonlinear process plan generation. Stud Inf Control 9:13–43
6. Grieco A, Matta A, Nucci F, Tolio T (2000) New policy to manage tools in flexible manufacturing systems using network part program. In: Proceedings of ASME 3rd conference on intelligent systems in design and manufacturing, Boston
7. Azab A, ElMaraghy HA (2007) Mathematical modeling for reconfigurable process planning. CIRP Ann Manufact Technol 56(1):467–472
8. Ma’rkus A, Va’ncza J (2001) Process planning with conditional and conflicting advice. CIRP Ann Manufact Technol 50(1):327–330
9. Ma′rkus A, Va’ncza J, Kova’cs A (2002) Constraint-based process planning in sheet metal bending. CIRP Ann Manufact Technol 51(1):425–428
10. Duflou JR, Va’ncza J (2005) Computer aided process planning: a state of the art. Comp Ind 56(7):747–771
11. Tolio T, Ceglarek D, ElMaraghy HA, Fischer A, Hu SJ, Laperrie‘ re L, Newman ST, Va’ncza J (2010) Co-evolution of products, processes and production systems. CIRP Ann Manufact Technol
12. Youssef AMA, ElMaraghy HA (2007) Optimal configuration selection for reconfigurable manufacturing systems. Published online: 30 June 2007 @ Springer Science+Business Media, LLC
13. Chu C-CP, Gadh R (1996) Feature-based approach for set-up minimization process design from product design. Comput-Aid Des 28:321–332
14. Cochran DS, Arinez JF, Duda JW, Linck J (2001) A decomposition approach for manufacturing system design. J Manuf Syst 20(6):371–438

15. ElMaraghy HA (1992) Integrating assembly planning and scheduling—CAPP related issues. Annls CIRP 41:11–14
16. Saygin C, Kilic SE (1999) Integrating flexible process plans with scheduling in flexible manufacturing systems. Int J Adv Mfg Technol 15:268–280
17. ElMaraghy HA (2005) Flexible and reconfigurable manufacturing systems paradigms. Int J Flex Manuf Syst 17(4):261–276 (Special issue on Reconfigurable Manufacturing Systems)

# Development of an Open-Architecture Electric Vehicle Using Adaptable Design

**Qingjin Peng, Yunhui Liu, Peihua Gu and Zhun Fan**

**Abstract** Open Architecture Product (OAP) offers public interfaces beyond the individual product. The interface can be shared by other products to enrich the product function and adaptability. Adaptable design (AD) meets OAP objectives for different requirements through modification or adaptation of product modules in the product lifecycle. The product adaptability is achieved by adaptable design, adaptable modules and platforms, and interfaces. This paper introduces a miniature electric vehicle with open architecture developed using AD. The electric vehicle consists of common platforms, customized modules, and user personal components. The vehicle developed can easily meet the individualization of users' requirements and requirement changes in its lifecycle.

## 1 Introduction

To survive in the market, industries have to develop products that meet increasing demands of market driven by universality, scalability, modularity, and compatibility [1]. For variant products with personality, a cost-effective solution is required to increase the adaptability of products in dynamic market. The emergence of alternative energy and digital manufacturing systems has enabled the distributed product development. The product cost can be dramatically reduced when customized products and function modules can be made locally based on the individual requirement. Industries are taking actions moving from centralized

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manufacturing to distributed systems following the globalization and the diversity of energy development. It is therefore required to have right product architecture and design methods to meet today's global marketplace with the product quality, productivity, and sustainability [2].

Product architecture is a framework of product structure represented by physical shapes and formats linking all product components together. It realizes desirable functions of a product using components, modules, and appropriate interfaces [3]. Product architecture ensures required functions of a product, such as flexibility and adaptability. A product with flexibility is the ability to change the state. A product with adaptability emphasizes the positive function change and the response to external influences [1]. Therefore, the appropriate product architecture is vital to meet the requirement changes throughout the product lifecycle.

Ideal product architecture offers ability for the product to change its structure actively on all levels at low costs in response to external or internal function changing requirements. This research uses the concept of open architecture product (OAP) for the development of an electric vehicle. As adaptability is the most important feature of an OAP, the adaptable design method is used for the development of OAP. Adaptable design (AD) combines commonality and modularity into the product development and application to create design and products that can be easily adapted for different requirements [4]. AD meets OAP objectives through modification or adaptation of product modules for different requirements in the product lifecycle. The product adaptability can be achieved by adaptable design, adaptable components, modules, platforms, and adaptable interfaces. This paper will introduce related research, proposed methods and applications. The development of a miniature electric vehicle is introduced with the open architecture using adaptable design. The solution and further work are also discussed.

## 2 Related Research

"Open" means that a system interface is beyond the individual system to be shared by other systems. Open architecture compared to closed architecture rests on the question of whether or not the interface specification of a product is made public, such as trucks in the automobile industry and personal computers in the computer industry, both of them can be classified as open architecture products [5–7].

Koren proposed a real-time open control system and open-architecture controllers for manufacturing systems [8, 9]. Wright defined open-architecture manufacturing as an enabling technology for either the agile manufacturing or CIM paradigms to specify computer platforms, operating systems, and languages. The open-architecture manufacturing system is reviewed using perspectives of cost, flexibility, delivery, and quality [10]. Gu et al. defined a real-time open-architecture control system with the capacity of parallel processing of real-time events, extraction of information from real-time data, and intelligent decision-making [11]. A scalable open cross-platform was proposed by Grigoriev et al. [12] to ensure the independence of a control system from the specific platform with broad opportunities to configure the CNC system for multi-axis machine tools. An open architecture CNC system was proposed by Li et al. [13] for the adaption of graphic features and geometric parameters from CAD data to control the motion between cutting tools and parts. Open architecture was used in the simulator of a chemical processing [14], and car's battery design using interfaces standardized across the auto firms [3]. Open architecture was also defined as the confluence of business and technical practices with public interfaces to enable reuse of components, rapid technology adoption, and reduction of maintenance constraints [15].

Based on the literature, open architecture product (OAP) can be defined as a product framework with public specifications including officially approved standards and privately designed structure made public by designers. The full meaning of open architecture includes interchangeability, expandability, adaptability, and sustainability. As shown in Fig. 1, a typical OAP consists of three types of functional modules: the common platforms made by manufacturers using mass production methods, the customized function modules made by producers with mass customization methods, and personally functional modules designed and made or purchased by users. These three parts are connected by adaptable interfaces to form a final OAP. Besides OAP advantages in design and manufacturing, the adoption of open architecture principles can also bring benefits of simplified product maintenance, and reduced inventory and cost [15].

Based on the open nature of OAP, OAP design methods have to meet needs of designers, manufacturers, and product users in developing, upgrading, adapting, and reusing of OAP. Based on the market requirement, OAP is designed according to mapping of functional requirements and structural elements. Decisions are made for how to realize desirable functions of the product; how to assign functions into

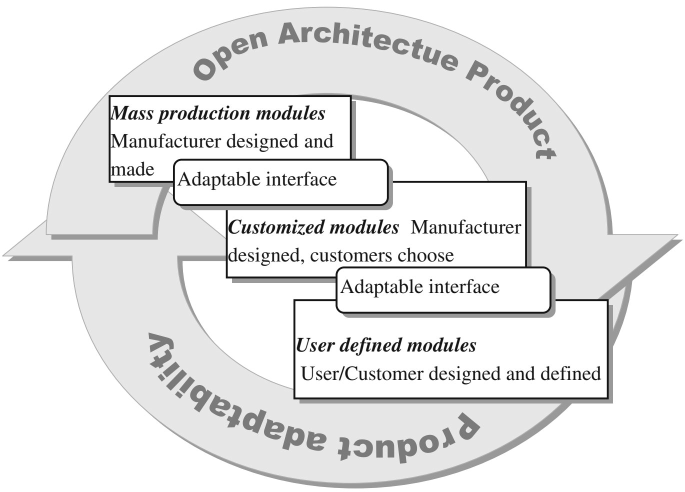


**Fig. 1** OAP definition

components, modules, and platforms, and how to design interfaces among components and modules for variant users and requirements. Changeable functions are achieved in an existing OAP using relatively independent modules to be attached, detached, modified, relocated, or replaced. These modules can be designed, made, or purchased by OAP users.

Modularity and commonality are two factors in product design to support the adoption of the open architecture. Their use in product design has made automobiles, aircraft, computers, and other machines reusable beyond their original lifecycle [15]. The modularity forms the independent product module and platform based on the product function requirements to enable the product extendable and upgradable. Modular design can be utilized for OAP to form function blocks for a verity of function requirements. The commonality usually takes open architecture features allowing modules from different resources used in same product. For example, a computer hard disk drive can be upgraded by any hard disk made by different makers to increase its capacity. Software system development has greatly benefited from the concept of open architecture. The existing methods of modularity and commonality enable products to meet requirements of multiple users with different needs. However, these methods are not enough to meet the requirement of OAP.

Modular design develops product modules with independent functions and structures. The module can be attached and replaced in a product based on users' need [16, 17]. A product platform can be formed by the aggregation of one or more functional modules shared by all products in a certain product family. Product platform enables that a product family shares the same platform with different add-on modules or module variants [18]. But modular and platform designs only consider the product need at the time to deliver the product. They are often used to reduce design and manufacturing efforts [4]. Mass customization product design develops products based on the need of individual customer with near mass production efficiency. It identifies patterns of customer needs with families of products, common components and modules. Various design elements can be reused to match customer needs of variety [4]. Design for mass personalization aims at effectively and efficiently satisfying customer by offering personally unique product [19]. However, mass customization and mass personalization products are not necessary with open architecture. The product may not be developed with expandability and upgradeability. Reconfigurable design considers the product structure changeability for different users in different applications, such as applications in machine tools [20], robots design [21], and electronic assembly systems [22]. A reconfigurable machine can have functions of several machines by reconfiguration of components in the machine. These reconfigurable requirements are considered in the design stage and have to be satisfied at the time of product release [4].

AD allows a product to be extended in functions, exchanged with modules, and upgraded by users. AD offers the product with features of extendibility, exchangeability, upgradeability, adaptability, and reusability, which is superior to other methods for the product lifecycle requirement. Therefore, compared to other design methods, AD offers a feasible solution for the OAP development. AD method can meet the need of OAP requirements to extend the function of a product through product adaptation. Changing requirements are met by adding functional units to an existing product through modularization, platforming and adaptable interfacing. OAP objectives are achieved using relatively independent modules, standard interfaces, and layout platforms. Therefore, OAP can be extended and upgraded in the product lifecycle for sustainability.

## 3 Adaptable Design Process for OAP

AD extends functions of a product and design through the design and product adaptation to meet OAP requirements. AD meets changing requirements by adding or replacing functional units to an existing product through modularization and adaptable interfaces. Producers can use design adaptability to reuse design methods, knowledge, and data. Users can increase product functions with the product adaptation [4, 16]. AD methods consider four basic elements in product design: product functional structures, adaptable modules, adaptable interfaces, and product adaptabilities as shown in Fig. 2 [4, 16]. Product requirements are modeled using functional structures. Modular architectures are used to achieve adaptable functions. Modules are integrated by interfaces. The design solutions are evaluated by product adaptabilities. A design is represented by product structures and parameters to meet the functional requirement. AD methods can be reused for the efficiency of OAP development.

The design adaptability is an ability of an existing design to be adapted to create a new or modified design based on the change requirements. For design adaptability, a new design can be created by modifying the existing design. Thus most of the existing design solutions and production processes can be reused. The product adaptability is for an existing product to be adapted for the change

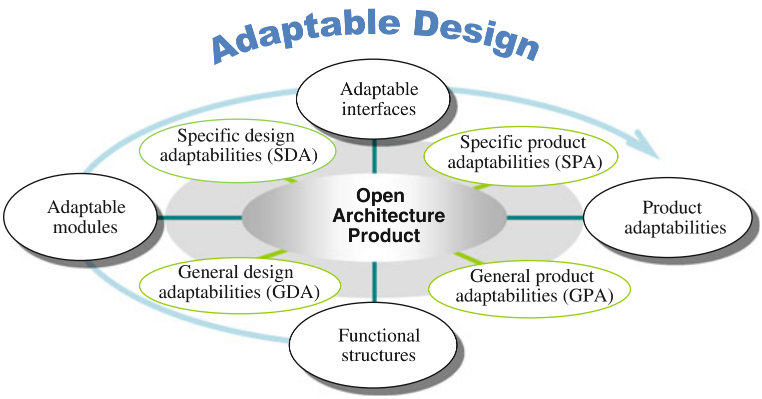


**Fig. 2** Basic elements and four adaptabilities of adaptable design

requirements. For product adaptability, a new product can be made by modifying the existing product, such as adding new components or modules, replacing or upgrading the existing components or modules with new ones, and reconfiguring the existing components or modules [4, 16]. With the product adaptability, most components or modules of an existing product can be reused. Both design and product adaptabilities should be included in OAP.

As the open feature is critical for OAP, the OAP design needs to focus on product architecture to meet the product functional requirement [23]. To meet requirements of product functional changes in the product lifecycle, it is necessary to model both product changeable and unchangeable functions. Generally, product design can be considered as a process to satisfy functional requirements and design constraints. An iteration search process may be applied for the optimal OAP development. The design solutions can be evaluated based on the selected evaluation measures such as design performance, production cost, operation cost, and maintenance cost. The best design is identified from all feasible design solutions based on the design evaluations.

Design and production are two processes in product development. The change of product requirements can be satisfied through two approaches of AD: the existing design can be adapted to create a new design and product, and the existing product can be adapted directly to satisfy the new requirement. Therefore, OAP using AD can offer both design and product adaptabilities. As the requirement change and the change probability in the product lifecycle may or may not be predictable, design adaptabilities can be classified into two categories: general adaptabilities and specific adaptabilities. When an adaptation and change probability can be predicted, the adaptability is considered as the specific adaptability. On the other hand, when the adaptation and/or its probability cannot be predicted, the adaptability is considered as the general adaptability. Since both product and design may have the specific and general adaptable requirements, OAP adaptabilities can be classified as: specific design adaptability (SDA), general design adaptability (GDA), specific product adaptability (SPA), and general product adaptability (GPA), as shown in Fig. 2.

Different strategies are required for these adaptabilities. For the general design and product adaptabilities, design guidelines can be suggested based on Suh's independent axiom [16]. The interface design has to be adaptable to meet potential product changes. Methods for market prediction are required for both new and remanufactured product demands to capture hidden and upcoming trends for an optimal OAP lifecycle design strategy [24]. The general design and product adaptabilities are dynamic product features reflected by the product evolution [25]. A generational variety index can be used to identify product variants that are most likely to require redesign in the future [26]. Scoring models that include occurrence probabilities and weighting factors can provide a less restrictive support for the solution evaluations. For the specific design and product adaptabilities where the adaptation and its probability can be predicted, design steps of an OAP are shown in Fig. 3 and suggested as follows:

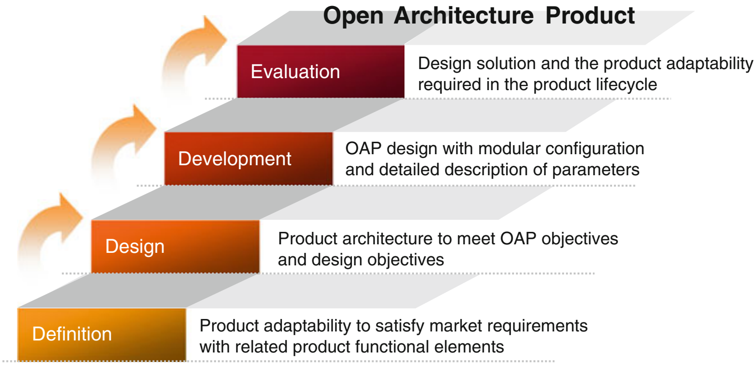


**Fig. 3** Design steps of OAP

1. Definition of the product adaptability to satisfy market requirements with related product functional elements.
2. Design of the product architecture to meet OAP objectives and design objectives.
3. Development of OAP design with modular configuration and detailed description of parameters. A product schematic can be used to represent product functional elements, modules, interfaces, and their relationships. The elements in the schematic are clustered into modules or platforms based on the product lifecycle requirement.
4. Evaluation of the design solution and the product adaptabilities required in the product lifecycle. A geometric layout can be used to identify the element interactions. All the possible interferences, such as geometrical and operation interferences, between physical components should be checked. An iteration search process may be applied in above steps for the optimal OAP development. The evaluation of product adaptability can combine different measures of OAP performance with weighting factors based on the product requirement, such as extendibility of product functions, upgradeability of modules, and customizability of components [27].

Both the tree structure and AND-OR graph can be used for product function and design modeling. Product function requirements and function solutions can be represented by nodes in the tree structure or AND-OR graph. The root node of a tree or AND-OR graph represents the overall function of a product. The network scheme is used for function modeling to show relations among all the functions in a product, which can be represented by three types of flows: materials flows, energy flows, and information flows [28]. The artifacts and attributes are normally used for design modeling. Both qualitative information and quantitative information can be modeled using artifacts and attributes [4].

To evaluate the product adaptability, different measures can be combined for the OAP performance with weighting factors based on cost of the product adaptation, extendibility of product functions, upgradeability of modules, and customizability of components. A specific product adaptability index is introduced to combine these measures to convert them into dimensionless evaluation measures. The weighting factors can be selected based on importance of each factor in the product. The specific product adaptability index $A(P)_i$ of each design candidate ranges from 0 to 1. When $A(P)_i = 0$, there is no product adaptability. When $A(P)_i = 1$, the design candidate has complete product adaptability [4]. Using the definition of the product adaptability measure A(P), the total efforts saved through the development of an OAP vehicle can be evaluated.

## 4 Example

A miniature electric vehicle shown in Fig. 4 is developed based on the method proposed in this research. The miniature electric vehicle has advantages of small size, highly mobility, simple operation, and low cost. It can go through large streets and small lanes with easy parking. Comparing with electric motor bicycles and tricycles, it provides better protection to drivers and passengers with the better steering stability and safety. The vehicle can be used by residents in urban and suburban areas for a multi-purpose such as commuting, shopping and picking up children, or used by small businesses, municipal sanitation for delivery and service. It can also be used as a short-distance transportation tool in industrial facilities, mining areas, parks and residential areas.

Applying the OAP concept, the vehicle is designed with an open architecture for needs of different consumers in variant applications. Vehicle functions and design parameters are mapped using rationalized functional structures as shown in Fig. 5. Product elements and design parameters are decided based on the vehicle specifications to meet basic functions and flexible requirements in the vehicle

**Fig. 4** Electric vehicle

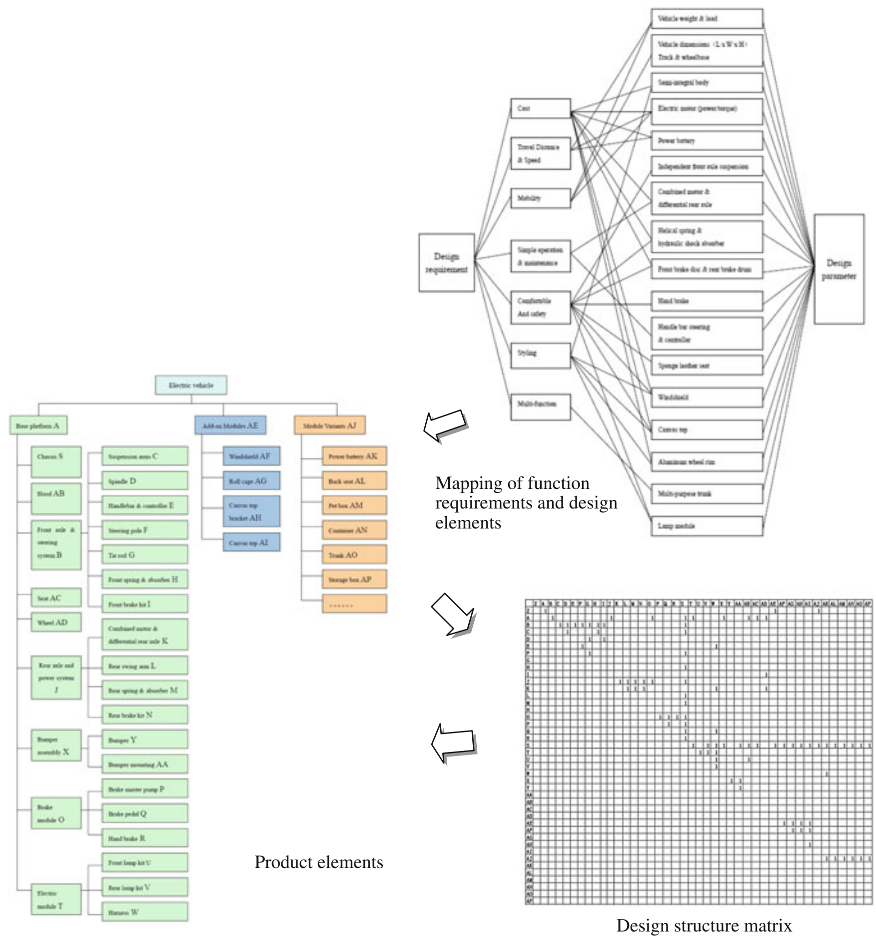


**Fig. 5** OAP design from function requirements to product modules

lifecycle. Modular architectures are used to achieve OAP with common platforms, functional modules and personal feature elements. Modules are integrated by adaptable mechanical, electrical, and software interfaces. Mechanical interfaces are composed of connectors with positioning and locating features, locking and release mechanisms for assembly and disassembly, and components for transmission and transformation of energy, materials, and signals. Mapping follows the axiomatic design to maintain the module independence of functional requirements. The design structure matrix is used for recording and analyzing of interaction relationships between product elements to form various modules.

Following above-mentioned processes, the vehicle is designed with three types of modules: common platforms shown in Fig. 6 are provided by the manufacturer with module numbers 1–6; functional modules in Fig. 7 are made by the producer

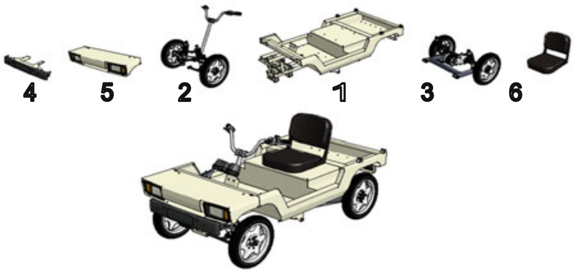


**Fig. 6** Common platforms

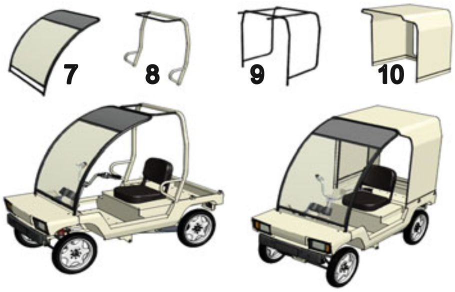


**Fig. 7** Functional modules

and chosen by users with module numbers 7–10; and personal feature elements in Fig. 8 are designed, made, or purchased by users with module numbers 11–16. OAP solutions are achieved to meet different consumer requirements with various vehicle assemblies as shown in Fig. 8.

This design achieves the product specific adaptability by providing personal feature elements for predicted consumers' requirements. For the general product adaptability, common interfaces are designed for adopting potential function modules. We are in the development of adaptable interface measures to quantitatively evaluate the interface efficiency for the module replacement operated by users. Design evaluations of the vehicle will be done after data and benchmarks are collected for the comparable products, the evaluation will look at cost for the adaptation of personal feature elements, and feasibility of the function extension, the module upgrading and function changes for users' requirements.

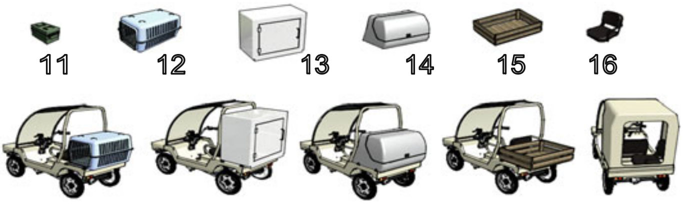


**Fig. 8** Personal feature elements

## 5 Conclusions

Open architecture product (OAP) offers a sustainable solution for customer-driven problems. Adaptable design (AD) is suggested in this research for development of OAP to meet different requirements in the product lifecycle. AD allows OAP to perform functional changes through modification or adaptation of physical components of the product to meet dynamical market changes, which is a typical knowledge-based processing based on the systematic reuse of standard and predefined components to deliver highly customized products that meet both customer-specific requirements and manufacturers' capacity and constraints. Using AD methods, different adaptabilities of OAP can be achieved to meet product design and application requirements in different environments. OAP performances can be evaluated using the measure developed in adaptable design. Methods and tools developed in this research can be similarly used for other OAP design and development, which provides a cost-effective solution for OAPs.

Proposed methods need to be improved with the intelligent decision-making in design of product module, module interface, and adaptabilities. It is critical to address complex issues of OAPs such as changeability and the product evolution over the product lifecycle. It is necessary for adaptable products to have a user-friendly interface to support the product open nature in design, manufacturing, and applications for adaptation. OAP design should be extended to support multi-channel data input and output for the product development by different users in different user environments.

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## References

1. Horbach S, Ackermann J, Mulle E, Schutze J (2011) Building blocks for adaptable factory systems. Robot Comput-Integr Manuf 27:735–740
2. Briere-Cote A, Rives L, Desrochers A (2010) Adaptive generic product structure modeling for design reuse in engineer-to-order products. Comput Ind 61:53–65
3. Park Y, Fujimoto T, Hong P (2012) Product architecture, organizational capabilities and IT integration for competitive advantage. Int J Inf Manage. doi:10.1016/j.ijinfomgt.2011.12.002
4. Gu P, Xue D, Nee AYC (2009) Adaptable design: concepts, methods and applications. Proc Inst Mech Eng Part B: J Eng Manuf 223(11): 1367–1387
5. Ulrich KT (1995) The role of product architecture in the manufacturing firm. Res Policy 24(3):419–440
6. Shibata T, Yano M, Kodama F (2005) Empirical analysis of evolution of product architecture: Fanuc numerical controllers from 1962 to 1997. Res Policy 34:13–31
7. Hassan S, Anwer N, Khattak Z, Yoon JW (2010) Open architecture dynamic manipulator design philosophy (DMD). Robot Comput-Integr Manuf 26:156–161
8. Koren Y, Pasek ZJ, Ulsoy AG, Benchetrit U (1996) Real-time open control architectures and system performance. CIRP Ann-Manuf Technol 45(1):377–380

9. Koren Y (1998) Open-architecture controllers for manufacturing systems. Open architecture control systems–summary of global activity, pp 15–37
10. Wrigh PK (1995) Principles of open-architecture manufacturing. J Manuf Syst 14(3):188–202
11. Gu JS, Silva CW (2004) Development and implementation of a real-time open-architecture control system for industrial robot systems. Eng Appl Artif Intell 17:469–483
12. Grigoriev SN, Martinov GM (2012) Scalable open cross-platform kernel of PCNC system for multi-axis machine tool. Procedia CIRP 1:238–243
13. Li P, Gao T, Wang J, Liu H (2010) Open architecture of CNC system research based on CAD graph-driven technology. Robot Comput Integr Manuf 26:720–724
14. Shacham M, Brauner N, Cutlip MB (2010) Open architecture modelling and simulation in process hazard assessment. Comput Chem Eng 24:415–421
15. Ferrer G (2010) Open architecture, inventory pooling and maintenance modules. Int J Product Econ 128:393–403
16. Gu P, Hashemina M, Nee AYC (2004) Adaptable design. CIRP Ann Manuf Technol 53(2):539–557
17. Xue D, Hua G, Mehrad V, Gu P (2012) Optimal adaptable design for creating the changeable product based on changeable requirements considering the whole product life-cycle. J Manuf Syst 31:59–68
18. Francalanza E, Borg JC, Constantinescu CL (2012) A case for assisting 'product family' manufacturing system designers. Procedia CIRP 3:376–381
19. Tseng MM, Jiao RJ, Wang C (2010) Design for mass personalization. CIRP Ann Manuf Technol 59:175–178
20. Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, Brussel HV (1989) Reconfigurable manufacturing systems. CIRP Ann Manuf Technol 48(2):527–540
21. Makris S, Michalos G, Eytan A, Chryssolouris G (2012) Cooperating robots for reconfigurable assembly operations: review and challenges. Procedia CIRP 3:346–351
22. Peters BA, Rajasekharan M (1996) A genetic algorithm for determining facility design and configuration of single-stage flexible electronic assembly systems. J Manuf Syst 15(5):316–324
23. Ulrich KT, Eppinger SD (2000) Product design and development. McGraw-Hill, New York
24. Ma J, Kwak M, Kim H (2012) Pre-life and end-of-life combined profit optimization with predictive product lifecycle design. Proceedings of the ASME IDETC/CIE 2012, DETC2012-70528
25. Löffler C, Westkämper E, Unger K (2012) Changeability in structure planning of automotive manufacturing. Procedia CIRP 3:167–172
26. Martin MV, Ishii K (2012) Design for variety: developing standardized and modularized product platform architectures. Res Eng Des 13(4):213–235
27. Li Y, Xue D, Gu P (2008) Design for product adaptability. Concurr Eng 16(3):221–232
28. Pahl G, Beitz W (1988) Engineering design: a systematic approach. Springer, Berlin

# Ergonomics Issues in Furniture Design: A Case of a Tabloid Chair Design

**R. M. Shah, M. A. U. Bhuiyan, R. Debnath, M. Iqbal and A. Shamsuzzoha**

**Abstract** Ergonomics is a science that is focused on the study of human fit, and decreased fatigue and discomfort through product design. This science is extensively applied to various furniture designs in home and office taken into consideration how the furniture is designed to fit to its users. This research work concentrates to problems faced by students at Shah Jalal University of Science and Technology, Sylhet, Bangladesh, who are using tabloid chair in their day to day classroom environment. The objective of this research is to identify ergonomics viewpoints by using tabloid chair for sitting in classroom environment and its associated limitations or problems. To find out the limitations or constraints in using the tabloid chair, a survey on 160 university students were carried out by using the chair for sitting position in the classroom more than 1 h per day and accompanying body discomfort was critically investigated. The outcomes from this survey showed that body discomforts are found at elbow, back, neck, and thigh of 46, 41, 31, 33 students respectively. Based on the anthropometric data taken from those 160 students, an updated tabloid chair was designed and developed and presented in this paper. The tabloid chair as fabricated considering the proposed ergonomics design was also validated with respect to its materials and overhead costs.

## 1 Introduction

The concept of ergonomics is to bring comfort and wellbeing to human. With this view, this research concerns to analyze commonly used chair for sitting in elsewhere, especially to classroom environment. One could imagine that there are as

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many different types of chairs available as there are people of different heights and weights. The chair is an object that is usable and available to most of everyone. In its different embodiments, a chair can be humble or regal and made of traditional wood or high-tech polymers, simple in concept or highly charged with meaning. Fundamentally, the requirements for a chair are few. It is essentially a horizontal surface at a logical height from the ground meaning to support the human body while sitting position. A vertical surface of a chair is provided for back support. It can have arms or be armless. While these are the basic elements, a chair is more than the sum of its component parts.

The psychological relationship with the user and a chair is perhaps stronger than with any other types of household furniture. Basic form of a chair is comprised of three factors: functional, aesthetics, and material. Among all other general types of chairs, tablet arm chair is widely used in educational institutions and business organizations due to its less space consumption in comparison to its functionality. Usually, a user sit on a chair for long time that causes fatigue or fill uncomfortable when the chair is not designed ergonomically. With the view to achieve better performance, a chair should be designed as perfectly as possible following the general ergonomics principles. The resultant chair will provide to the user better comfort in total.

The study focuses the users of tabloid chair who are the university students of Bangladesh. The aim of this study is to find out the problems faced by the user and their recommendation which will help in designing a new tabloid chair. In this research, an ergonomically tabloid chair was designed and fabricated with the objective to bring comfort enough for the human being, especially for classroom environment. This proposed chair was also tested using various anthropometric data from 160 students at the Shah Jalal University of Science and Technology, Bangladesh. The outcomes from the test are presented in the results and analysis section, where the tests findings are elaborated extensively.

## 2 Literature Review

Ergonomics (*or human factors*) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance [1–3]. This discipline is described as an innovation and safety factor for the execution of design projects of new products. Within the context of a design project, ergonomics study describes and analyzes each phase of the design process from a design model based on concurrent engineering [4]. Peck [5] did a research on the benefits of ergonomically designed chairs in the shop floor environment, where he focused on measuring the changes in productivity related to ergonomic improvements. Another research work was done by Azad and Reza (2004), where they presented an up-to-date design of an ergonomic chair for a VDT Workstation at the

Department of Industrial and Production Engineering, Shah Jalal University of Science and Technology.

Several design efforts were carried out for school furniture (e.g., chair and table) by different researchers in order to improve their overall comfort ability after strictly following the ergonomics principles. For instance, Aagaard, and Storr-Paulsen [6] proposed a better seat design of a school chair and it's accompanied table-top that was initially fabricated after following ISO standards. Agha [7] considered the anthropometry to the dimensions of school furniture and determining whether the furniture used matches the students' anthropometry. This study measured 600 male several students' body dimensions including elbow-seat height, shoulder height, knee height, popliteal height, and buttock-popliteal length with the objective to find the mismatch between the students' body dimensions and the classroom furniture. It appears that the mismatches in seat height, seat depth, and desk height occurred for 99 % of the students, while the mismatch for the back rest height was only 35 %. Domljan et al. [8] recommended adjustable chairs to be introduced in Croatian schools after studying 556 pupils from three primary schools in Zabreb, Croatia, and two types of chairs.

## 3 Research Methodology

In order to accomplish the research goal, a survey was conducted on 160 users of different tabloid chairs at Shah Jalal University of Science and Technology, Bangladesh. The majority of the population was male. The majority of the population weight ranged from 55 to 70 kg. Majority of the population age ranged from 20 to 23 years. The data has been gathered through questionnaires. Each of the questions is taken from an individual user after the user spent minimum 1 h sitting on tabloid chair. The questionnaires were consisted of two parts: one to find out the problems faced by the users and the other for identification of the users recommendations. Finally all data has been analyzed by using various types of tables and graphs.

This study was conducted following five major steps:

Firstly, a survey plan was set up to conduct the study at the campus of Shah Jalal University of Science and Technology, Sylhet, Bangladesh. Within this survey plan 160 students with different body fit in terms of height, weight, duration of sitting in the classroom environment were considered.

Secondly, a set of questionnaires were prepared and distributed to the 160 students to support this ergonomic problem survey. These questionnaires were consists of different anthropometric measures such as comfort level, fatigue problem, duration of sitting, etc., with the tabloid chair used in the classroom environment.

Thirdly, the responses or data from this survey was collected and analyzed with the objective to identify and prioritize the problems as needed to prepare the improvement plan of the general tabloid chair following recommended ergonomics guideline.

Fourthly, the necessary anthropometric dimensions of the surveyed population are obtained or approximated from the result of the available anthropometric surveys reasonably represent the user group.

And finally, design and develop proposed new tabloid arm chair complying with the collected anthropometric data from the conducted survey.

## 4 Results and Analysis

The outcomes from the study survey were collected and analyzed with respect to their importance and suitability to design and fabricate the proposed new tabloid chair. The results were also categorized based on their corresponding anthropometric values, measures, and explanations which are presented in the following sub-sections.

### *4.1 Determination of Average Time Spent on a Tabloid Chair by a User*

Various types of pain faced by a user of a tabloid chair must be dependent on the time duration usually s/he spent to sit on the chair. The average time spent by the individual user was presented in Table 1. From Table 1, it is seen that out of 110 users 31 users spent 1 h, 36 users spent 2 h, 49 users spent 3 h, and 34 28 users spent 4 h.

By using the data from Table 1, a pie chart was also developed as presented as in Fig. 1, which shows that 21 percent of the user sits 1 h, 24 % sits 2 h, 32 % sits 3 h, and 23 % sits 4 h.

**Table 1** Average time spent by the users on tabloid chair

| Duration | 1 h | 2 h | 3 h | 4 h |
|---|---|---|---|---|
| Number of user | 31 | 36 | 49 | 34 |

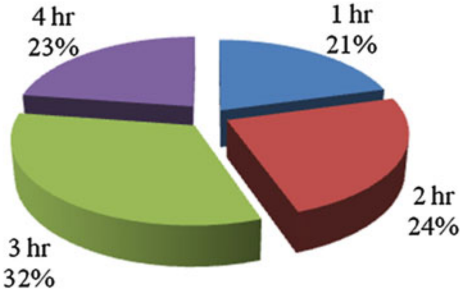


**Fig. 1** Average time spent on a tabloid chair by the users

### 4.2 Assessment for Frequency of Pain Felt by Users

The frequency of pain felt by the users depends on some factors such as sitting duration, condition of the seat and some other minor factors. These survey assess the pain felt by the users while they were sitting on the chair. After processing of the data it is seen that 22 users never felt any pain, 111 users sometimes felt pain, and 17 users always felt pain. Table 2 displays the frequency of pain felt by the users.

### 4.3 Assessment of the Condition of Existing Seat Pan

One of the major causes behind the pain felt by a chair user is the condition of the seat pan. For a poorly designed seat, the user can feel pain on thigh and posture. To assess the present condition of the seat, five categories were selected such as very bad, bad, fair, good, and excellent. Different ratings of the tabloid chair users are based on the condition of existing seat pan are shown in Table 3.

### 4.4 Assessment of Comfort Ability of the Existing Chair

To find out the comfort ability of the existing chair, a scale of 1–5 was selected, which allow the users to rate the chairs they are using. The assessment shows that majority of the chair's comfort ability is average. From Table 4, it is clearly seen that a large number of user rate their chairs 3. 22 users felt very low comfort of rating 1, 34 users rated 2, and 8 users rated 3.

**Table 2** Frequency of pain felt by users

| Frequency | Never | Sometime | Always |
|---|---|---|---|
| Number of user | 22 | 111 | 17 |
| Percentage | 16 | 27 | 11 |

**Table 3** Condition of existing seat pan

| Condition | Very bad | Bad | Fair | Good | Excellent |
|---|---|---|---|---|---|
| Number of user | 10 | 36 | 68 | 34 | 2 |
| Percentage | 7 | 24 | 54 | 23 | 1 |

**Table 4** Comfort ability of the existing chair

| Rating | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Number of user | 22 | 34 | 83 | 8 | 3 |

## 4.5 Assessment of Tab Height of the Existing Chair

Tab height is a vital factor in a tabloid chair. Inappropriate tab height causes elbow, shoulder, and neck pain. Inappropriate tab height refers both the tab which is above and lowers comparing to elbow rest height. Table 5 shows that tab height is appropriate for 51 users (out of 108) and 57 users feel that the tab height is not appropriate for them.

## 4.6 Assessment of Pain on Hand While Writing

The frequency of pain felt on hand by the users while writing depends on the factors such as tab height and tab size. Improper tab height is responsible for shoulder and neck pain. Elbow and wrist pain causes due to improper tab size. Table 6 presents the assessment of pain on hand while writing. From Table 6 it is noticed that 21 users do not feel any problem which means that tab height is appropriate for them, 111 users sometimes feel pain that mean if they were sitting for a long time which causes pain and if the duration is shorter they do not feel pain, 18 users always feel pain on hand while writing. In percentage, it can be explained that 14, 74, and 12 % of the users never, sometime, and always felt pain on hand respectively while writing.

## 4.7 Assessment of Health Problem Faced by the Users

Various types of health problems faced by the users of tabloid chair are presented in Table 7. From Table 7, it is seen that majority of the user feels elbow pain (46), back pain (41), posture pain (35), thigh pain (33), and neck pain (31). Because of existing tabloid chair's tab height, back rest angle, and seat pan inappropriate for those users. So there is a lot of scope to improve the condition of the existing tabloid chair.

**Table 5** Suitability of tab height

| Tab height | Appropriate | Inappropriate |
|---|---|---|
| Number of user | 51 | 57 |

**Table 6** Pain felt by the user while writing

| Frequency | Never | Sometime | Always |
|---|---|---|---|
| Number of user | 21 | 111 | 18 |
| Percentage | 14 | 74 | 12 |

**Table 7** Various types of problems and their causes

| Problems | Number of population | Causes |
|---|---|---|
| Shoulder pain | 9 | Improper tab height |
| Neck pain | 31 | Improper tab height, back rest angle |
| Elbow pain | 46 | Improper tab height and size |
| Wrist pain | 7 | Improper tab height and size |
| Back pain | 41 | Improper back rest angle |
| Lower back pain | 8 | Improper back rest angle and seat depth |
| Posture pain | 35 | Poor condition of seat pan |
| Thigh pain | 33 | Improper seat height and depth |
| Knee pain | 12 | Improper seat height |

### *4.8 Preferable Chair for Classroom Environment*

The study tries to find out which kind of chair preferred by the user for classroom environment and the results are presented in Table 8. From Table 8 it is seen that majority of the users prefer armless chair with foam (40 %). Preference for tabloid arm chair is 29 %, while armless wooden chair is preferable to 15 and 15 % for arm chair.

### *4.9 Preference of Tablet Arm Chair for Classroom Purpose*

Nowadays tabloid chair is common in the classroom environment because it consumes less space in comparison to other combination of chair and desk. To find out the user's preference of tabloid chair for classroom environment, a scale of 1–5 was developed and the outcomes are presented in Table 9. From Table 9, it is observed that maximum 57 users marked 3, maximum 32 users marked 4, 30 users

**Table 8** Preferable chair for classroom purpose

| Types of chair | Tablet arm chair | Armless wooden chair | Arm chair | Stool | Armless chair with foam |
|---|---|---|---|---|---|
| Number of users | 43 | 23 | 22 | 1 | 61 |
| Percentage | 29 | 15 | 15 | 1 | 40 |

**Table 9** Preference of tabloid chair

| Rating | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Number of users | 26 | 30 | 57 | 32 | 5 |
| Percentage | 17 | 20 | 38 | 21 | 4 |

**Table 10** User requirement

| Feature | Total population | Yes (%) | No (%) |
|---|---|---|---|
| Seat height Adjustability | 110 | 83 | 17 |
| Tab height Adjustability | 110 | 89 | 11 |
| Space for bag/file | 110 | 98 | 2 |

marked 2, 26 users marked 1, and 5 users marked 5, which in percentages are 38, 21, 20, 17, and 4 % respectively.

### 4.10 Assessment of the User Requirement

Table 10 below shows the users' requirements in terms of seat height adjustability, tab height adjustability, and space for bag/file.

## 5 Design and Fabrication

After analyzing the survey outcomes of various health problems faced by the users of tabloid chairs, it was seen that nobody felt comfort except a small portion of the population, which means that there is an opportunities to improve the comfort ability of the tabloid chair. It was also noticed from the previous section that 70 % of the users sometimes and 12 % of the users always felt different types of pains such as pains on back, elbow, neck, and posture. The reason behind this is the improper match between the user and the tabloid chair, which was not designed following the ergonomics principles. This section presents the design procedure of a tabloid chair following the ergonomics guidelines.

In order to design anything according to ergonomic principles requires the anthropometric data base, which should be taken from such population for which the design is being developed. Here the design is being developed for the student of Department of Industrial and Production Engineering, Shah Jalal University of Science and Technology, Sylhet, Bangladesh. Anthropometric data of 160 students were collected and processed for designing a new tabloid chair. The design methodology as taken to fabricate the new tabloid chair can be seen as in Fig. 2.


**Fig. 2** Method of tabloid chair design

## 5.1 Anthropometric Data

Anthropometric data was collected from the students of 2007–2008 sessions to 2010–2011 sessions and the data was tabulated in Microsoft Excel. A statistical formula named *percentile* was used, which returns the k-th percentile of values in a range. To calculate 95, 50, 5th percentile of various anthropometric measurement, the values of k = 95, 50, 5 were used. The processed data are presented in Table 11.

## 5.2 Design Specification

Various design specifications of the tabloid chair such as seat height, seat depth, seat width, back rest height, and tab height are presented in Table 12. Different anthropometric measurements and the values of each of the specifications are also shown in Table 12.

## 5.3 Material Selection and Cost

The material selection to fabricate the any kinds of chair depends on its design feature, aesthetic view, and the overall user requirements. Generally, wood, steel

**Table 11** Anthropometric data of 95, 50, and 5th percentile

| | Minimum | Maximum | 95th percentile | 50th percentile | 5th percentile |
|---|---|---|---|---|---|
| Popliteal height | 37 | 51 | 47 | 44 | 40.25 |
| Buttock-Knee depth | 41 | 63 | 61 | 55 | 49 |
| Buttock popliteal depth | 38 | 54 | 50.75 | 46 | 41 |
| Elbow to elbow breadth | 38 | 56 | 51 | 45 | 41 |
| Sitting elbow height | 17 | 27 | 25 | 21 | 18 |
| Sitting shoulder height | 49 | 63 | 61 | 56 | 51 |
| Hip breadth | 28 | 40 | 37.75 | 33 | 30 |
| Thigh clearance | 10 | 18 | 16 | 14 | 12 |
| Stature | 143 | 182.88 | 176 | 167.22 | 159.5 |

**Table 12** Anthropometry in terms of chair measurement

| Specification | Measurement | Value (cm) |
|---|---|---|
| Seat height | Popliteal height + shoe allowance 3.81 cm | 49 |
| Seat depth | Buttock popliteal depth−clearance 12.7 cm | 37 |
| Seat width | Hip breadth × cloth allowance 1.3 | 43 |
| Back rest height | Sitting shoulder height × 0.8 | 45 |
| Tab height | Sitting elbow height + allowance | 25 |

(hollow round and square, angle) bars, foam, ply wood, and particle board are used in the chair manufacturing. Wood is the most common material used in chair manufacturing. It can be used in every part of the chair and comparatively low in cost. Metal or steel bar are usually used to make the frame of the chair. Metal has also good strength and machine ability. Its life time is more than the wood. Foam is usually used as the seat pan and backrest of the chair that brings comfort to the user through its soft surface. Ply wood are also used in seat pan, backrest, and tab of the chair.

In order to bring necessary comfort level and required weight and strength hollow square steel bar, wood, particle board, and foam were selected to fabricate the new tabloid chair to be used for the students in the classroom. More specific reasons behind to select those materials are given.

*Hollow Square Steel Bar* Square bar was selected for the frame of the chair. It can be bended to a certain angle which reduces time and machining cost.

*Wood* To support the foam of seat pan and backrest wood sheet was selected. Wood is fastened with the steel by means of screw to provide a support for foam.

*Particle Board* Tab is an important component of a tabloid chair. Tab should be strong and rigid enough to provide support to hand while writing and also light in weight. For this purposes particle board was selected for making the tab.

*Foam* About 53 % users prefer foam as seat pan material. So, in order to fulfilling majority of the users' preferences, foam was selected as the seat pan material. It is also used as the backrest material too.

## 5.4 Detailed Design

This section presents the detailed design of the newly designed tabloid arm chair. Different views such as isometric view, top view, front view, and right hand side (R.H.S) of the tabloid chair are presented in the following figures. For instance, Fig. 3 displays the isometric view, Fig. 4 presents the top view, Fig. 5 presents the front view and Fig. 6 presents the right hand side view of the tabloid chair.

## 5.5 Bill of Materials and Total Cost

The bill of materials (BOM) and the total cost to fabricate the proposed tabloid chair is presented in Table 13. From Table 13 it is seen that the total cost including the materials, labor, and overhead is 1820 Bangladesh Taka which is equivalent to USD 25.00. The cost looks pretty cheap in comparison to the available tabloid chair in the market which is between USD 40.00 to USD 100.00 in general. Manufacturability of this new chair is also less time consuming and operator's friendly.

**Fig. 3** Isometric view of the proposed tablet arm chair

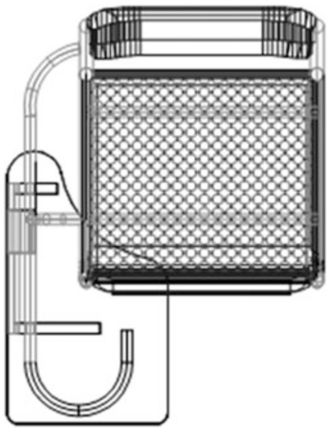

**Fig. 4** Top view of the proposed tabloid arm chair

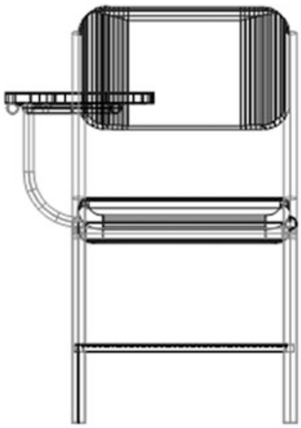

**Fig. 5** Front view of the proposed tabloid arm chair

**Fig. 6** Right hand side view of the proposed tabloid arm chair

**Table 13** Bill of materials

| No | Items | Quantity | Cost (Bangladesh Taka) |
|---|---|---|---|
| 1 | Round pipe | 20 ft | 480.00 |
| 2 | Wood | 3.1 $ft^2$ | 160.00 |
| 3 | Net | 1.723 $ft^2$ | 200.00 |
| 4 | Rexene | 4.5 $ft^2$ | 210.00 |
| 5 | Foam | 30 g | 30.00 |
| 6 | Particle board | 1.62 $ft^2$ | 120.00 |
| 7 | Cap | 10 piece | 20.00 |
| 8 | Labor cost | | 500.00 |
| 9 | Overhead cost | | 100.00 |
| Total cost | | | 1,820.00 |

# 6 Conclusion

The use of the tabloid chair in classroom is increasing day by day due to its usability and consumes less space. Without proper design of a chair, sitting will require greater muscular force and control to maintain the stability and equilibrium in general. These requirements are in turn results in greater fatigue and discomfort and are likely to lead to poor postural habits as well as neck or back complaints. The most common problem faced by the users of the tabloid chair is elbow pain. The survey conducted in this research study finds out that out of 160 users of the tabloid chair 138 users did face pain on hand while writing, and only 22 users did not. Among these 138 users 46 users also specified that they were faced elbow pain. Second most common pain faced by the users was back pain. The survey reveals that 41 users out of 160 users felt back pain. Due to the lack of proper knowledge about ergonomics principles, many users did not specify where they felt pain.

In this research work, the authors have tried to design a tabloid chair, which will give more advantages to the students. This paper addresses a better approach to design and fabricate a tabloid chair, which will provide support to the body to eliminate unexpected or unhealthy stress. This research also analyzed the suitability of different materials to be used to fabricate the chair and accompanying cost is also presented. The cost calculation shows that the proposed new chair has the enhanced manufacturability and cheaper in cost in comparison to the available chairs in the market, although research is needed to calculate the cost based on its effective life. There are several limitations or constraints in this research such as; (1) smaller sample size that may not be enough to generalize the design of the tabloid chair for class room environment, (2) waste of the materials used to fabricate the chair and whether the materials are recyclable are not considered extensively, (3) proposed design is not analyzed virtually by any suitable software, (4) sustainability of the chair design is not considered with respect to generic norms and conditions, etc. All such limitations or constraints can be overcome through future research and at the same time a deciding attribute 'style and appearance' can also be considered as the future research direction too.

## References


1. Skepper N, Straker L, Pollock C (2000) A case study of the use of ergonomics information in a heavy engineering design process. Int J Ind Ergon 26(3):425–435
2. Xu J, Zhang H (2013) Modern office furniture design based on ergonomics. Adv Mater Res 628:57–62
3. Alur S (2010) Organizational ergonomics in medical device design standards. J Med Mark: Device Diagn Pharmaceutical Mark 10(4):312–322
4. Sagot J-C, Gouin V, Gomes S (2003) Ergonomics in product design: safety factor. Saf Sci 41(2–3):137–154
5. Peck JC (1992) A benefits study of ergonomically designed chairs with direct labour employees. Int J Cloth Sci Technol 4(2/3):39–44
6. Aagaard J, Storr-Paulsen A (1995) A comparative study of three different kinds of school furniture. Ergonomics 38(5):1025–1035
7. Agha SR (2010) School furniture match to students' anthropometry in the Gaza Strip. Ergonomics 53(3):344–354
8. Domljan D, Grbac I, Haina J (2008) Classroom furniture design—correlation of pupils and chair dimensions. Collegium Antropologicum 32(1):257–265

# Solid Wood Panel Manufacturing Using Low Quality Materials

**Omar Espinoza, Urs Buehlmann and Maurice Deaver**

**Abstract** Low-value hardwoods are not used to its full potential because they possess a challenging economic proposition to entrepreneurs in search of profit. In particular, high extraction and processing costs for low-value and underutilized hardwoods are not offset by products that carry a high enough value to customers to assure favorable economics. Thus, the low-value biomass is not used sufficiently in U.S. forests to support sustainable quality forest management practices. Furthermore, economic opportunities are lost for rural economies and forest landowners. The main purpose of the project described is to design the manufacture of a high value product from low-value hardwood timber achieving positive economics, thereby assuring the efficient and effective use of the resource. In particular, the project assesses the markets and the technical potential for manufacturing solid, finger-jointed edge-glued hardwood panels from low-value hardwoods. In fact, the technical feasibility of manufacturing edge-glued panels has been proven and is a major product of wood components manufacturers in the U.S. However, the use of low-value hardwoods for this purpose has not received much attention. This study intends to fill this gap by conducting an exhaustive analysis of secondary sources to assess raw material availability for such panels from low-value hardwoods. Also, appropriate processing routes to achieve competitive target prices while assuring positive economics are investigated.

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## 1 Introduction

The U.S. manufacturing sector has seen challenging years during the past decades, with manufacturing employment reaching its lowest level since 1950 [1]. A major driver behind the decline of U.S. manufacturing prowess is, besides the temporary economic challenges facing the nation, the ongoing globalization of trade, which has brought the comparative disadvantage of the United States as a manufacturing location to the forefront. Unfortunately, many U.S. based hardwood lumber consuming industries, such as furniture, flooring, or millwork were hard hit by the worldwide opening of markets for goods and services [2–6] and the recent decline in economic activity [7, 8]. The resulting decline in hardwood use diminishes the demand for hardwood lumber, affecting the industries and forest landowners upstream from the final manufacturer [5]. U.S. hardwood lumber production tumbled from over 11 billion board feet[1] in 2006 to less than 7 billion board feet in 2009 and has only recovered slightly since. Decreasing demand for U.S. hardwoods leads to decreasing value of forest lands and forest ownership profits, which threatens forest management and rural economies in the eastern U.S. hardwood regions. The slump in demand (which is responsible for the steep decrease in production) has depressed lumber prices; especially prices of lumber made from the lower quality, smaller diameter harvest, and have trickled down to log prices, leaving the landowners with smaller benefits from their landholdings. With ample supply of logs at affordable prices, higher grade logs, and lumber can be used for purposes such as, for example, industrial packaging, and transportation, normally considered uneconomical. Thus, at the present time, markets offer limited incentive to find uses for lower quality, smaller diameter trees that make up almost a third of the U.S. eastern hardwood stands [9].

The quality of the U.S. hardwood timber supply is changing [10, 11]. In the U.S. Appalachian region (comprising 13 states, from New York to Mississippi), timber resources have changed in composition during the last decades due to selective-cutting and harvesting activities [12]. Volumes of northern red oak, for example, have declined by double-digit numbers, while red maple's volume has increased. However, tree grades for red maple are generally lower compared to red oak [12]. Inconsistent growth ring counts, pin knots, and highly heterogeneous stands (in species and diameter) are other negative effects of selective harvesting. Wiedenbeck et al. also pointed to the need of developing new markets to promote sound forest management for healthy and productive forests [13]. Another important forest region, the Northern Lake States (states of Minnesota, Wisconsin, and Michigan), has one of the highest forest biomass densities in the U.S. [14], although this resource is of different composition than in the Appalachian area. Minnesota in particular, has vast aspen resources; this short-lived, fast growing species is by far the most abundant in the state, the volume of live trees on forest land is estimated at 3.4 billion cubic feet (19 % of the total), and a volume of saw

[1] A board foot describes a volume of one foot by one foot by one inch.

timber of 6.2 billion board feet (16.5 % of the total). The majority of the aspen resource in the state belongs to the "small" stand class size [15]. Almost all aspen is harvested for pulpwood (1.36 million cords[2] of a total 1.45) [16], but in recent years there has been a reduction in the harvest levels, partly due to mill shutdowns, slowdowns, and downsizings (harvest levels are down by 0.7 million cords from 2000 to 2008, 16). Thus, new value-added uses for this resource are desperately needed and will enhance the economic wellbeing of rural communities that rely on forest products industries in the entire region.

Consensus exists that traditional markets for hardwoods cannot absorb all the low quality timber in existence [17]. Thus, it is possible that low-grade logs yield a limited amount of high-grade boards. In a survey among hardwood lumber manufacturers [18], almost half of respondents thought the production of low-grade material has increased during the last 5 years, reflecting the growing importance of low grade logs being harvested in the U.S. hardwood forests. A large volume of low-value and underutilized forest stock exists [17]. Hardwood growing stock with diameters between 5 and 11 inches (defined as pole timber) make up 32–42 % of total volume of eastern hardwood forests and 93–95 % of the total number of growing stock trees [17]. Since there is little incentive today to remove the low value and thus underutilized material from the forests the risk of catastrophic fires or the occurrence and spread of pests is increased. Also, the practice of high-grading (harvesting only high value timber) in the U.S. eastern hardwood forest has left more residual, low quality timber [11]. Several uses have been suggested for this material, such as the use of small-diameter material for recreational buildings [19]; or to make lumber, pallet, and container parts [20]; or for biomass-based energy uses [21]. However, as Levan-Green and Livingston [22] have suggested, the utilization of small-diameter timber requires higher value markets for this resource to make harvesting economically viable for companies and loggers. The total volume of standing inventory that is below 11 inches of diameter, considered pole timber, based on the inventory carried out by the Forest Service in 2010, is 137.90 billion cubic feet (Forest Inventory Analysis online tool, 9). Thus, based on the data from the U.S. Forest Service's Forest Inventory Analysis [9], almost a third of the U.S. hardwood forest is made up of low-value and underutilized trees. Proper forest management mandates that such trees can be removed at a sustainable rate to assure the existence of the highly sought after quality hardwood trees for future generations. However, the removal of low-value and underutilized trees will only happen if loggers can profit from the material harvested.

Low-grade lumber, small-diameter roundwood, and sawmill slabs are underutilized and undervalued hardwood resources that are abundant in today's market. Processing such material to remove defects results in short and narrow clear cuttings. These short and narrow pieces can be finger-jointed for length and edge-glued for width to produce panels of various sizes and qualities. The main

[2] A cord describes a volume of stacked wood 4 feet high, 8 feet long, and 4 feet deep.

objective of this research was to investigate the market potential for the manufacturing of solid wood edge-glued panels from low-quality, underutilized hardwoods. The supporting objectives are listed below.

1. Identify the market opportunity for solid hardwood panels from underutilized raw material.
2. Define raw material and raw material availability for the production of finger-jointed, edge-glued hardwood panels from underutilized hardwood resource.
3. Develop a supply chain and manufacturing strategy for the product proposed.

## 2 Methods

The methods used for this research were a combination of secondary and primary sources of information. For the market opportunity and product identification, an extensive literature review was conducted. Sources such as the Wood Components Manufacturers Association [23] were consulted for statistics on current markets for hardwood solid panels. Raw materials availability was evaluated based on statistics published by the U.S. Forest Service; such as their Forest Inventory Analysis [9], and online tool that allows users to search for volumes of standing timber with certain characteristics, such as diameter, species, etc. A suitable cutting list for wooden parts was developed based on past research and resulting yields[3] were estimated with the help of rough mill simulation software. The manufacturing strategy was developed based on past research on efficiency improvements in solid wood panel manufacturing.

## 3 Results and Discussion

### 3.1 Defining the Product and the Market Opportunity

Several alternatives have been proposed to use underutilized low-value hardwood resources. Among these are their uses in engineered wood panels, such as oriented strand board (OSB) panels, medium-density fiberboard (MDF), as raw material for pulp and paper, and for wood-based energy generation. However, all of these uses add very little value to the wood resource. In this research, the use of underutilized low-value hardwoods for the manufacture of solid, edge-glued panels is considered. The authors believe that developments such as the market trend toward the customization of consumer products, which makes the outsourcing of solid panel production an attractive option for manufacturers of cabinets, furniture, doors, and

[3] Yield is the surface ratio between the incoming material and the output of the operation.

other wood products [24], could make the production of solid wood, edge-glued panels an attractive enterprise.

Solid wood, edge-glued panels, finger-jointed or not, are a versatile product. Such panels can be manufactured for specific uses or in standard sizes. Production of such panels allow for the utilization of small-diameter, low-value tree stems [25]. Indeed, a considerable amount of edge-glued panels are manufactured as an intermediate product by the wood components industry every year. Lawser [26] estimates that the North American wood components sector ships panels and components worth approximately $5 billion per year. These approximately 500 facilities process lumber into parts and components (blanks) that are shipped to other companies, which in turn use these materials to make end-products. This industry has grown significantly during the last decade due to a trend by manufacturers to outsource the production of wooden parts, allowing them to focus on their core competencies, thereby reducing overhead, capital costs, and waste. Components manufacturers are highly specialized and provide value to their customers by potentially better quality and reduced waste. Major markets for wood components manufacturers are cabinets (33 %), furniture (21 %), and building products (32 %). In a survey of 1,867 office furniture and door manufacturers, the market potential for wood-based panels was assessed [27]. Edge-glued panels were the third largest panel input for office furniture manufacturers, with 19 % of raw material by volume being in the form of panels, and was the most commonly used wood-based panel product for door manufacturers, with 59 % by volume [27]. Edge-glued panels represent about 13 % of the $5-billion wood components market [28]. Solid hardwood panels have the potential to (1) improve raw material utilization, (2) offer primary manufacturers a value-added product for low-grade lumber and sawmill residuals, and (3) reduce manufacturing costs for secondary manufacturers [29].

In the U.S., the Wood Components Manufacturers Association maintains the “Rules & Specifications for Dimension & Woodwork” [23], which include standards for grading the quality of solid panels. The grade is assigned based on the occurrence and size of defects, such as mineral streak, pitch pockets, discoloration, pin knots, and sound knots. Uses for these panels include tops, doors, drawer fronts (grade A), and end panels, shelves, and inside drawer fronts (grade B). Research has shown that yield is optimized when cutting bills contain 5 widths and 10 lengths [30] and thus the cutting bill (a cutting bill is a list of part sizes and quantities that need to be cut from lumber) to be used in the manufacturing of the proposed product will contain the widths and lengths listed in Table 1.

*Defining the Product* The product to be offered is a solid hardwood panel, made from slats of regular sizes, made from low-value hardwood. The product dimensions will be of 4 by 8 feet, by 1 inch in thickness. The panels considered in this research will have an “A/B” grade, derived from the “A” and “B” designations contained in the WCMA standard. Minor modifications were made to the existing grades to maximize yield using the low-quality, low-value, underutilized material proposed in this research. The panels will be factory-sanded to a 120 grit surface.

**Table 1** Slat dimensions for solid hardwood panels

| Widths (inches) | Lengths (inches) | |
|---|---|---|
| 1.00 | 5 | 23 |
| 1.75 | 11 | 26 |
| 2.50 | 14 | 29 |
| 3.50 | 17 | 32 |
| 5.00 | 20 | 40 |

A slat is a piece of wood which then is finger-jointed longitudinal glued perpendicular to become a wooden panel
There are 50 width-length combinations

## 3.2 Defining the Material

Low-value, low quality hardwoods have a wide range of meanings for different people and different purposes. For the sake of this research, it is, therefore, critical to define the resource clearly and to assess specifically the available volume of this resource. Only after having created this determination, profitable new uses for it can be suggested. Luppold and Bumgardner indicated that low-value and low-grade[4] hardwoods are related but different concepts [31]. While value is determined by the market, grade is determined according to pre-established standards. A description of what will be considered acceptable raw materials for the proposed product follows below.

*Small Diameter Timber* Small-diameter roundwood, with diameters between 5 and 11 inches (defined as pole timber) make up 32–42 % of the total volume of the hardwood growing stock in the U.S., and 93–95 % of the total number of growing stock trees [17]. This roundwood yields low grade lumber increasing the cost of producing lumber [32]. Log grades are defined by the U.S. Forest Service, and are designed in a way to provide a 20 % value separation between grades. Logs of different grades will yield different amounts of lumber of a specific grade [33]. Lumber grade in this context is defined by the National Hardwood Lumber Association Grading rules. Factory-class logs are suitable for the manufacture of lumber, which in turn is converted into other value-added products. These logs can fall under grade 1, 2, or 3 categories. In general, grade 1 logs yield 60 % of No. 1 Common lumber (Table 2), grade 2 logs would yield 40–60 % of the same lumber quality, and grade 3 logs would yield less than 40 % of No. 1 Common lumber.

*Lumber Grade* Hardwood lumber in the U.S. is graded according to the National Hardwood Lumber Association rules [34], which are based, among other factors, on the size and number of defect-free cuttings that can be obtained from an individual board, and on the length and width of the board (Table 2 illustrates NHLA allowable cutting and board sizes). Higher grades require greater sizes. For

[4] Grade refers to the quality of the material in trees, logs, and lumber. Grades rank different qualities of material and are widely accepted as standards for trading and value determination in markets.

**Table 2** NHLA hardwood lumber grades, board and cutting minimum sizes, and clear area requirements

| Quality | Grade | Minimum board size | | Cutting minimum size | | Clear area (%) |
|---|---|---|---|---|---|---|
| | | Width (inches) | Length (feet) | Width (inches) | Length (feet) | |
| Higher | FAS | 6 | 8 | 4 | 5 | 83.3 |
| | | | | 3 | 7 | |
| ↓ | No. 1 common | 3 | 4 | 3 | 3 | 66.7 |
| | | | | 4 | 2 | |
| | No. 2A | 3 | 4 | 3 | 2 | 50.0 |
| | No. 3A | 3 | 4 | 3 | 2 | 33.3 |
| Lower | No. 3B | 3 | 4 | 1.5 | 2 | 25.0 |

example, the highest grade, FAS, requires a minimum width of 6 inches. Small-diameter roundwood yield relatively narrow boards, and contain other down-grading features under the NHLA rules, such as pith and high concentration of knots, thus no or few high grade boards can be produced from low-value trees.

*Low-Grade Lumber* This term depends on perception. A survey of industry practitioners concluded that a majority industry representatives consider No. 3A Common and lower grades as low-grade lumber [18].

*Slabs* Slabs are the by-product from lumber manufacturing, where the sawyer removes part of the log to expose an “open” face to decide what sawing pattern would optimize the value obtained from a particular log. Log grade, the amount of taper, and sweep are some of the determinants for slab dimensions. Slabs are commonly sent to a chipper, even though it may contain clear areas that can be used for higher value products.

*Other Materials* There are materials not considered in NHLA rules, such as logs shorter than 8 feet, lumber of less than 4 feet in length or 3 inches in width that could potentially yield usable material for the proposed product.

*Defining the Raw Material* The raw material for the proposed product will be small-diameter hardwood logs (diameter at breast height, or DBH, of 5–11 inches), low grade lumber, and sawmill slabs. The technical and economic feasibility depends mainly on whether the yield that can be achieved from processing the low-value hardwood resource is high enough to justify the proposed operation. A simulation approach was used to assess potential yields from the intended raw material. ROMI, a lumber cut-up simulation software [35] developed for the U.S. Forest Service, was used to simulate the cut-up of the low value material. ROMI uses 3,000 digitized lumber pieces (actual boards in which defects have been translated into digital parameters), a cutting bill and other process specifications, simulates the cutting operation, calculating outputs such as yield and yield distributions, cutting bill results, cutting solutions, and grade mix. The software is flexible enough to allow the creation of custom board samples, according to a specific lumber supply realities [35]. Table 3 lists the simulation parameters used.

Results from the simulations were evaluated. Yield is the ratio between output and the incoming material. Sawing efficiency is the average number of cuts required to produce a unit volume of parts. These two measures are critical in calculating the amount of raw material needed (yield) and the production costs for the proposed product (sawing efficiency). Table 4 lists the results from the simulation runs. An overall yield of 61.4 % was obtained which in general could be considered as a satisfactory value [36]. However, the number of cuts required was relatively high, which increases processing costs. However, since raw material is usually the predominant cost in cutting operations (about 50 % of total manufacturing costs, 38), it is believed that the high yield will more than compensate for the increased processing costs. These results show that low-quality, underutilized resources can be a feasible raw material for manufacturing solid hardwood panels. Furthermore, by using simulations to design and validate the cutting bill, yield from the hardwood underutilized material can be maximized.

An initial plant capacity of about 500 panels a day is proposed, which translates into 16,000 board feet per day in finished products. Based on results from the simulation, an approximate 40 % loss can be expected in the rough mill, plus 8 % in kiln-dying (due to wood shrinkage and drying degrade), and 4 % loss from finger-joining and edge-trimming. This results in an estimated total yield of 48 %,

**Table 3** Cut-up simulation parameters

| Simulation variables | Value(s) |
|---|---|
| Cutting bill sizes | 5 width and 10 length values. See Table 1 |
| Allowable defects | Sound knot size limit of 1/4 inch |
| | Sap and mineral streak |
| | Pin work hole of less than 1/16 inch |
| | Bird peck |
| Processing parameters | Re-ripping is allowed for salvage |
| | 24-inch wide arbor, 3/16 inch saw kerf |
| | Rip saw optimizer active |
| | Priority updating frequency at every 200 board feet |
| Material | Species: red oak |
| | Digitized lumber from Forest service data bank [53] |
| | Predominant log diameter range: 8–11 inches |
| | Log grade: 2 or 3 |
| | Lumber grade mix: 5 % selects, 10 % no. 1 common, 25 % no. 2 common, and 60 % no. 3 common |
| | Lumber dimensions: width between 4 and 10 inches, length from 40 to 104 inches |
| | Amount of lumber processed: 5,854 board feet in 1,603 boards |
| Simulation runs | 7 log runs |

**Table 4** Cut-up simulation results

| Measures | Results |
|---|---|
| Total yield | 61.4 % (3,592 board feet of parts produced from 5,836 board feet of lumber) |
| Yield per lumber grade | Selects: 79.1 % |
| | No. 1 common: 70.6 % |
| | No. 2A common: 64.3 % |
| | No. 3A common 56.2 % |
| Sawing efficiency | 8.6 cuts per board feet (30,965 cuts needed to obtain 3,592 board feet of parts) |
| | 12,154 parts produced |

which translates into a total raw material need of 33,000 board feet per day, or 7.7 million board feet a year.

### *3.3 Developing the Supply Chain Strategy*

A supply chain strategy for the manufacture of solid hardwood panels from low-value material is of critical importance, since material costs may account about 50 % of total manufacturing costs [37]. The position of the proposed operation in the forest products supply chain is depicted in Fig. 1. Lumber from small-diameter logs and slabs will be acquired from nearby sawmills. Ideally, the company will be located in an area of high concentration of wood products manufacturing facilities, close to the forest resource and supplying sawmills. One potential location is in the North Carolina's Piedmont Triad Area (Greensboro, High Point, and Winston Salem). This area contains a strong furniture sector and wood products supporting industries. The available workforce is highly skilled and there are several higher education institutions with strong programs in wood science and forest products nearby. Furthermore, this area has abundant forest resources and the logistics infrastructure is convenient, with access to road, rail, air, and water transportation. The raw material needed for the operation will be acquired from sawmills, which will cut small-diameter timber on contract. Small-diameter logs can be obtained from thinning operations. Slabs of a minimum size will be obtained from several local sawmills. It is estimated that 15 % of the slab output from a typical sawmill can yield blanks 2 inches wide by 12 inches long, and 1 inch thick [38].

### *3.4 Developing the Manufacturing Strategy*

Based on outcomes from previous research, a manufacturing strategy was developed. Several approaches were proposed since the 1980s to improve hardwood utilization,

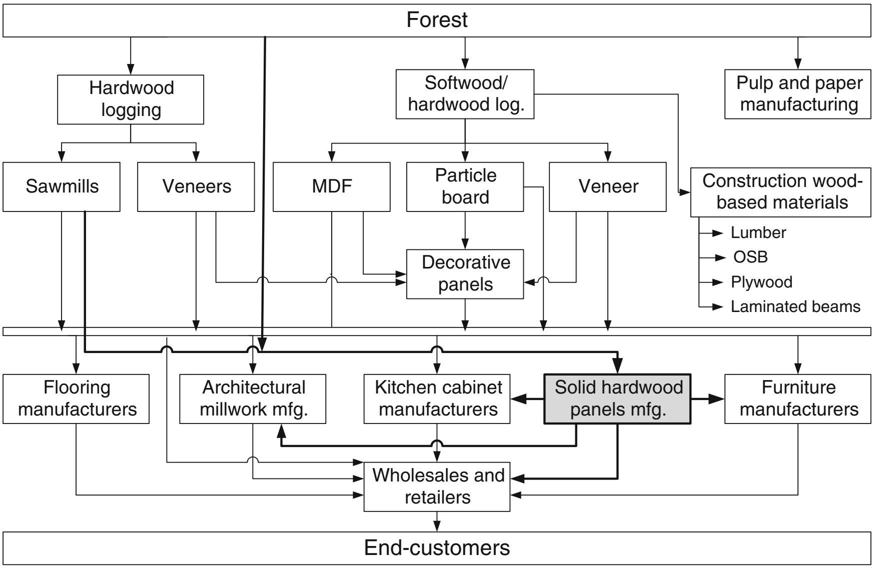


**Fig. 1** Supply chain strategy [29]

especially from the low-grade forest resource. Examples are *green dimensioning* [39–42], where logs are sawn directly into defect-free dimension parts. This eliminates the intermediate steps of lumber manufacturing, grading, trading, transportation, drying, and storage; typical of traditional operations. As a result yields are improved, and transportation and drying costs are reduced since only usable parts are dried and shipped [39]. In another approach, called *3-sided cant system* [43], three "screens" are used to identify acceptable quality residue, including a check before the sawmill (where potential bolts, or logs shorter than 8 feet, are separated), during the sawmill process (a slab is sawn to expose face quality), and after the sawing process (to verify a minimum part dimension of 1.5-inch wide and 12-inch length). In a system known as *standard-size blanks* [25, 44, 45], created based on extensive analysis of cutting bills used in furniture and cabinet manufacturing, authors listed 148 blank sizes with the purpose of minimizing losses to producers. Lastly, a system called "System 6" was developed [46, 47], which is essentially a manufacturing process conceived to produce standard blanks from low-grade, small diameter logs. The major differences between System 6 and traditional methods are that standard blanks are the end product instead of lumber; automated processes are used whenever possible; all boards with a minimum size are processed; and human decisions are reduced to a minimum. This research draws from these past efforts to develop a suitable manufacturing strategy that allows the production of edge-glued panels from underutilized forest resource. The manufacturing process is illustrated in Fig. 2. The cutting bill developed with aid from simulation software allows for processing with low complexity and thus costs.

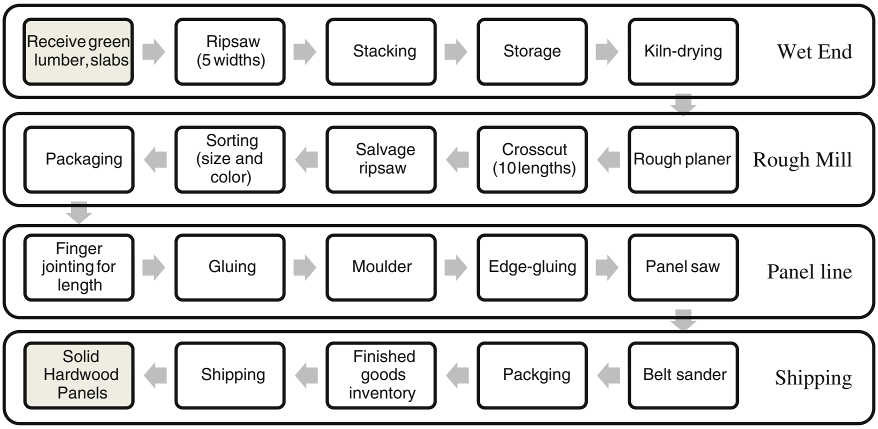


**Fig. 2** Manufacturing flowchart for solid wood panels

## *3.5 Next Steps*

Having identified the market opportunity, raw material, and a suitable manufacturing strategy, additional steps necessary to develop an economically feasible operation to make solid hardwood panels from low-value material include:

*Market research* The potential demand needs to be quantified to assess economic viability of this project. Both domestic and international markets need to be evaluated. Exports of hardwood products from the U.S. have shown big increases during the last few years [48, 49], especially in hardwood lumber, thus there is an opportunity in exporting wood components, such as the proposed hardwood panels. Willingness to pay also needs investigating; conjoint analysis is a tool that could potentially be used to investigate the relative impacts of specific product features on the prices that potential customers are willing to pay.

*Quantitative analysis of raw material availability* Raw materials to be used in the proposed operation have been identified, and further work requires the availability of these raw materials to be quantified. Potential sources to be consulted for this are the U.S. Forest Service's Forest Inventory and Analysis [9] and the databases of state agencies for natural resources in individual states. This task also involves assessing the cost of the raw material, including extraction and transportation as this is critical information for assessing economic feasibility of the project. This information can be generated through collaboration with U.S. Forest Service and state agencies specialists, as well as through interviews with trade specialists and industry participants.

*Manufacturing operations management approach* Although the technical feasibility of this approach is demonstrated, the implications of the manufacturing system proposed on operations management should be investigated. For example, the system proposed may have a significant impact on strategic sourcing decisions, since the material to be used has lower economic value, and transportation may represent a larger share of operating costs. This can also have an impact on location decisions. Likewise, production scheduling needs attention, since the low value of the raw material shifts the focus from grade recovery to yield. Lastly, drying and handling the material may prove to be the major obstacles to the implementation of the manufacturing system here suggested, and need to be investigated. Drying low quality material is more challenging, since it is in general prone to more drying defects than regular material. Narrower, shorter pieces may also prove to be difficult to handle with current systems.

*Target costing* Target costing is the "top-down assignment of a component-level cost target that the engineer may not surpass [50]." Target costing was developed in Japan, as an adaptation of the concept of value engineering and is aimed at simultaneously maximize desirable product attributes while minimize costs [51]. Thus, target costing can be defined as "a cost management tool for reducing the overall cost of a product over its entire life cycle with the help of production, engineering, R&D, marketing, and accounting departments [51]." In the context of this research, target costing will help to conceive product concepts that satisfy quality and price expectations, as determined in the market research (see above), and at the same time allow covering the extraction and processing costs typical for the forest resource of interest. In target costing, market research finds the product characteristics appealing to customers, including the willingness to pay (WTP), from which a planned price is determined and a desired profit subtracted and thus a "target cost" is calculated. From there, design, engineering, and supplier pricing are managed in a way to achieve the cost targeted. The major difference to traditional approaches is that in target-costing, costs are controlled before and early in the product development process, whereas with traditional approaches, costs are added-up later in the product's lifecycle. Probably the most important feature of target-costing is its market orientation and it's compatibility with Concurrent Engineering techniques [52], which makes this tool relevant for the purposes of this research.

## 4 Summary

This research aims at finding new uses for the low-value, underutilized hardwood resource in U.S. forests. The study also addresses the need to find market opportunities for an industry that was hit hard by the worst recession since the Great Depression that started in 2008 and other developments, such as the emergence of electronic media, the globalization of manufacturing, and a threat from substitute materials. It is believed that manufacturing solid hardwood panels with underutilized low-value hardwood resources represents an economically attractive opportunity for entrepreneurs, and can create much needed employment, especially in rural communities. In this paper, the market opportunity and the raw material were identified, and a suitable manufacturing strategy is presented.

The project proposes to use the low-value, underutilized hardwood resource to manufacture solid wood, edge-glued panels. This is a versatile product that can be used by, among others, cabinet and furniture manufacturers. It is estimated that the trend toward outsourcing by value-added product manufacturers will favor the growth of the wood components industry, a $5 billion sector in the U.S. Solid panels are already a major product of this industry today. Exports of wood components have also been increasing, and may represent an important market for the proposed operation.

The raw material identified in this research comes from three major sources: small diameter timber resource, which represents 32–42 % of the total volume of hardwood growing stock; lumber that is too short or narrow to be graded under the industry standard; and sawmill slabs (a by-product from lumber manufacturing). Cut-up simulations have shown that this is a suitable raw material base to manufacture the proposed product, with an estimated yield slightly higher than 60 %. It is believed that the relatively high yield can more than offset the additional manufacturing cost from reduced sawing efficiency (more cuts needed to obtain the same volume of lumber).

The manufacturing strategy developed in this study is based on two decades of research on increasing the value of the low-grade forest resource, such as green dimensioning, standard-size blanks, and System 6. The manufacturing strategy proposed bypasses several steps of typical manufacturing operations and produces suitable blanks for finger-jointing. The research described here contributes to the state-of-the-art by addressing a trend that is only expected to continue: the decreasing quality of the hardwood resource in the U.S. A specific manufacturing solution is suggested to make value-added products out of this low quality, underutilized material. This research addresses the theme of the 2013 FAIM conference "The Challenge of Sustaining Global Competitive Manufacturing Systems" by suggesting an approach for adapting current manufacturing technologies to the changing nature of the raw material base.

Further steps needed to develop an economically feasible strategy to produce solid panels from the underutilized, low-value hardwood resource were discussed. Market research will help to estimate demand and price points, essential inputs for scaling the operation. A regionally-specific quantitative analysis of raw material availability is also needed, since raw material can represent roughly 50 % of total manufacturing cost. Lastly, a target costing analysis will help to determine the best processing pathway and ensure competitiveness.

## References

1. Forbes K (2004) U.S. manufacturing: challenges and recommendations. Bus Econ 39(3):30–37
2. Associated Press (2008) Hard times hit the U.S. hardwood lumber industry. Associated Press, Charleston

3. Buehlmann U, Schuler A (2009) The U.S. household furniture industry: status and opportunities. For Prod J 59(9):20–28
4. Schuler A, Buehlmann U (2003) Identifying future competitive business strategies for the U.S. residential wood furniture industry: benchmarking and paradigm shifts. US Department of Agriculture, Forest Service. Northeastern Research Station, Newton Square, p 19
5. Grushecky ST et al (2006) Decline in the US furniture industry: A case study of the impacts to the hardwood lumber supply chain. Wood Fiber Sci 38(2):365–376
6. Cole N (2008) Hardwood sawmills in state feeling strain. Arkansas Democrat Gazette
7. Reddy S (2008) U.S. factories slash output amid slump. Wall Street J
8. Schneider H, Shin A (2009) Industrial output falling sharply. Washington Post 2009, Washington, DC
9. US Forest Service. Forest Inventory and Analysis (2012) [cited 2012 June 27]. http://www.fia.fs.fed.us/
10. Fajvan MA, Grushecky ST, Hassler CC (1998) The effects of harvesting practices on west virginia's wood supply. J For 96(5):33–39
11. Nyland RD (1992) Exploitation and greed in eastern hardwood forests. J For 90(1):33–37
12. Luppold WG, Bumgardner MS (2008) Timber value issues resulting from harvest activity in appalachian forests. In: Proceedings of 2008 southern forest economics workers annual meeting. Savannah, center for forest business, Warnell School Of Forestry And Natural Resources, University of Georgia, GA
13. Wiedenbeck JK et al (2003) Small-diameter hardwood utilization with emphasis on higher value products. In: Proceedings of enhancing the southern appalachian forest resource 2003. Department of Forestry, College Of Natural Resources, North Carolina State University
14. Brown SL, Schroeder P, Kern JS (1999) Spatial distribution of biomass in forests of the eastern USA. For Ecol Manage 123(1):81–90
15. Miles PD, Van der Schaaf CL (2012) Minnesota's forest resources, 2011, 2012. U.S. Department of agriculture, Forest Service, Northern Research Station: Newtown Square, PA, p 4
16. DNR (2010) Minnesota's Forest Resources 2010, 2011. Department of Natural Resources, Division of Forestry, Saint Paul, p 59
17. Bumgardner MS et al (2000) Options for small-diameter hardwood utilization: past and present. In: Proceedings of the annual meeting of the southern forest economics workers (SOFEW), hardwoods—an underdeveloped resource, 26–28 Mar 2001 , Lexington
18. Cumbo D, Smith R, Araman P (2003) Low-grade hardwood lumber production, markets, and issues. For Prod J 53(9):17–24
19. Cantrell R, Paun D, LeVan-Green S (2004) An empirical analysis of an innovative application for an underutilized resource: small-diameter roundwood in recreational buildings. For Prod J 54(9):28–35
20. Perkins BR (2006) A business model for a red oak small diameter timber processing facility in southwest Virginia. Wood Science and Forest Products 2006, Virginia Polytechnic Institute and State University, Blacksburg, p 149
21. Becker DR, Eaton LM (2012) Something old and something new: forest bioenergy production in Minnesota. CURA Reporter 42:8
22. Levan-Green SL, Livingston J (2001) Exploring the uses for small-diameter trees. For Prod J 51(9):10
23. WCMA (2011) Wood component manufacturers association 2011 [cited 2011 March 15]. http://woodcomponents.org/
24. Lawser S (2004) Market outlook for wood components. In: Proceedings of exploring new paths conference 2004, Edmonton, p 31
25. Bowyer JL et al (1986) Standard blanks: a new alternative to hardwood lumber. For Prod J 36(2):67–73
26. Lawser S (2009) Changing markets for wood components in remaining competitive in the wood components industry. Princeton, p 25

27. Tabarsi E et al (2003) A market assessment of the potential for OSB products in the North American office furniture and door manufacturing industries. For Prod J 53(7/8):19–27
28. McDaniel PWP (2003) Opportunities for the utilization of non-traditional species in wood-based component manufacturing. Wood Science and Forest Products, Virginia Tech, Blacksburg
29. Deaver ME (2006) Economic feasibility of a solid hardwood panel manufacturing enterprise. Wood and Paper Science, North Carolina State University, Raleigh, p 193
30. Shepley BP (2002) Simulating optimal part yield from no. 3A common lumber. Wood Science and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, p 148
31. Luppold W, Bumgardner M (2003) What is low-value and/or low-grade hardwood? For Prod J 53(3):54
32. Cumbo DW, Smith RL, Becker Iii CW (2004) Value analysis of lumber produced from small-diameter timber. For Prod J 54(10):29–34
33. Wengert EM, Meyer DA (1994) Guidelines for grading hardwood logs. University of Wisonsin-Madison, College of Agricultural and Life Sciences, Extension, Madison, p 6
34. NHLA (2011) National hardwood lumber association. 2011 [cited 2011 March 15]. http://www.nhla.com/
35. Weiss JM, Thomas RE (2005) ROMI-3: rough-mill simulator version 3.0: user's guide. U.S. Department of Agriculture, Forest Service, Northeastern Research Station: Newtown Square, p 75
36. Wiedenbeck JK, Thomas E (1995) Don't gamble your fortunes—focus on rough mill yield. Wood Wood Prod 100(7):148–149
37. Mitchell PH, Wiedenbeck J, Ammerman B (2003) Rough mill improvement guide for managers and supervisors. USDA Forest Service, Delaware, p 69
38. Buelmann U, Wiendenbeck JK, Strasser L (2005) Sawmill—log utilization study. North Carolina State University, Raleigh, p 51
39. Gephart JS, Petersen HD, Bratkovich SM (1995) Green dimensioning: a review of processing, handling, drying, and marketing. For Prod J 45(5):69–73
40. Lin W, Kline DE, Araman AP (1994) Dimension yields from factory grade 2 and 3 red oak logs. For Prod J 44(9):19–25
41. Wenjie L et al (1995) Producing hardwood dimension parts directly from logs: an economic feasibility study. For Prod J 45(6):38–46
42. Bratkovich SM et al (2000) Green dimensioning below-grade red oak logs: a minnesota case study. For Prod J 50(2):65
43. Reynolds HW, Schroeder J (1978) Furniture cuttings made from logging residue: the three-sided cant system. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Broomall, p 4
44. Araman PA (1982) Rough-part sizes needed from lumber for manufacturing furniture and kitchen cabinets. United States Department of Agriculture, Forest Service, Northeast Forest Experiment Station, p 8
45. Araman PA, Gatchell CJ, Reynolds HW (1982) Meeting the solid wood needs of the furniture and cabinet industries: standard-size hardwood blanks. United States Department of Agriculture, Forest Service, Northeast Forest Experiment Station, p 27
46. Reynolds HW, Gatchell CJ (1982) New technology for low-grade hardwood utilization: system 6. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Broomall, p 8
47. Reynolds HW, Araman PA (1983) System 6: making frame-quality blanks from white oak thinnings. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Broomall, p 9
48. Buehlmann U et al (2010) Trends in the US hardwood lumber distribution industry: changing products, customers, and services. For Prod J 60(6):547–553
49. Espinoza O et al (2011) Assessing changes in the U.S. hardwood sawmill industry with a focus on markets and distribution. BioResources 6(3):2676–2689

50. Mihm J (2010) Incentives in new product development projects and the role of target costing. Manage Sci 56(8):1324–1344
51. Feil P, Yook K-H, Kim I-W (2004) Japanese target costing: a historical perspective. Int J Strateg Cost Manag 2004(Spring):10–19
52. Prasad B (1996) Concurrent engineering fundamentals—integrated product and process organization. Prentice Hall, Upper Saddle River
53. Gatchell CJ, Thomas RE, Walker ES (1998) Data bank for kiln-dried red oak lumber. United States Department of Agriculture, Forest Service, Northeastern Research Station. p 64

# Performance-Oriented Manufacturability Analysis of a 5 GHz Satellite Oscillator

**Harri Eskelinen, Pekka Eskelinen and Juhana Ylinen**

**Abstract** Modern communication and radar systems, especially if used for space or defense applications, need signal sources having high spectral purity and ultimate frequency stability. Most current and future designs must also include some way of frequency tuning. Digital synthesizers and multipliers are the conventional electronic solutions to these challenges, but unfortunately, they suffer from increased phase noise. The idea in the present survey was to study the feasibility and performance of fundamental frequency microwave dielectric resonator oscillators (DRO's) as a substitute to frequency synthesis. If atomic frequency standards (such as cesium clocks or hydrogen masers) are excluded, all resonator-type oscillators (quartz crystals, dielectric resonators, surface acoustic wave devices) are of the mechanical vibration type. Dimensional tolerances and constructional rigidity issues, particularly in the resonator element itself, are thus of vital importance. The sharpness of the resonance curve defines the frequency accuracy to a certain extent, and therefore, we need the highest possible quality factor of the resonator, which calls for uncompromised surface quality. Usually, the electrical performance of this type of component is ensured with some computer-assisted tools before manufacturing the first prototype. This research showed that it is useful to simulate also the manufacturing stages beforehand to be able to find solutions for possible bottlenecks in the production. One of the key findings of the computer aided manufacturing (CAM) simulations was the importance of utilizing the optimum combination of the milling tool path, tool diameter, and the stepover to maximize the Q-value of the resonator but keeping the production at a reasonable level.

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# 1 Introduction

## 1.1 Related Previous DFMA Research for Electrical Engineering

Lappeenranta University of Technology (LUT) has carried out a number of studies during the past decades about improving the manufacturability and assembly aspects (design for manufacturing and assembly = DFMA) of different types of constructions for electrical engineering [1–8]. These studies have included topics involving electronic systems in general [1, 5] and different applications of MW and RF technology, e.g., [4]. These research projects have covered a wide range of different types of manufacturing technologies for electrical engineering, including, e.g., machining [2], sheet metal work [8], and different joining technologies. The key result so far has been that it is profitable to integrate and utilize different types of well-known DFMA approaches together and it is worth trying to develop those approaches further to match better the novel cross-technological design tasks. The other result of these former projects has been that in electrical engineering it is typical that performance-oriented DFMA, which is also called functional optimization, is utilized instead of cost-oriented or productivity-oriented DFMA. Based on the literature [9, p. 144], functional optimization of subassemblies is probably given the highest priority in electrical engineering. This level consists of two main stages, which are (1) performance-oriented optimization and (2) structural optimization. Our experiences from military and aerospace applications [1] have shown that in electrical engineering the functional requirements of the product due to environmental aspects might cause serious limitations for traditional DFMA. As relevant background information we have utilized electronic designs of a military grade microwave cavity resonator assemblies documented in [10–12].

## 1.2 Mechanical Construction of the Test Oscillator

Our test oscillator was designed for the 5 GHz satellite and radar bands. The electronic circuit uses two cascaded bipolar microwave transistors (type BFP420) in a common emitter feedback amplifier configuration which is combined with a cylindrical dielectric resonator. Three miniature coupling loops are included to it, one for amplifier input (to the base of transistor 1), one for amplifier output via a Wilkinson power divider (from the collector of transistor 2) and yet another for the optional tuning varactor diode, which would allow voltage-controlled oscillator (VCO) like operation if needed. The loops are manufactured with a wire saw of a beryllium copper alloy. All amplifier components are mounted on a RT/Duroid 5870 board (thickness 0.5 mm, 0.5 oz gold plated copper). A signal output is obtained through a female SMA connector which has a 2.15 mm dielectric insulator. A separate supply regulator board provides the necessary filtered bias voltages.

Three mechanical "compartments" have been defined. Besides the actual resonator, we have the amplifier slot and on the reverse side of the milled enclosure we put the supply circuits whereby the best possible interference rejection is obtained. Feed-through filters are used to bring all DC voltages through the amplifier slot floor. The resonator cavity itself is cylindrical with a diameter of 30 mm and a height of 25 mm. A separate cover with an M5 fine threaded screw and associated locking nut are provided for mechanical frequency tuning. The resonator "puck" is of E4230 and has a diameter of 11.70 mm and height of 4.2 mm. It is fastened with cyanoacrylate on top of a quartz tube, which in turn is located above a central spigot, machined in the middle of the cavity bottom. The mechanical construction of the oscillator is presented in Fig. 1. An alternative resonator material is sapphire, which gives even higher Q-values, but using it would require modifications to the feedback electronics. The entire mechanical setup is milled of a solid aluminum alloy block and given a chemical nickel gold surface finish. Table 1 shows a set of simulated and measured characteristics of the first prototype.

## *1.3 Importance of the Q-Value*

The electrical optimization of the oscillator cavity is based on maximizing its Q-value (quality factor). The general requirements for an oscillator cavity are based on electromagnetic wave propagation, transmission line theory and the electromagnetic properties of applied construction materials. Focus areas include impedance matching of the resonator and the 3-D field pattern and polarization characteristics. Mathematically the quality factor Q of an oscillator is defined as its resonance frequency divided by its resonance width. Therefore, high resonance frequency and a narrow resonance width are both desired for increasing the Q-value. Maximized Q-value and its stability and the electric shielding performance of the selected construction are all important issues in a satellite application

**Fig. 1** Machining features and their tool access directions

**Table 1** Oscillator parameters

| Parameter | Simulated | Measured |
|---|---|---|
| Center frequency | 5.618 GHz | 5.234 GHz |
| Electronic tuning range | – | 102 kHz |
| Mechanical tuning range | – | 1.78 MHz |
| Operating temperature max | – | 54 °C |
| Operating temperature min | – | −14 °C |
| Power level | 15 dBm | 7 dBm |
| Harmonics | −15 dBc | −35 dBc |
| SSB phase noise @ 1 kHz | −115 dBc/Hz | −94 dBc/Hz |
| SSB phase noise @ 10 kHz | −135 dBc/Hz | −122 dBc/Hz |
| SSB phase noise @ 100 kHz | −148 dBc/Hz | −143 dBc/Hz |
| Frequency drift with temp | – | 321 kHz (within temp. range) |
| Frequency pulling | – | 21 kHz p–p (10 dB return loss) |
| Frequency pushing | – | 26 kHz/V |
| Mechanical tuning linearity | – | 10 ppm |
| Mechanical tuning sensitivity | – | 0.32 MHz/turn |
| Power supply | – | 8 V/41 mA |

to ensure its performance. Possible defects in the mechanical properties of the cavity, such as imperfections in the cross sectional geometry of the cavity, misalignments, material dents, oxidation, or non-perfect electrical joints can decrease the Q-value [9, p. 171].

## *1.4 Requirements of Space Technology*

The environmental loading of the constructions for space technology can be divided into four main groups: corrosion is space, erosion due to atomic sputtering, thermal loading, and effects due to contaminants. All of these aspects should be taken into account when establishing the requirements of the researched oscillator. When comparing traditional corrosion to corrosion in space, the main difference is that the primary reason for corrosion is not the humidity but materials are subjected to vacuum, bombardment by ultraviolet light, x-rays, electrons, protons, ions, and free radicals. Different materials resist corrosion in space differently. For example, aluminum is slowly eroded by atomic oxygen, while gold, and platinum are highly corrosion-resistant. Gold-coated foils and thin layers of gold on exposed surfaces are therefore used to protect the space technology components from the harsh environment. The oscillator analyzed in this paper is gold-coated. One option for gold coating is to use a standard plating of 5ou″ electrolytic gold according to MIL-G-45204 over 5ou″ Electrolytic Nickel according to QQ-N-290. Thin layers of silicon dioxide deposited on the surfaces can also protect metals in the space environment. In addition, titanium-aluminum-nitride coatings have been tested for satellite temperature control applications [13]. The second problem for structures subjected to outer space is erosion of the material due to sputtering caused by fast atoms and micrometeorites. The third environmental problem is material fatigue caused by cyclic heating and cooling together with thermal expansion, which causes mechanical stresses in the construction. The fourth problem is currently the cloud of contaminants around the satellites. Together with atomic bombardment, this may cause the malfunctioning of, e.g., the optical and solar systems of the satellite. Although the construction researched in this paper is a very special prototype for the satellite oscillator, the same types of mechanical structures of electrical devices for the space industry can be listed. These devices have two common properties with the researched oscillator: first, aluminum bodies, which are either gold-coated or include gold-coated parts, are widely utilized, and second, a number of different types of materials are used for mechanical and electrical reasons (e.g., [14]). This fact makes it reasonable to try to generalize the results achieved from this research.

### *1.5 Motivation and Scope*

The motivation of this research rises from three main research questions: Firstly, is it possible to increase the Q-value of the resonator by improving the manufacturing quality of the milled geometries of the oscillator? Secondly, is it possible to compensate the assembly inaccuracy of the glued joints and the dimensional uncertainty of surface coating and powder metallurgy by utilizing high-accuracy machining of the resonator cavity? Thirdly, is it possible to increase productivity and avoid bottlenecks in production by utilizing DFMA approaches for developing the machining phases of the oscillator body? The scope of this paper focuses on the machining phases of the oscillator body. The aspects dealing with glued joints, the manufacturing of ceramic components and surface coating are discussed only in that context. The main manufacturing phases are presented in sequential order in Fig. 2. This research focuses on analyzing the machining phases which are highlighted with a gray background in Fig. 2.

## 2 Applied Research Methods

To find the answers to the research questions, four different research methods have been applied. Firstly, computer aided EdgeCAM simulations were used to evaluate the efficiency of the machining phases of the oscillator body and to establish the relative machining times for each machining phase. Secondly, laboratory tests were conducted to measure the achievable surface quality of the resonator cavity. Thirdly, dimensional and geometric tolerances of the milled resonator cavity were measured. Fourthly, an interview was arranged in a high-tech commercial company to obtain answers to questions dealing with production and productivity.

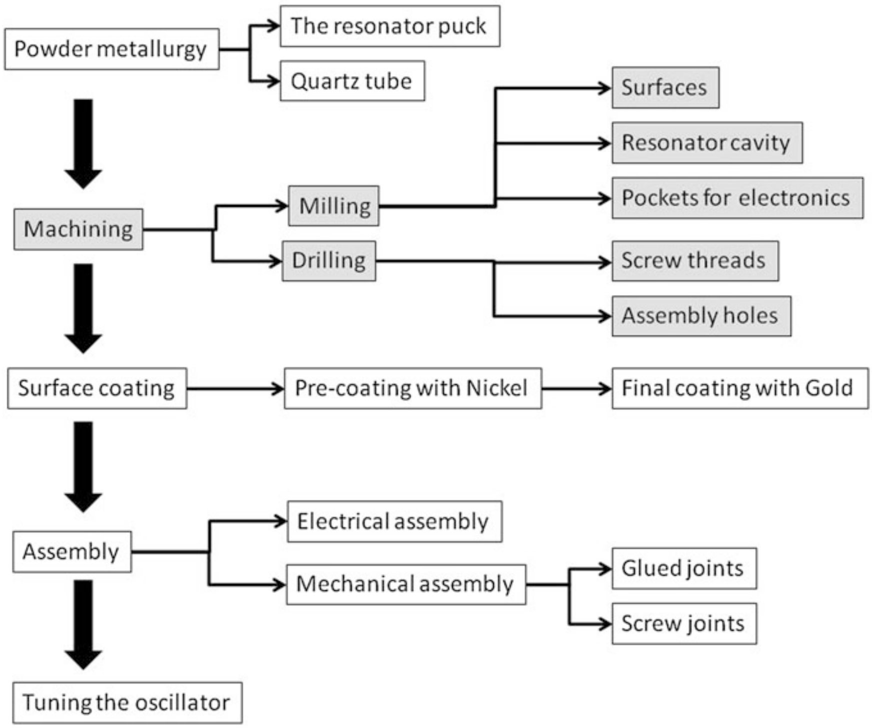



**Fig. 2** Manufacturing phases of the oscillator

# 3 Results

## *3.1 Edgecam Simulations*

EdgeCAM simulations started with analyzing the required number of different fixing positions of the component during the machining phases. Basically, machining (milling, drilling, and/or threads) is needed from six different directions, as illustrated in Fig. 3, but the number of re-fixings of the component depends on the type of the machining center. If a six-axis machine is in use, only two fixings are required. One reason for manufacturing inaccuracy is evidently the possible assembly errors during the re-fixing of the workpiece.

The second important result of the EdgeCAM simulations was the recognition of difficult or challenging milling and drilling phases. Four machined geometries required special attention: Firstly, the long drilling length of the mounting holes for the coupling loops is difficult not only due to the long drilling distance but also because of the fact that the opposite wall against the drilling tool happened to be a rounded surface. Secondly, the central spigot in the middle of the cavity bottom causes extra work for designing the required tool path geometry. Thirdly, the

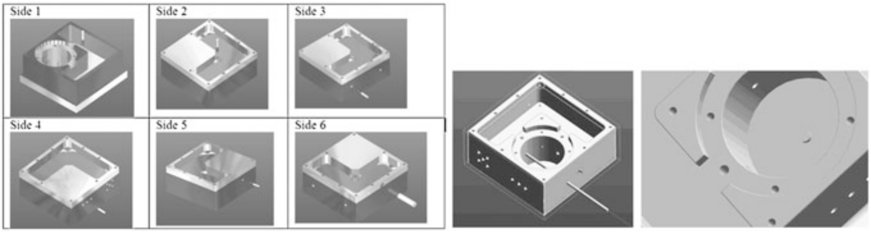



**Fig. 3** Simulation of different fixing positions *left*. Difficult geometries for accurate machining *right*

standardized connectors require special types of holes for mounting. Fourthly, there are a number of small (sizes of M2.5 and M3, originally base on UNC dimensioning) holes with a thread inside, which cause a relatively long portion of the total machining time. These details are presented in Fig. 3.

One of the most desired changes to the original geometry would be the replacement of the spigot at the bottom of the cavity with a milled sinking. These two alternatives are illustrated in Fig. 4. For milling operations, the tool path would become easier and the surface of the cavity bottom would become smoother if there were no spigot to be followed with the cutting tool edge. The problematic detail is also the joint between the quartz tube and the cavity bottom. Because of the different thermal expanding properties of aluminum and quartz, the glued joint between the tube and the bottom must withstand some non-equal dimensional changes due to temperature variation in the space environment.

On the other hand, either a spigot or a sinking is needed to ensure the accurate positioning of the quartz tube which directly affects the positioning of the resonator puck itself. If we analyze the machining times (see Table 2), we notice that only 20 % of the machining time is spent on milling the cavity itself. Approximately 60 % of the time is used for drilling and threading the small assembly holes. The other important change would be the decrease of the number of assembly screws. However, to ensure the electrical shielding properties of the device, the contact between the cover and the body of the oscillator must be arranged properly in one way or another. The machining parameters in this case were f = 200 min/min, v = 200 rpm and s = 0.1 mm/r. Machining speeds could be increased in optimal manufacturing, e.g., the drilling speed could be much higher, yet the relative time proportions will remain the same.

**Fig. 4** Two optional geometries of the cavity

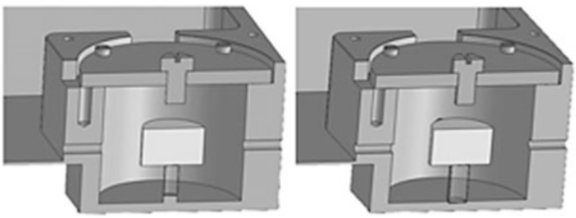
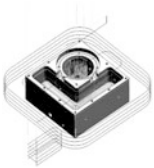
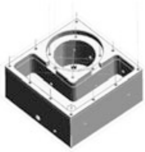
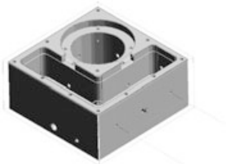
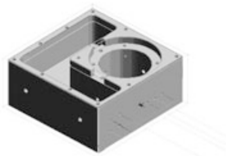
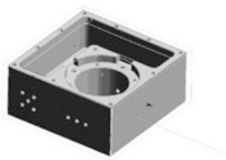


**Table 2** Simulated machining times and relative time proportions of different machining phases

| Manufacturing phase | Machined geometries | Simulated machining time | Relative time proportion (%) |
|---|---|---|---|
| Milling top view (side 1) |  | 8 min. 26 s. | 31.06 |
| Drilling + threads top view (side 1) |  | 4 min. 33 s. | 16.76 |
| Milling Drilling + threads bottom view (side 2) |  | 3 min. 10 s.<br>6 min. 26 s. | 11.66<br>23.70 |
| Drilling + threads front view (side 3) |  | 1 min. 3 s. | 3.87 |
| Drilling + threads right view (side 4) |  | 2 min. 25 s. | 8.90 |
| Drilling + threads back view (side 5) |  | 24 s. | 1.47 |
| Drilling + threads left view (side 6) |  | 42 s. | 2.58 |
| **TOTAL** | | **27 min. 9 s.** | **100** |

## 3.2 Laboratory Tests

The surface quality in the metal cavity partly defines the obtainable quality factor of the entire resonator. Dielectric losses are obviously minimal in this case since there is only air surrounding the center slab. The conductor loss is partly related to the material properties (gold) and partly to the surface roughness which, theoretically, should be as small as possible. Because the geometrical accuracy and the surface smoothness directly affect the Q-value of the oscillator, we carried out laboratory tests to find out the best combination of machining parameters and different tool paths. In this application, the best option was to use the tool path which causes radial milling tracks at the bottom of the cavity. During the laboratory tests of the surface quality inside the cylindrical cavity, two main parameters were varied: the tool size (diameters 5, 8, and 10 mm) and the stepover (10 and 50 %). Special attention was paid to the stability of the tool fixing and the free length of the tool. The best results were achieved by using the tool diameter of 10 mm with a stepover of 50 %. The measured surface roughness was Ra = 0.1…0.2 μm. From the macrophoto of the specimen, the applied tool path can be clearly seen (see Fig. 5).

The second set of laboratory tests focused on the geometric accuracy of the cavity. The dimensional measurements were made at two height levels of the cavity with a 3-D coordinate measuring system. One example of the resulting graph is shown in Fig. 6. The laboratory tests showed that the circularity of the prototype oscillator cavity was between 0.019…0.022 mm and the tolerance zone was 0.03 mm. Dimensional tolerance varied between 29.950…29.980. These values indicate that the required tolerance grade was set to IT4.

## 3.3 Interview

The interview was arranged in a Finnish commercial company (Imatran Kone oy). The questionnaire included open questions to the manufacturer about their opinion of how to improve the manufacturability aspects of the oscillator body. In addition, we had twenty formal questions to find out where is the bottleneck of the production due to the increased quality requirements of the oscillator. We noticed that

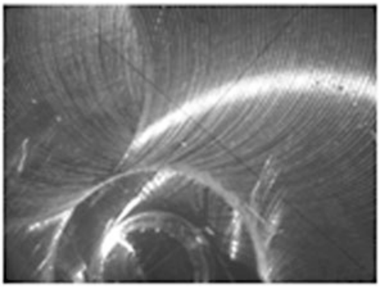
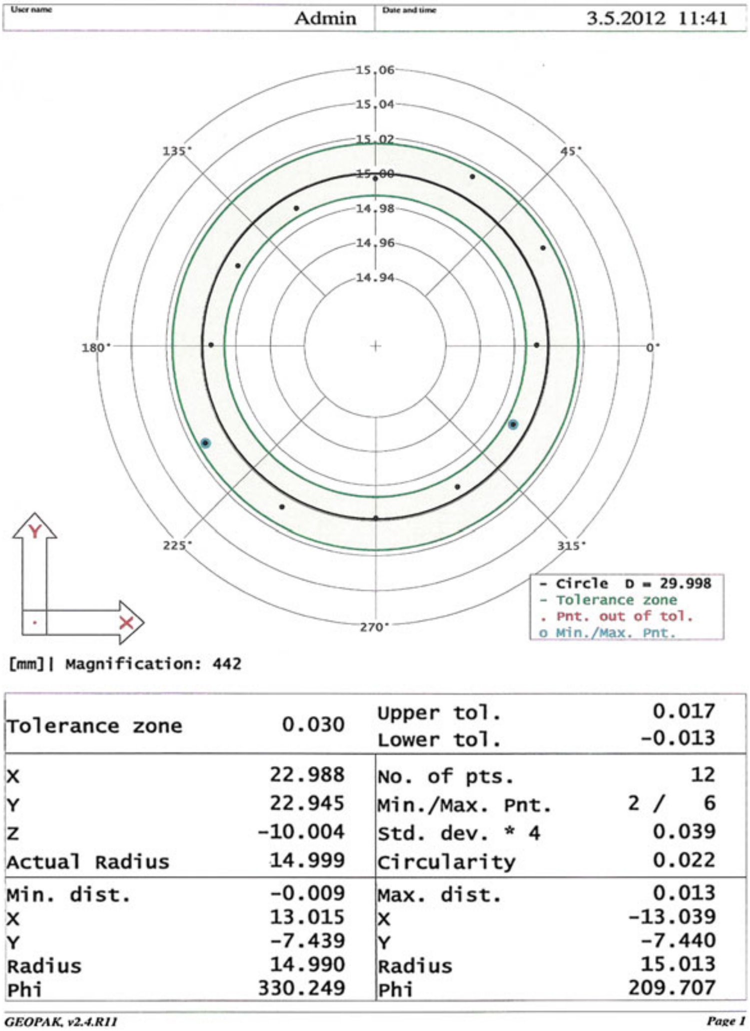


**Fig. 5** An examples of laboratory tests for finding the optimum combination of tool size, tool path, and stepover. From the macro photo of specimen the tool path can clearly be recognized




| | | | |
|---|---|---|---|
| Tolerance zone | 0.030 | Upper tol.<br>Lower tol. | 0.017<br>-0.013 |
| X | 22.988 | No. of pts. | 12 |
| Y | 22.945 | Min./Max. Pnt. | 2 / 6 |
| Z | -10.004 | Std. dev. * 4 | 0.039 |
| Actual Radius | 14.999 | Circularity | 0.022 |
| Min. dist. | -0.009 | Max. dist. | 0.013 |
| X | 13.015 | X | -13.039 |
| Y | -7.439 | Y | -7.440 |
| Radius | 14.990 | Radius | 15.013 |
| Phi | 330.249 | Phi | 209.707 |

**Fig. 6** Result of circularity test

tolerance grade IT4 is the critical limit. The suggested changes of the oscillator body and its construction are based partially to the results of this interview.

## 4 Discussion and Scientific Contribution

The first key observation is that both the resulting surface roughness and the geometric accuracy of the cavity seem to exceed the theoretical minimum requirements given in scientific literature. The required values for similar applications in this frequency range would be IT10 and Ra = 12.8 μm [9, p. 114]. However, we know that some unwanted, excessive structural inaccuracy of the construction could be caused by (1) the gluing process of the resonator buck and the quartz tube, (2) the machining challenges of these ceramic components, (3) the difficult positioning control of the power feeding loops and the resonator puck, and (4) some errors of the gold coating process of the cavity (e.g., pinholes, nicks, or unwanted roughness [15]). Therefore, it would be valuable to be able to produce a "buffer" against these inaccuracies by handling the machining phases of the cavity geometry in the optimum way.

The second viewpoint worth highlighting is the importance of machining simulations. Usually the electrical performance of these components is ensured first with some computer-assisted tools before manufacturing the first prototype. This research showed that it is useful to simulate also the manufacturing stages beforehand to be able to find solutions to possible bottlenecks of the production. In this case, three important improvements to the construction could have been made based on CAD/CAM simulations to make the product easier and more cost-effective to manufacture: (1) Reducing drilling times of the assembly holes, (2) using a sinking instead of a spigot for joining the quartz tube, and (3) Finding the optimum combination of the milling tool path, tool diameter and the stepover to maximize the Q-value of the resonator, yet keeping the production at a reasonable level.

During this research, we arranged a brief interview at a workshop to ensure that these productivity aspects are valid also from the commercial or business-oriented viewpoint. It was encouraging to notice that the wishes for geometrical changes were the same as the results in our CAD/CAM simulations.

The findings presented in this paper are in line with the traditional viewpoints presented by Wall and Sinnadurai [16], who identified the trends of the component industry, examined the methods of achieving "space quality", discussed the challenges of the space industry, and finally, considered the performance specifications.

Also the problem of a wide range of different materials used in space applications is known. In analogy to the observations in this research, in most of the cases the materials for space applications are selected based on their high thermal conductivity and low coefficient of thermal expansion [17]. A challenging topic for further research would be analyzing the options to apply structural integrity technology, as presented, e.g., in [18], to support the manufacturability analysis presented in this paper. It might be possible to generalize the special results dealing with the machining phases also to other dimensional sizes of oscillators which form a product family at least in the geometric sense, as illustrated in Fig. 7.

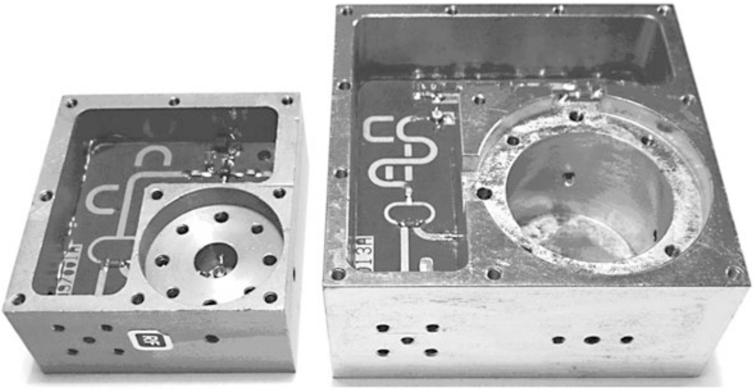


**Fig. 7** An attractive vision to apply the manufacturability results dealing with the machining phases to a product family

## 5 Conclusions

Both the resulting surface roughness and the geometric accuracy of the cavity, which were measured in the laboratory tests, exceeded the theoretical minimum tolerance requirements of the oscillator even with six IT-grades without any productive difficulties. This result affects significantly to the stability of the desired Q-value of the oscillator and of course it gives options to increase the absolute magnitude of the Q-value as well. Based on the manufacturing time simulations in Table 2, and the results of the interview carried out in a commercial company, it is possible to reduce the total machining time of the oscillator body about 40 % from original without sacrificing the Q-value.

## References


1. Eskelinen H (1999) Manufacturability analysis—a useful subset of systems engineering. IEEE Aerosp Electron Syst Mag 14(2):33–35
2. Eskelinen H (2000) Application of concurrent engineering in innovative manufacturing and design of a milled microwave filter construction. In: Proceedings of the managing innovative manufacturing MIM 2000 conference, Birmingham, 17–19 July 2000
3. Eskelinen H (2000) Developing design methodology and DFMA-approach for passive microwave mechanics. In: Proceedings of nord design 2000 conference, Copenhagen, 24–25 Aug 2000
4. Eskelinen H (2000) Novel DFMA-tools for passive MW- and RF-components in cost-effective mass production. In: Proceedings of EuMW conference, Paris, 3–5 Oct 2000
5. Eskelinen H (2001) Improving the productivity of complex electronic systems design by utilizing applied design methodologies. IEEE Aerosp Electron Syst Mag 16(10):26–28

6. Eskelinen H, Varis J, Ström J, Heinola J-P (2006) DFM(A)- aspects for an E-plane waveguide ring resonator design. In: Proceedings of 23rd international manufacturing conference (IMC23), 30 Aug –1 Sep 2006, University of Ulster, Northern Ireland
7. Eskelinen H, Ström J-P (2008) DFM(A)-aspects of an advanced cable gland design. Lappeenranta University of Technology, Faculty of Technology, Department of Mechanical Engineering, Research Report 73/2008
8. Lohtander M, Eskelinen H (2011) Review of design for manufacturing and assembly aspects to designing modern microwave and sheet metal products. Key Eng Mater 486:9–12, Trans Tech Publications, Switzerland
9. Eskelinen H, Eskelinen P (2003) Microwave mechanics components. Artech House, New York, 3/2003
10. Ramo S, Whinnery J, van Duzer T (1994) Fields and waves in communication electronics. Wiley, New York
11. Collin R (1992) Foundations for microwave engineering. McGraw-Hill, New York
12. Matthaei GL, Young L, Jones EMT (1990) Microwave filters, impedance matching networks and coupling structures. McGraw-Hill, New York
13. Brogren M (2000) Titanium-aluminum-nitride coatings for satellite temperature control. Thin Solid Films 370:268–277, Elsevier Science
14. Milmega (2002) An X-band, high power, MMIC-based microwave amplifier introduction to a new high power. Microwave J 1 Feb 2002
15. Tsai DM, Lin BT (2002) Defect detection of gold-plated surfaces on PCBs using entropy measures. Int J Adv Manuf Technol 20(6):420–428 Springer
16. Wall J, Sinnadurai N (1998) The past, present and future of EEE components for space application: COTS—the next generation. Microelectron Int 15(3):7–16 MCB University Press
17. Barcena J (2008) Innovative packaging solution for power and thermal management of wide-band gap semiconductor devices in space applications. Acta Astronautica 62:422–430 Elsevier Ltd
18. Tu S (2007) Emerging challenges to structural integrity technology for high-temperature applications. Mech Eng 2(4):375–387

# Concept of the System for Optimization of Manufacturing Processes

**Silvia Palajová and Milan Gregor**

**Abstract** This paper deals with the optimization of manufacturing and logistics processes with the support of progressive computer simulation approaches. It briefly discusses systems and tools developed at the University of Zilina, from the Laboratory of Intelligent Systems ZIMS, through the use of emulation and software as a service, to own computer applications based on Genetic Algorithms (GAsfoS, GAsfoS2), scheduling of custom production (SSEM) and metamodeling (SAGME). The alignment of developed tools is represented in the system OSMAP.

## 1 Introduction

In a time of economic crises and constantly changing market conditions, it can be difficult to survive in such a competitive environment. At the same time, increasing, and often changing customer requirements and exigencies place great pressure on manufacturers and businessmen, and a company has to adapt to these changes if it wants to survive. Production is more frequently customer orientated in order to fulfill the requirements of a wide spectra of customers and to satisfy their individual demands. Furthermore, production volume is changed according to the actual market situation and customers in an effort to economise. Not only production but also scheduling and production control have to be adapted to this.

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There are several solutions and support tools that help find the 'right' setup of a system and to resolve the complications that occur within the production process. These are progressive approaches based on advanced computer simulation that help to optimize production and logistics processes, but they can also be used in the non-manufacturing sphere. Our approach in simulation is represented by number of own created tools, such as simulation optimizer GAsfoS, simulation based scheduling module SSEM, and metamodelling system SAGME. In the next section, we will present particular approaches and the integration of these solutions into one system OSMAP. It is useful as a support in managers' decision making process without deeper knowledge of computer simulation of manufacturing processes, and it helps to find problems solution close to optimal or directly optimal.

First of all it is necessary to identify the production systems and their development in the future in order that their characteristics are taken into account within the proposal itself. Given the complexity of today's production systems, a range of potential solutions and their evaluation are available to support the means of artificial intelligence.

## 2 Production Systems

In order to survive in the global environment, it is necessary to plan, control, and continually improve the production processes. Therefore, a company has to apply a global strategy to its development in order to ensure a strong position in the market. The main characteristics of a world class enterprise are a superbly trained and motivated staff, zero failures, low fluctuation, low inventory and down-times, extremely short setup times, and a continuous improvement of the enterprise processes.

Apart from generating the required innovation—rapid preparation and initiation of production is necessary because he who comes into the market sooner reaps the advantages (new market segments, determining pricing, etc.). Therefore, modern technical preparation should integrate design, technological and projective production preparation, team work organization, simultaneous engineering, approaches and techniques of system engineering (projection control, simulation), strong computer support (CAPP, means of simulation).

Forecasters have identified digitization and digital technologies as the main driver of productivity growth in the 21st century [1]. They are also strongly applied in manufacturing plants. Nowadays productivity growth is also facilitated with the help of artificial intelligence that moves from laboratory conditions to practice specifications, beginning with sensors, control units, through to systems for image, or sound identification, pending autonomous robotic workstations used, e.g., in the automotive industry.

## 2.1 Intelligent Manufacturing Systems

An intelligent system recognizes and understands the reasons for changes and uses this knowledge to learn. Repeated system's inputs deepen its learning. The intelligent machines, along with people and animals are classified as 'intelligent' systems. They are increasingly being used in industrial practice and they help to eliminate human error.

The Intelligent manufacturing system (IMS) is defined as a system with an autonomous ability to adapt to unexpected changes, inter alia also changes in the market, technologies, social needs, etc. The main properties of IMS are:

- systematization of all elements of the production and its set-up,
- flexible integration of the whole company to an optimal cooperation between human and intelligent technical means,
- versatility of use,
- self-learning and adaptability,
- information directness,
- scalability.

The efforts in the IMS area are also developed in Slovakia, at the University of Zilina.

## 2.2 ZIMS

Zilina Intelligent Manufacturing System (ZIMS) is the initiative of the University of Zilina that supports an innovation course named IMS in cooperation with practice. ZIMS is designed in a single version for the purpose of representing advanced production systems and simultaneously to allow experimentation and further research in the intelligent manufacturing systems area (Fig. 1).

It includes specialized workstations needed for the development and creation of a product:

- constructional workstation for a product design,
- scanning workstation, projection system CEIT-table used for the planning of a production system in virtual reality,
- simulation station,
- ergonomic station with various endurance tests,
- fully automated assembly line,
- camera control station,
- working machines are planned.

Furthermore in this laboratory, there are automated guided vehicles developed by the Central European Institute of Technology (CEIT) in cooperation with the

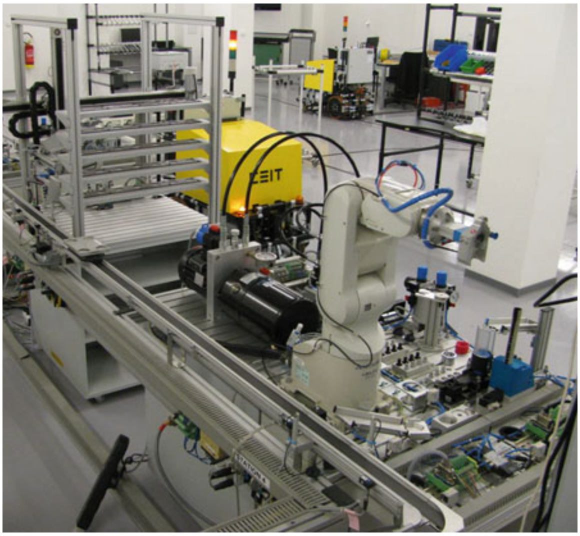


**Fig. 1** Workstation of an automated assembly in ZIMS [11]

University of Zilina. Nowadays ZIMS uses the technologies of partner organizations such as Siemens, Festo, Mitsubishi, CEIT. On the ZIMS development further industrial partners are participating in successful innovations.

Our research and development uses approaches for the designing and testing of new products and production processes. These approaches make use of rapid prototyping technologies, digitizing, virtual reality, and simulation. Virtual reality can be used in the area of product development, designing of production processes, workstations, production systems, systems for planning and production control, and so on. Digital Factory currently represents the most progressive approach for complex, integrated designing and simulation of products, production processes, and systems. Tools of the Digital Factory used at our department are described in [2].

The Concept of Digital Factory is based on three elements:

- digital product with its static and dynamic aspects,
- digital production planning,
- digital production with application of planning data in order to increase the efficiency of enterprise processes.

According to prognosticators computer simulation will become the dominant technology in the 21st century [3]. It is described in the following section.

## 3 Simulation Optimization

Simulation as a supporting tool for the decision making process, analysis, optimization, and forecasting is mainly used for process optimization, planning and process control, projection, and the analysis of production systems, improving logistical conceptions, staff training, etc. The heart of simulation is experimentation with the model of a system and thus seeking solutions to the problems of real systems, or looking for a suitable layout of a conceptual system. Satisfactory results are then applied to the real system.

Each of the tools mentioned below represents an advanced approach in simulation optimization. They provide answers to frequently asked question such as: "What happens if…?", "Where is it possible to save?", "Is it possible to meet the deadline and price?", "Why do we have higher costs than our competitors?", "What is the reason?", etc.

### 3.1 Optimizing System for Manufacturing Processes: Osmap

The tools GAsfoS2, SSEM, SAGME are powerful means of optimization, however, their unification and interconnection forms a complex system for the optimization of production and logistical processes. OSMAP combines under "one roof" all the created modules and helps to find solutions close to the optimal or directly optimal. Its fundamental structure is displayed in the Fig. 2. In the next figure, we can see the basic structures of particular modules/tools (Fig. 3).

In order to understand system functioning, it is necessary to define terms such a parametric simulation model, emulation, or cloud computing. In the next part of the paper principles of tools mentioned above will be explained.

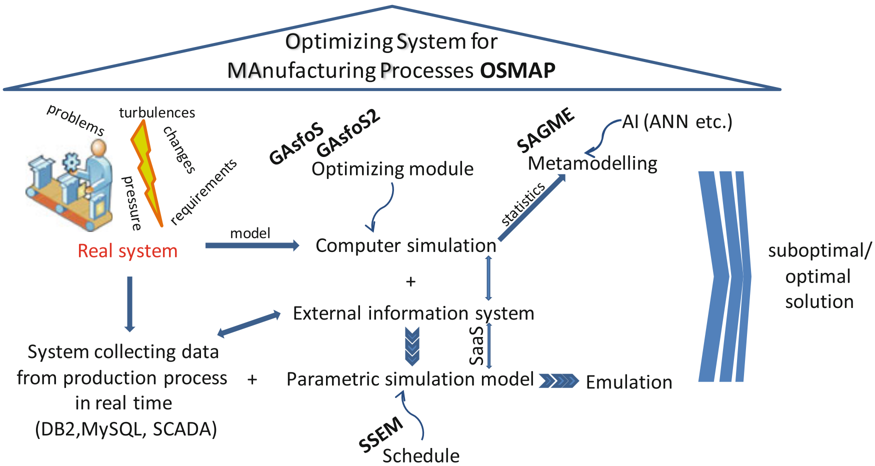



**Fig. 2** Concept of the OSMAP system

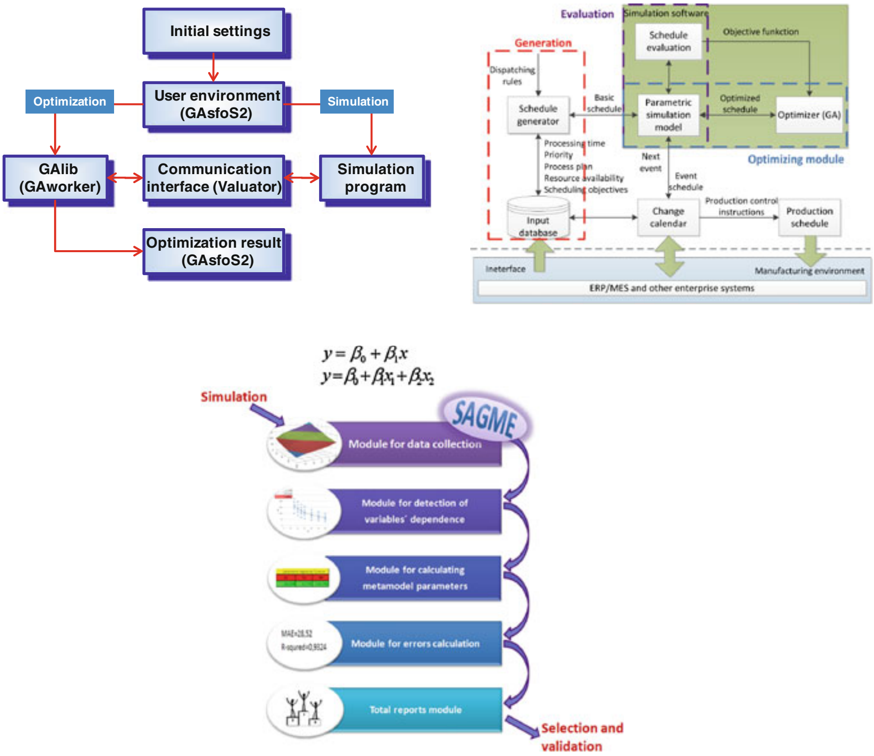



**Fig. 3** Structures of applications GAsfoS2, SSEM, SAGME

## 3.2 Parametric Simulation Model

An acceptable result in simulation is an extreme value of optimal criteria (i.e., either a selected objective function or the values of some numeric characteristics of the manufacturing system) and it can be achieved by means of an appropriate alignment of a system's resource possibilities. The most commonly used objective and universal optimal criterion in production systems are the total production costs. The conventional off-line optimization consists in a sequential alternating of input values in a simulation model, consecutive simulation runs a realization after each variation, and the consequences of system changes evaluation. Resetting the input factors' values can be performed without an in-depth knowledge of the simulation software, namely in the environment of an external information system (e.g., MS Excel). Value variation is automatically loaded into the created simulation model and simulation run can be executed. Experimental results, numeric characteristics of the system (e.g., average throughput time, production performance, capacity utilization, etc.) are retransferred into an external information system, and on this basis corrective action can be taken. This process is repeated until a satisfying result is achieved. A sample of different variations of a simulation model of a real production system and the results of its runs are presented in [4].

### 3.3 Reality and Simulation Model Integration

In the case of the connection of an external information system, as well as a simulation program, with the real system we are talking about emulation [5]. Production data mining is executed with the help of database system (MySQL, DB2, SCADA …) that enables simple data handling. Such a solution also provides information in real time and therefore enables the simulation and resolving of recently occurred problems. Another advantage is the set-up option of the real system from a computer. Thereby we can determine the effect of changes of regulation in production by the virtual model with a direct integration into the real production system. The emulation environment enables us to:

- monitor the manufacturing or logistics systems,
- evaluate collected data in real time,
- update the model on the base of real system's data,
- perform experiments on an accurate, updated, and verified simulation model.

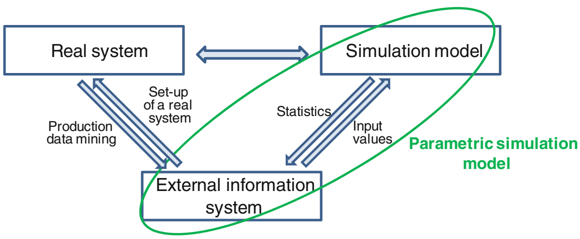
At our department the real production system has been replaced with a lego modular production system and will be tested later in the ZIMS environment.

This approach is practically sound for the variation of a current problem's solution and the optimization of production and logistics processes. However, a major problem still remains which is the high purchase cost of simulation software and the necessary tools required for advanced approaches in simulation, especially for small and medium enterprises (Fig. 4).

### 3.4 SaaS

One possibility to eliminate the problem of such an expensive solution is the exploitation of cloud computing. The target is delivering software as a service (SaaS), in this case simulation software. It means that a customer's data is stored in

**Fig. 4** Emulation



a "cloud" in databases placed on a server on the internet, and users can access them through a web browser or client application and use them practically anywhere. It means that a company doesn't need to own simulation software and it saves the costs connected with the purchase of special software and with staff training. The company simply pays for the valid use of the software, and it eliminates the responsibility for operation and maintenance programs. The substance of simulation software as a service whereby the customer simply opens excel interface and sets up values of the desired production factors. These values are loaded into a parametric simulation model stored on the server of an external company. Right there simulation runs are executed and the statistical results are automatically sent back to the customer. On their basis the customer decides whether and/or what corrective actions are to be taken.

### *3.5 GAsfoS2*

The simulation optimizers that can be a part of simulation program or can be in-programmed help on a large scale for simulation optimization. Our application named GAsfoS2 (designed in [6]) is based on the genetic algorithm (GA) and can optimize any production system. It enables the start of the simulation model, set-up simulation run, start simulation, set-up genetic algorithm, and consequently optimizes the production system. These acts are executed in a user operating environment GAsfoS2. The library supporting the work with GA is a part of *GA core* that forms the basis of the program *GAworker*. The communication interface between *GAworker* and the simulation program is *Valuator*. The operation principle rests in the evaluation of each generation, results of individual simulation runs are noted down and evolution continues until one of two conditions is fulfilled:

- number of generations has been achieved,
- required value of optimization criteria has been achieved.

GAsfoS2 is a modified application of GAsfoS designed by [7], for a more general usage. It may be used for any simulation model but currently it uses only one GA. Here we see the possibility of further development.

### *3.6 Simulation and Scheduling: SSEM*

Raising the productivity of labor and activities that are associated with the execution of production become the key parameters required to be at maximum level. The important task in production on an operative level is the generation of a manufacturing schedule. In general, scheduling problem is given by finite number of products set that are manufactured on a limited number of production machines. To solve these problems, there are besides exact and heuristic methods, increasingly used meta-heuristic methods and simulation techniques. There also exist several planning or ERP systems that generate production schedules. However, they are quite limited and dedicated to rough planning. On the other side, Advanced Planning Systems (APS) accept different constraints and use optimization algorithms but their purchase is connected with high costs. Therefore, a modular system for the scheduling of custom manufacturing with the support of simulation and evolutionary methods was created. It was named *SSEM* (Scheduling using Simulation and Evolutionary Methods) [8], and it consists of three parts:

- schedule generation or scheduling with the use of preferred rules that have a common base,
- schedule evaluation by means of a parametric simulation model according to the selected criteria,
- optimization by evolutionary methods in order to achieve better solutions.

The basic principle is that the simulation software communicates with the schedule generator, optimizing module (GA), and change calendar. Input for parametric simulation model is a primary schedule. After the simulation run objective function is calculated by the selected preferred rule. The optimizing module provides a set of realizable solutions of simulation model in terms of selected criteria power with the help of a genetic algorithm. The result of the optimization is an optimized schedule according to specific criteria on the basis of the fitness function. Facts obtained from the simulation model or schedule generator are apportioned into a change calendar and on the basis of management instructions a production schedule is generated.

## 3.7 Simulation Metamodelling: SAGME

In a state of simulation results acquiring it is possible to simplify, combine inputs from simulation, and eventually eliminate those that have shown to be needless. This enables the so-called metamodels or models of simulation models that substitute simulation data with a function curve and reliably approximate them. This approach was named as *approximation control*. It is based on the replacing of empirical data with a suitable type of theoretical function that realistically describes authentic data acquired from a system or from the simulation. Our system for the automatic generation of metamodels, *SAGME* [9] was created for such purposes. The system *SAGME* consists of five modules:

- module for data collection,
- module for variables' dependences detection,
- module for calculating the metamodel parameters,

- module for error calculating,
- module of total reports.

The *SAGME* system enables well-arranged simulation results in the form of contingent tables and charts, finding recovery factors with the strongest influence on monitoring responses, function parameters accounting, metamodel validation in regard to the simulation model, and all the received results in summarization into synoptic charts. On their basis it is possible to define the approximate rate of accuracy, or to accept metamodel in finding a better solution.

It is possible to use artificial neural networks (ANN) for simulation data substitution because they are regarded as universal approximator functions. For discovery correlation of simulation outputs to corresponding inputs, ANN together with a teacher, or ANN with supervised learning is used. The idea is the attempt to teach ANN behavior in a monitored system way and consequently to apply the acquired rules on any input value. This principle was demonstrated in a real model described in [10]. Evaluating the effect of downtimes occurrences and repair times on average throughput time was monitored.

## 4 Conclusion

These progressive approaches afford the opportunity to use simulation in terms of practice easier. They can respond flexibly to customers' requirements and provide them with a tailored service, and enable the rapid use of simulation in the commercial sector, not only in terms of research. The above mentioned progressive simulation approaches allow:

- to easily enter own values of elective variables (loading input data from an external source),
- to operate parametric simulation model by managers and operators in the production shop,
- to test various managing and optimizing methods without a deeper knowledge of modelling and simulation methods, and simulation software,
- to execute simulation runs and process optimization while without being in possession of simulation software,
- to find the best solution of company problems in a very short time,
- to save on financial resources.

The approaches described in this paper focus on the improvement of companies' interest in the simulation of manufacturing and logistics systems.

## References

1. European Commission (2004) MANUFUTURE—a vision for 2020, assuring the future of manufacturing in Europe. Report of the High Level Group, DG Research, Brussels, Nov 2004
2. Hnát J (2011) SIEMENS PLM solution at the University of Zilina. In: Proceedings of the international conference InvEnt 2011—industrial engineering of the future, 19.9.-21.9.2011, ISBN 978-80-554-0409-7, Zilina, pp 32–35
3. Gregor M, Matuszek J, Magvaši P (2012) Where do advanced manufacturing systems lead up? Unpublished study, Zilina
4. Štefánik A, Grznár P (2005) Quick and appropriate changes with support of modelling and computer simulation. In: Proceedings of TRANSCOM 2005: 6th european conference of young research and science workers in transport and telecommunications, 27–29 June 2005, ISBN 80-8070-414-7, Zilina, pp 173–176
5. Palajová S, Figa S (2011) An advanced approach of simulation of manufacturing and logistics processes. In: Proceedings of digital factory 2011—path to the future [electronic source]: 10.-11.5.2011, ISBN 978-80-970440-1-5, Zilina
6. Heglas M (2011) Simulation of manufacturing system with the use of evolutionary methods. Diploma thesis, Zilina, p 69
7. Škorík P (2009) Simulation of manufacturing systems with support of virtual reality. Doctoral thesis, Zilina, p 123
8. Figa S (2012) Manufacture scheduling using simulation and evolutionary methods. Doctoral thesis, Zilina, p 109
9. Palajová S (2012) Simulation metamodelling of manufacturing systems. Doctoral thesis, Zilina, p 128
10. Gregor M, Palajová S, Gregor M (2012) Simulation metamodelling of manufacturing systems with the use of artificial neural networks. In: Proceedings of 14th international conference on MITIP 2012, ISBN 978-963-311-373-8, Budapest, p 178–189
11. Gregor et al M (2011) ZIMS—Zilina intelligent manufacturing system. CEIT study, Zilina, p 178

# Structured Analysis of Reconfigurable Manufacturing Systems

**Erik Puik, Daniel Telgen, Leo van Moergestel and Darek Ceglarek**

**Abstract** The realization of a short product-time-to-market is a key-challenge in the design of modern manufacturing equipment. Compression of lead-times for product design and manufacturing require a concurrent way of engineering. This implies that structural decisions about manufacturing-equipment need to be made when products are still under development. This introduces development risks; changes in the layout of production systems, due to late modifications in the product design, are inefficient for lead-time and cost. It is preferable that the production system can be designed in a ‘first-time-right’ fashion. Therefore, the architectural freeze of a manufacturing system is preferably pushed backwards in time to sustain modifications of the product design as long as possible. Reconfigurable Manufacturing Systems (RMS) have been developed for this purpose. With their modular structure, they can be integrated in a short period of time. Though this leaves more time for product development, it does not exclude the industrialization risks. Since configuration of equipment only works reliably if its process technology is well understood, it is needed that poorly functioning manufacturing processes are detected and addressed in an early stage. Only then, sufficient time is available for corrective actions to be taken. This paper presents a scientific framework to model the development of RMS. The method has the capability to uncover manufacturing risks during early development. In combination with RMS, the freeze of system architecture can indeed be pushed backwards in time. The method uses the ‘Structured Analysis Design Technique’ (SADT). The process risks, as outcome of the analysis process, are ranked using a Failure Mode Effect Analysis (FMEA) to determine the severity of their impact.

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It helps focussing on primary issues to be addressed. The method was applied to a true case; the development of a RMS for cell Phone lenses. The industrialization process may be considered successful. By application of this approach, engineers profit of a complete overview of what actions need to be taken and the effects if these actions are omitted. The method can also be used to inform higher management, to increase understanding of the cause and effect of management decisions related to manufacturing.

**Keywords** Reconfigurable manufacturing systems · Structured analysis · Time to market · SADT · FMEA · RMS

**Abbreviations**

| | |
|---|---|
| DfA | Design for assembly |
| FMEA | Failure mode effect analysis |
| FTR | First time right |
| QMAP | Qualitative modeling and analysis of processes |
| RMS | Reconfigurable manufacturing systems |
| SADT | Structured analysis design technique |

## 1 Introduction

Modern manufacturing is challenged to deal with short times to market. Product Design and Manufacturing-Engineering are concurrently executed to gain time in the completion of product and manufacturing means. Due to the concurrent design, structural decisions about manufacturing have to be made when product development is not yet complete. However, changes in the product design, during ongoing manufacturing engineering, are likely to cause modifications of the equipment. This requires substantial effort. The intent is to realize manufacturing-equipment in a 'First-Time-Right' fashion (FTR). FTR development requires extra precautions to prevent a sequence of modifications to occur. One of the precautions is to apply a 'Zig-Zagging' approach [1, 2]. Zig-Zagging is a two dimensional process; it combines hierarchical decomposition and concurrent engineering for complex problems. This is done while zig-zagging between the functional-, physical- and process-domains. It asks for a bidirectional attitude of the development personnel. On one side, product developers submit their design efforts to the framework of available manufacturing technologies, called 'Submissive Product Design' [3]. On the other side, manufacturing engineers try to enhance flexibility in manufacturing technology, known as 'Agile Manufacturing' [3, 4]. This combination of methods, which may be seen as a fortified way of Design for Assembly (DfA), addresses two elementary goals:

- The functional risks of the product-manufacturing combination are brought forward in time and can be addressed at an earlier stage;
- Due to thorough understanding of processes, the architectural freeze of a manufacturing system can be postponed.

Zig-Zagging seems an ideal approach when manufacturing methods must allow for rapid product change. This may be seen as the main origin for Reconfigurable Manufacturing Systems (RMS) [5].

## 2 Integral System Engineering in Product Design and Design of Reconfigurable Manufacturing Systems

### *2.1 Modular Design Architecture and Modular Equipment Framework*

At the end of the 20th century, manufacturing entered a new era in which companies had to compete in a global economy. To stay competitive in modern manufacturing, methods must allow for rapid product change [5–7]. The principles of agile manufacturing combine a modular approach in product development and a matching modular approach in the development of manufacturing-means [2, 8]. This modular framework, which is applied to product design and manufacturing development, will help to reuse proven technological assemblies. Therefore, only a limited number of assemblies need to be redesigned. It reduces the total engineering effort, enabling shorter times to market. As a secondary effect it enables additional focus on those parts that actually do need to be changed.

### *2.2 Application of Modularity in MEMS Product Design for RMS*

Adding a modular approach does not automatically guarantee the advantages as mentioned above. The chosen modular framework, and the definition of interfaces, have to enable reuse of parts and manufacturing tools that have been developed in the past. Successful attempts of such frameworks have been presented for Micro Electro Mechanical Systems (MEMS) in the past [2, 9]. These frameworks have especially proved their advantages within a family of products. Secondly, modular building bricks have to be designed in such way that they can be reused in future designs [8]. By doing this, the investments in modular design and production methods can be used and reused. This leads to a change from 'Engineering of new products' to 'Configuration of new products', profiting of modular reuse many times. General guidelines for such an approach are found in literature [8].

### 2.3 Structured Design Analysis that Supports the Modular Structure of RMS

Qualitative Modeling and Analysis of Processes (QMAP) is a structured design tool based on SADT (Structured Analysis Design Technique) [10, 11]. The Philips company optimized SADT for manufacturing processes in the early eighties and gave the method its current name [12]. In a hierarchical approach, the manufacturing process is described in a layered structure. Due to the hierarchical approach, it breaks down the manufacturing process in sequential steps that support the modular structure of the RMS. To demonstrate this, the QMAP analysis is applied on a true case where it was used to analyze a manufacturing system for lenses of cell phone cameras.

QMAP starts with a top down decomposition of the production flow in 'Data-Diagrams' (Fig. 1). The production flow is broken down in elementary process steps. The functional blocks represent process actions in the envisioned manufacturing concept. As such, they represent the modular building blocks used to configure a production system. These modular building blocks can be [13]:

- Completely reused from earlier designs;
- Altered from earlier systems;
- Built up from the ground.

At the lower level, basic process-functionalities are described using an 'Activity Model' (Fig. 2). The Activity Model uses parameters to describe functionality of the particular function. Input parameters, can be 'Functional' (binding characteristics of a good product at start) or 'Dysfunctional' (representing potential hazards or errors of the product before the particular process has even started). Conditional input parameters, like 'Norms and Controls' reflect boundary conditions of the process. Parameters related to the transformation mechanism, comprising of 'Constants and Variables', are representing the process or equipment characteristics. All input parameters serve as determinants for the output parameters, again functional, or dysfunctional.

The QMAP analysis supports the modular structure of RMS well since all process steps are separately visualized at the data level of the QMAP analysis:

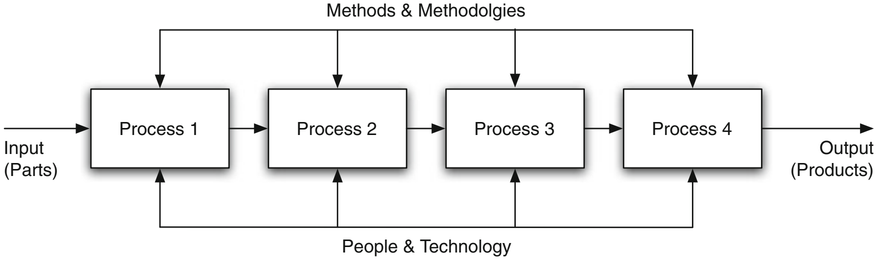


**Fig. 1** QMAP top level, the data diagram

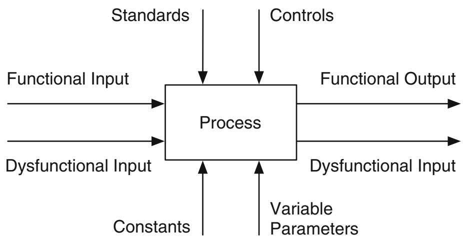


**Fig. 2** QMAP activity model

- First, it confronts the engineers with the logistic, but also the functional layout of the system;
- Secondly, the QMAP procedure decomposes system functions when moving from Data Level to Activity Model. During this stage, not only the modules are defined, but also their interfaces, both functional as physical;
- Thirdly, the general system architecture is finalized with the completion of Data Diagram and Activity Model, having defined all building blocks and their interfaces.

The QMAP analysis is executed by a diverse group of engineers. The participants have different backgrounds, from product- to manufacturing-engineering and even service-operations. The level of experience of the participants varies from junior+ to senior as it appears hard to contribute from the entry level of engineering.

## *2.4 Development Procedure; Zig-Zagging Through Product Design and Manufacturing*

Product/Process optimization using the QMAP procedure requires a number of cycles to enable Zig-Zagging and bring information from the stage of product design to manufacturing and vice versa. Having completed the QMAP for the first time, it typically appears that not all risks have been addressed adequately; the product design, the manufacturing means, or the combination of both will not meet all product and manufacturing specifications. Therefore, the analysis is repeated a number of times during the optimization process.

Though the completed QMAP analysis describes the manufacturing process in its elementary form, it is still a matter of good governance to decide which of the defined risks are most dominant. This can be evaluated by ranking the remaining risks using a risk analysis tool, e.g., Failure Mode Effect Analysis (FMEA) [14]. The outcome is a prioritized sequence in which actual problems can be addressed. The next step is to take action on these problems in the order of prioritization.

Optimizations of the product design and the production modules are verified by testing. These tests are typically performed on parts of the product-equipment combination in the early stage, but can also be done on a fully implemented solution. The outcome of the tests will lead to integrated proposals for optimization of the product-equipment combination. The consequences of supposed optimizations will be studied using the QMAP analysis again. This completes one Zig-Zagging cycle, bringing manufacturing knowledge back to product developers. This procedure is repeated a number of times, usually 3–4 cycles. The impact on the combination of product design and production concept, as well functional as logistic, will lead to optimizations in at least three areas [13]:

- First, the number of parts is minimized due to a less complicated structure at data level;
- Secondly, it realizes an enhanced level of standardization, by an increased ability to reuse (standard) components and process steps;
- Thirdly, it leads to an increased success in implementation of a design with common and independent parts and components showing less crossroads at data level.

## 3 Case: Manufacturing of Cell Phone Lenses

### *3.1 Definition of the Product*

The applied case, the manufacturing of Cell Phone Lenses, consist of 4–6 cylindrical plastic parts that are stacked on top of each other to form a small lens assembly. The stack is fixated by an adhesive from the side. The diameter of the parts is 5–6 mm and expected to decrease down to 2 mm in future designs. A reduction of the diameter should be foreseen in the equipment. The assemblies are shown in Fig. 3.

**Fig. 3** Two types of cell phone lens assemblies. 4–6 parts are stacked on *top* of each other. Not all parts are transparent, diaphragms can be integrated as well

This case introduces a new feature, a new procedure to align the cylindrical parts. Where the state of the art design uses a lens barrel for alignment of the optical parts, the new design aligns by pressing parts into a V-groove. No exterior lens barrel is used. The new alignment procedure is expected to realize a better accuracy and reduces the diameter of the lens assembly. However, this procedure needs design modifications and new manufacturing solutions. The modification has a disruptive character. To structure the development of the new alignment process, the QMAP method was applied, starting from the earliest design up to completion of a pre-production machine.

## 3.2 Application of the QMAP Data Diagram to Increase Understanding of the Assembly Sequence

To get a better understanding of the assembly sequence, QMAP analysis at data level was applied (Fig. 4).

The production is based on a $2^1/_2$D Pick & Place process. In its most basic form, Pick & Place actions P1 and P2 would be sequential for all parts ($P1_{(1)}$, $P2_{(1)}$ for part one, $P1_{(2)}$, $P2_{(2)}$ for part two, $P1_{(n)}$, $P2_{(n)}$ for the final part). Due to the fact, however, that the shape of the parts does not differ much, it is possible to manipulate all parts with the same gripper. The implementation of a cyclic process was carried through as first optimization. This is indicated with the loop for processes P1&P2. The process of stacking is followed by a sequence of processes; Clamping, Aligning, Bonding, and Exporting the part to the output tray (P3–P8).

## 3.3 Application of the QMAP-Activity Model in Combination with FMEA

All processes (P1–P8) were analyzed in detail. In this paper, the most characteristic process P4 is emphasized. This process, being most innovative, was expected to introduce the highest industrialization risk at the start of the industrialization process. P4 executes the alignment of the lens stack in the V-groove.

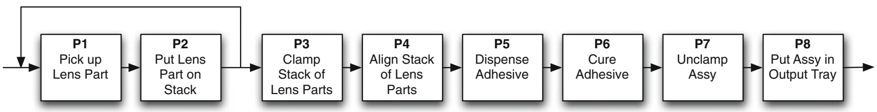


**Fig. 4** Description on the QMAP data-level. On the *left*, the combination of P1&P2 is performed as many times as there are parts. After completion of the stack, P3–P8 are performed in sequential order

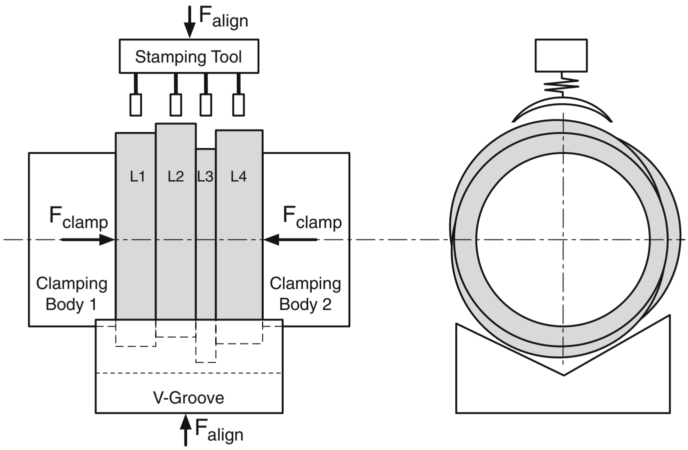


**Fig. 5** Process P4 aligns the lens parts L1–L4 using two balanced combinations of forces. The clamping forces makes sure the parts are mating well. The alignment forces close the parts within the geometrical shape of the *V-Groove*. The stamping tool is made of a flexible material to prevent over constrainedness

The input is formed by a stack of lenses that is clamped between two bodies that apply a light clamping force in the direction of the optical axis of the lens. The lens parts, though pre-aligned, are not yet completely into their final position as can be seen in Fig. 5. By applying an alignment force, perpendicular to the clamping force, the parts are aligned by pressing them into the V-groove. Micrometer accuracies are achieved when the process is performed well, depending on geometry, surface condition, dust particles, and tribo-electric charge of the parts.

The full analysis of P4 is given in Fig. 6. The analysis consists of a normalized cycle, of: (1) QMAP-Analysis, (2) Risk Inventory, (3) Risk Analysis, (4) Implementation of a Solution, and (5) An Effect Analysis. The cycle was repeated three times.

At the start of the analysis, three risks were detected during the first cycle. Only P4.1 and P4.3, having been defined most dominant by the risk analysis, were addressed in the first optimization cycle. P4.2 was forwarded to the second improvement cycle to enable increased focus on the main problems. The solution applied was a combination of a product design optimization and a new production technology; change in application of the optical coating and application of the V-groove. Together these changes offered a solution to the problem of lens alignment.

In the second improvement cycle, P4.2 was addressed together with two newly defined risks P4.4 and P4.5. Still, a complete production system, to test the solutions, was not needed. In a partial test setup, all three problems could be reduced and verified for functional performance (better gripper, cleaner environment, improved geometry of the stamping tool). In the third and final cycle, the RMS was actually configured. It was mostly consisting of standard modules.

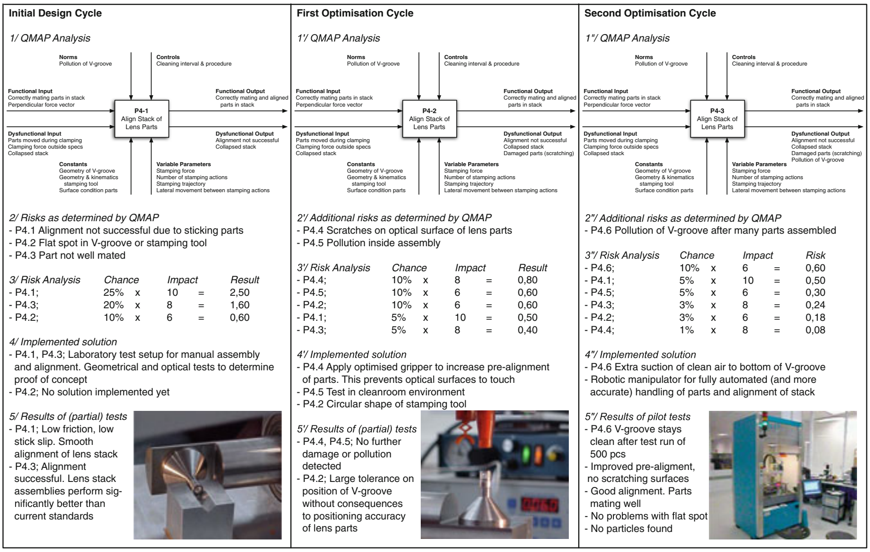


**Fig. 6** Full analysis of process P4. The cycle consists of (*1*) QMAP analysis, (*2*) Risk inventory, (*3*) Risk Analysis, (*4*) Implementing a solution, (*5*) Inventory of effect. The normalized cycle is executed three times for this process

The newly developed module for alignment was fully engineered while maintaining the construction of the test setup. Due to this synergy, test setup and final system were functionally comparable.

# 4 Discussion

## *4.1 Design Information Flow During Development of the RMS*

The industrialization process of a optimized lens design for cell phones was considered successful. The question arises if this could also have been the case if this method had not been applied. Processes of industrialization for hybrid micro systems are diverse and involve large investments. This makes an objective reference measurement expensive and heterogeneous.

What can be concluded is that the design of RMS can benefit from the combination of a structured analysis technique and a risk analysis tool. As such, accumulated engineering experience is optimally applied on new problems with artefacts that have been addressed in the past:

- At first, breakdown at QMAP data level leads to the revelation of many process artefacts. This increases the chances of a problem being discovered in the early phase of equipment development. It also has a downside. Uncertainties due to a lack of knowledge of the manufacturing process, might cause an overprotected attitude with the engineers. This could result in over-engineering. Hence, costs increase without added functionality.

- Secondly, the use of the QMAP analysis enables an improved structure of the process flow through the manufacturing system in the earliest stage. This supplies the researchers with an early indication of system complexity. Actions can be taken to optimize the process flow in an early stage, while the product is still under development. This will most certainly be more cost efficient than applying changes in a later phase of the project.
- Thirdly, the use of the risk analysis, to visualize the nature of remaining risks in the production system, will lead to better understanding of the project risks. This will spin-off to a broader scope than just the engineering level. Though the engineers profit by a complete description of what to do and the effects when actions are omitted, the higher level of management will also be capable of understanding the cause and effect of certain choices. This reduces discrepancy in the estimates of needed effort to complete the work; less explanation to the management level is needed.

These three effects together lead to a quicker and more thorough analysis of product and production means before the first hardware investments in equipment need to be done. It will lead to improved flexibility to adapt to changes, and it supports design for assembly in an optimal way. This, in its turn, will lead to a better system architecture of as well product and production means at a more competitive cost.

### *4.2 Future Work*

Designation of the FMEA can be tangling. For these situations, a qualitative analysis could provide a solution. Future work will focus on augmentation of the FMEA with qualitative analysis and risk plotting.

The QMAP method manages to uncover many artefacts in an early development phase. Not all artefacts however, will appear to cause problems in the equipment design. The exhaustive information could lead to over-engineering. Future work will focus on better disposal of uncovered problems.

## 5 Conclusion

The combination of QMAP and FMEA style risk analysis can be successfully applied to reduce the risks during the development and reconfiguration of RMS. The tools force decomposition of the product design and the chosen manufacturing solution. Results are made available at an early stage when influence in the product design is still possible, thus optimizing the combination of product design and manufacturing.

The method can be applied with limited time spent, making it an interesting procedure for an industrial scene of action.

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## References

1. Suh NP (1990) The principles of design, ISBN 9780195043457. Oxford University Press, USA
2. Puik E, Rijfers A, Tillie L (2002) A lower threshold to the world, by combining a modular approach and a matching production framework. In: Proceedings of COMS
3. Puik E, Moergestel L (2010) Agile multi-parallel micro manufacturing using a grid of equiplets. Paper presented at the IPAS2010, vol 315(32). Berlin, Heidelberg, pp 271–282
4. Gunasekaran A (2001) Agile manufacturing, ISBN 9780080435671. Elsevier Science, Oxford
5. Koren Y (2006) General RMS characteristics; comparison with dedicated and flexible systems, vol 3. Springer, Berlin, pp 27–45
6. Wiendahl H-P, ElMaraghy HA, Nyhuis P, Zäh MF, Wiendahl HH, Duffie N, Brieke M (2007) Changeable manufacturing—classification design and operation. CIRP Ann Manuf Technol 56(2):783–809
7. Kerbrat O, Mognol P, Hascoet J-Y (2010) Manufacturing complexity evaluation at the design stage for both machining and layered manufacturing. CIRP J Manuf Sci Technol 2(3):208–215
8. Gutierrez A (1999) MEMS/MST fabrication technology based on micro bricks: a strategy for industry growth. MST News 1(99):4–8
9. Grosser V, Reichl H, Kergel H, Schuenemann M (2000) A fabrication framework for modular microsystems. MST News 1:4–8
10. Ross DT (1977) Structured analysis (SA): a language for communicating ideas. Softw Eng IEEE Trans 1:16–34
11. Buseif I Using IDEF0/SADT model for design flexible manufacturing systems (FMS's) prototype. knu.edu.tw
12. Bullema JE, Stollman G, Nederhand B, Bekkers P Default design for processability aanpak. Philips Centre of Fabrication Technology
13. Abdi M (2006) Products design and analysis for transformable production and reconfigurable manufacturing. ISBN 9783540293910, Springer, pp 461–478
14. Werdich M (2011) FMEA-Einführung und moderation, ISBN 9783834814333. Springer Fachmedien Wiesbaden GmbH, 1e Auflage

# A Methodology for the Estimation of Build Time for Operation Sequencing in Process Planning for a Hybrid Process

**Zicheng Zhu, Vimal G. Dhokia, Aydin Nassehi and Stephen T. Newman**

**Abstract** The on-going industrial trend toward production of highly complex and accurate part geometries with reduced costs has led to the emergence of hybrid manufacturing processes where varied manufacturing operations are carried out in either parallel or serial manner. One such hybrid process being currently developed is the iAtractive process, which combines additive, subtractive, and inspection processes. The enabler for realizing the hybrid process production is the process planning algorithm. The production time estimation for the additive process, namely build time, is one of the key drivers for the major elements in the algorithm. This paper describes a method for predicting build times for operation sequencing for process planning of the iAtractive process. An analytical model is first proposed, theoretically analyzing the factors that affect build times, which is used to help with the design of four test parts together with 64 sets of variations. The experimental results indicate that part volume, and interactions of volume and porosity, height and intermittent factor have significant effect on build times. Finally, the build time estimation model has been developed, which were subsequently evaluated and validated by applying a wide range of the identified influential factors.

## 1 Introduction

Manufacturing technology has enjoyed rapid development with a number of evolutionary improvements over the past 60 years [1]. The ever-increasing demand for high quality products with low cost has led to the emergence of hybrid

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manufacturing technologies [2]. This new generation of manufacturing technologies integrate various different individual manufacturing processes on a single platform, exploiting their unique independent advantages while minimizing the drawbacks.

However, machining of highly accurate and complex structures (such as internal features and cavities) without assembly is still considered to be extremely difficult due to limited cutting tool accessibility. A concept currently being pioneered is the iAtractive process, which combines additive (i.e., fused filament fabrication, FFF [1]), subtractive (computer numerically controlled machining, CNC), and inspection processes for precision manufacture of complex part geometries. The enabler for realizing such hybrid process production is the process planning algorithm. Production time estimation is one of the key drivers for the major elements in the algorithm, such as determination of part orientation and operation sequencing. As the build time used in fabricating a prototype by using the FFF process contributes to the majority of production time, reliable and accurate build time estimation becomes crucial for both the efficient utilization of the individual processes and scheduling of operation sequences in the process planning stage.

Research has been conducted on estimating build times for certain additive processes. Han et al. [3] theoretically analyzed the deposition parameters and identified that layer thickness, deposition speed, and deposition road width are the major parameters that determine the build time for a fused deposition modeling (FDM) process. Pham and Wang [4] discussed the interrelation between build time, roller travel speed, build height, laser scan speed, scan area, and part volume in a selective laser sintering process. Subsequently an approximate build time estimation method was introduced, incorporating those key factors. In the paper by Kechagias et al. [5], an algorithm for predicting build times for laminated object manufacturing was presented, in which the part volume and surface area and the flat area were taken into account. The prediction errors were within 7.6 % of the actual build times. Instead of using an STL file (a file format for additive processes) to represent the part design, Campbell et al. [6] proposed a build time estimator, which is able to predict build times for the Stereolithography process with maximum 23.4 % percentage of error.

This paper reports on the development of a method for establishing a build time estimation model to be used at the process planning stage for the iAtractive process. A series of test parts with various combinations of features have been designed for developing and validating the model. Statistical analysis was carried out and the influential factors related to part geometries and material deposition toolpath has been identified.

## 2 The Proposed Hybrid Process and Process Planning Algorithm

### *2.1 Fused Filament Fabrication Process*

The additive process used is termed Fused Filament Fabrication (FFF), whereby material in filament form, Polylactic Acid (PLA) in this research, is fed into a liquefier chamber where it is heated to a semi-liquid state and deposited through a nozzle onto a build platform where it quickly solidifies [1]. A part is sliced into a number of layers and the material is deposited layer by layer until the final part is built. A schematic is depicted in Fig. 1.

### *2.2 The IAtractive Hybrid Process and the Overview of the Process Planning Algorithm*

Traditionally, the applications of manufacturing processes remain somewhat constrained due to the manufacturing capabilities either from technical limitations, such as limited materials and complex part geometries, or production costs. The hybrid process (iAtractive) currently being investigated at the University of Bath consists of combining additive, subtractive, and inspection processes [7]. Incorporating an additive process releases design constraints often caused by tool accessibility issues in CNC machining. Using CNC machining capabilities the final part can be produced with a high degree of accuracy comparable to that of an entirely CNC machined part. Furthermore, dimensional information of the existing part can be obtained by using an inspection technique enabling the existing part to

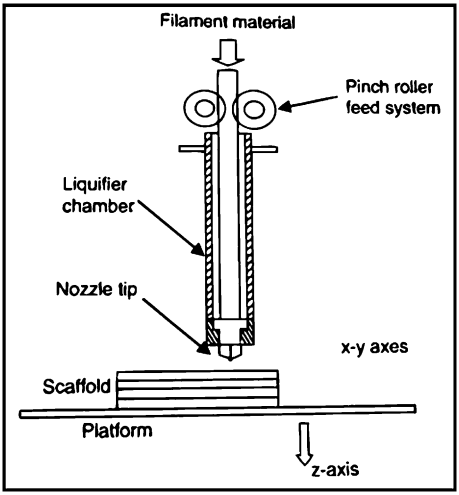


**Fig. 1** Fused filament fabrication (FFF) process [1]

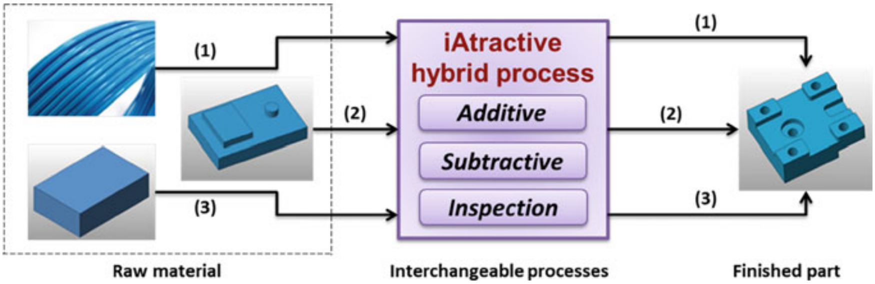


**Fig. 2** Vision of the iAtractive process production

be further manufactured by the additive and/or subtractive process, providing new functionalities. Figure 2 provides the authors' vision for hybrid process production, where raw material can be (1) zero (filament for deposition from zero); or (2) an existing/legacy product; or (3) a billet. By using the additive, subtractive, and inspection processes interchangeably, the given raw materials can be further produced to the finished part.

The process planning algorithm is the enabler for the iAtractive process. Its overall goal is to generate the process plan from a given part design. The key elements involved in the algorithm are decomposition of the part into a number of subparts, selection, and sequencing of the operations for producing the subparts. If there are certain feasible operation sequences, the most appropriate sequence in terms of production time has to be identified, which requires the estimation of production time. The total production time for manufacturing a part is defined as the sum of the time used in additive, subtractive, and inspection operations as well as switching time between additive and subtractive operations.

Machining time estimation has been extensively researched and a method proposed by Maropoulos et al. [8] is adopted in the process planning algorithm. Since the part is decomposed into a number of small subparts with fewer features, the inspection time can be considered as constant at this stage. By contrast, the additive process consumes considerably longer time than that of other processes. Therefore, one of the major challenges of this research was to develop a model for estimating build times, as this directly determines the operation sequencing. Apart from the estimation accuracy, the major requirement of the model is the efficiency, i.e., being capable to predict build times from a CAD model or 2D drawings which is the most accessible geometrical information for the process planning algorithm.

## 3 The Method for Developing a Build Time Estimation Model

Build times of the actual additive processes depend on part geometries, part orientation, and the parameters of the additive processes involved. The parameters affecting build times may vary depending on the specific additive processes. In order to develop a build time estimation model for the FFF process, an analytic analysis was first carried out to theoretically analyze the influential parameters. Two test parts were designed and initial tests were conducted, identifying and determining the most significant parameters that were to be used in the model. Subsequently, four test parts with varying combinations of features were designed and the fractional factorial design strategy was employed to design a series of experiments. The statistical analysis techniques, namely multi-factor regression analysis and analysis of variance (ANOVA) were used iteratively to develop the model. Finally, three test parts with specific features and volumes, combined with the *t*-tests method was used to evaluate and validate the developed model. Figure 3 illustrates the method used for developing such an estimation model.

# 4 Selection and Determination of Parameters

## *4.1 Analytical Model*

Build time ($T_{\text{total}}$) is defined as the amount of time that is required to fabricate a single or a group of parts by using the FFF process. As introduced before, the estimation of build time involves a number of parameters, which need to be taken into consideration and can be split into process parameters and geometry parameters. Geometry parameters are the variables to be considered prior to FFF process,

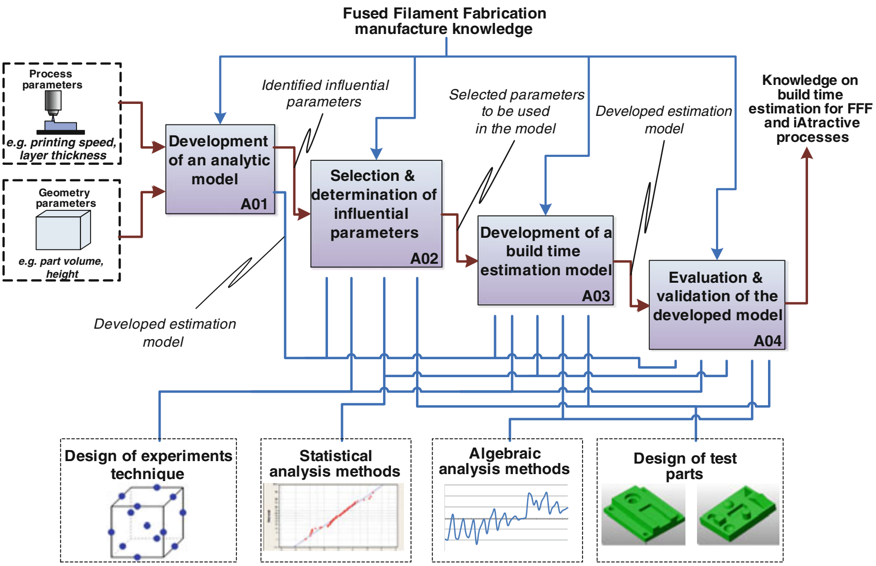


**Fig. 3** The method for developing a build time estimation model

**Table 1** Fused filament fabrication process parameters

| Parameters name | Unit |
|---|---|
| Layer thickness, $\theta$ | mm |
| Printing speed in XY plane, $V_{pr}$ | mm/s |
| Repositioning speed in XY plane, $V_{xy}$ | mm/s |
| Repositioning speed in $Z$ axis, $V_z$ | mm/s |
| Acceleration/deceleration in $XY$ plane, $A_{xy}/D_{xy}$ | mm/s$^2$ |
| Acceleration/deceleration in $Z$ axis, $A_z/D_z$ | mm/s$^2$ |
| Filament retraction speed, $V_{ret}$ | mm/s |
| Hatch spacing, $\lambda$ | mm |

such as part volume, surface area, and height. They are primary factors that have direct effect on build times. Process parameters—such as layer thickness, nozzle travel speeds—are the controllable factors, and changing them can lead to the increase/decrease in build time. The important process parameters are summarized in Table 1 below, which will be used in the development of the analytical model. Given the purpose of predicting build time, the process parameters are kept constant during the development of estimation model.

Assuming that a part is sliced into $N$ layers, the overall build time of producing the part can be described as

$$T_{total} = \sum_{n=1}^{N} T_n + T_{bed} + T_{heater} \tag{1}$$

where $T_{bed}$ is the time for warming up the bed to the glass transition temperature of the material to be deposited; $T_{heater}$ is the time used in turning on the heater until it reaches the material melting temperature; $T_n$ is the time used in printing $n$th layer, $n \in [1, N]$. For each layer, the build time $T_n$ is divided into two parts, namely, deposition time ($T_{dep\_n}$) and idle time ($T_{idel\_n}$). Idle time includes deposition head repositioning time in the $XY$ plane and $Z$ axis ($T_{rep\_n\_xy}$ and $T_{rep\_n\_z}$), which can be calculated using Eq. 2, where $S_{rep\_j\_xy}$ is the $j$th ($j \in [1, J]$) repositioning displacement (unit: mm) before depositing the $j$th continuous deposition path.

$$T_{idle\_n} = T_{rep\_n\_xy} + T_{rep\_n\_z} = \frac{\theta}{V_z} + \sum_{j=1}^{J} \left( \frac{S_{rep\_j\_xy}}{V_{xy}} - \frac{V_{xy}}{A_{xy}} \right) \tag{2}$$

Deposition time ($T_{dep}$) is the time when the material is being extruded, which is expressed as

$$T_{dep\_n} = \sum_{k=1}^{K} \left( \frac{2 \times L_{ret\_k}}{V_{ret}} + \frac{S_{pr\_k}}{V_{pr}} - \frac{V_{pr}}{A_{xy}} + T_{delay} \right) \tag{3}$$

where, $S_{pr\_k}$ is the length of the $k$th ($k \in [1, K]$) continuous deposition path; $L_{ret\_k}$ is the length of the filament retracted before depositing the $k$th deposition path; $T_{delay}$ is the delay time before depositing material on each individual continuous path.

Based on the analysis outlined in the proceeding Eqs. 1, 2, and 3, a full representation of the build time for a single part is derived, namely

$$T_{total} = \sum_{n=1}^{N} \left[ \sum_{j=1}^{J} \left( \frac{S_{rep\_j\_xy}}{V_{xy}} - \frac{V_{xy}}{A_{xy}} \right) + \sum_{k=1}^{K} \left( \frac{2 \cdot L_{retraction\_k}}{V_{retraction}} + \frac{S_{pr\_k}}{V_{pr}} - \frac{V_{pr}}{A_{xy}} + T_{delay} \right) + \frac{\theta}{V_z} \right] + T_{bed} + T_{heater} \tag{4}$$

## 4.2 Initial Selection of the Parameters

Based on the analysis above, the following statements can be made:

- Calculation of the build time using an analytical approach is generally not practical or viable in the proposed process-planning algorithm when only CAD models or 2D drawings are given.
- Length of continuous deposition path ($S_{pr}$) primarily determines build times when certain printing speed and acceleration/deceleration are applied. The length of continuous deposition path is proportional to build times. Therefore, part volume ($V$) is considered as one of the major parameters that directly contribute to the total amount of build time.
- Hatch spacing ($\lambda$) is defined as the distance between the centrelines of adjacent parallel hatch vectors. Even though it is not represented in Eq. 4, it plays an important role. A high value of hatch spacing indicates low density of the part (i.e., the part is more porous), which in turn reduces the total length of the deposition path. As a result, part porosity ($\rho$) is introduced in the build time estimation model.
- Reducing the time taken to reposition as well as length of repositioning toolpath ($S_{rep}$) could lead to the decrease in build time. The reasons that cause deposition head repositioning are (1) start printing next layer; and (2) certain areas do not require material, such as printing pockets. The importance of head repositioning needs to be investigated further in order to decide whether or not to include this parameter in the model.
- Part height ($H$) has potential effect on build time. Since the layer thickness has been kept unchanged, different height of the part resulted from part orientation could possibly require different build times. However, different orientations also lead to change in the lengths of deposition toolpath and the repositioning toolpath as well as the number of repositioning times, etc. It is unclear whether part height should be considered in the complete model. As a result, in the next subsection, a series of simplified experiments were conducted in order to finalize the decision regarding the parameters to be investigated in the development of a build time estimation model.

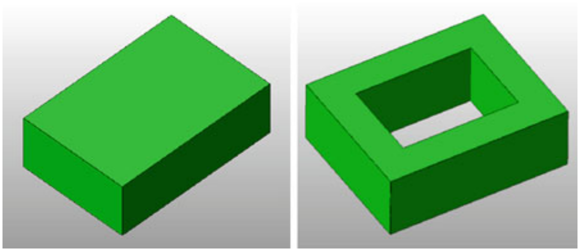

**Fig. 4** Test part *I* (*left*) and *II* (*right*)

## 4.3 Determination of the Parameters

According to the statements made in the previous section, the following two tests have been designed to evaluate the importance of two interrelated parameters, namely, part height and deposition head repositioning. Test part *I* and *II* are shown in Fig. 4. The $2^k$ full factorial design of experiments (DoE) strategy is used for the tests.

- Test 1: For the same rectangular blocks (test part *I*) with the same porosity, changing the block orientations means changing the part height. Thus, four sets of rectangular blocks are used. For each set of test part *I*, the volumes are kept the same but the height values vary.
- Test 2: Five sets of parts with four different sizes of the through pockets have been designed (test part *II*). Producing rectangular blocks with pockets requires repositioning the deposition head repeatedly and frequently since the pockets do not actually need material. The four sizes of the pockets are applied to all sets of test part *II*.

The build times were calculated by using the developed analytical model (Eq. 4), which can be considered as the actual build times. The results were analyzed by using the ANOVA technique, revealing that part height and deposition head repositioning are significant parameters in relation to the total build times. Test 2 also demonstrates that build time is not only dependent on part volume, but also the distribution of material. However, the length of repositioning toolpath and the number of times for repositioning cannot be obtained from 2D drawings, which also depend on the slicing strategy employed. An intermittent factor ($\eta$) is whereupon proposed to reflect the influence of the above two variables against total build times. High intermittent factor implies a long time used in repositioning the deposition head and other related actions such as filament retraction and print delay ($T_{delay}$). To this end, part volume ($V$), part porosity ($\rho$), part height ($H$), and intermittent factor ($\eta$) have been selected and defined to be investigated in the experiments for developing the build time estimation model.

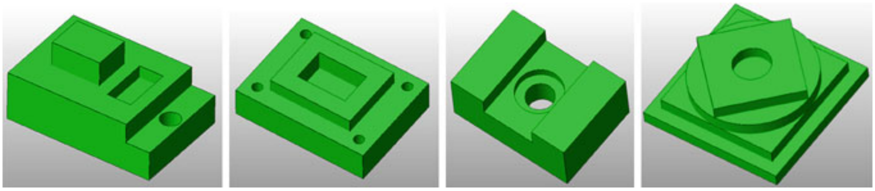

**Fig. 5** Test part *III*, *IV*, *V*, and *VI* (from *left* to *right*)

# 5 Developing a Build Time Estimation Model

## 5.1 Design of Experiments

Four test parts (test part *III–VI*) have been designed as shown in Fig. 5, which contain various combinations of features, volumes, heights, and intermittent factors. Given that these four factors are multi-level variables and their outcome effects are not linearly related, four levels are thus chosen to apply to part volume, height, and porosity for each test part design. Due to factor interactions, four variables can be expanded into 14 different combinations. In addition, the intermittent factor represents the geometrical attributes, which are constant and unique for each test part. The four test parts are scaled up 1.2, 1.4, and 1.6 times, by which the part volume, height vary accordingly. It is also noted that the length of repositioning toolpath in *XY* plane and *Z* axis are changed accordingly as well. Four levels of porosity, namely 25, 50, 75, and 100 % are used for each part volume and height variables. As a result, 64 experimental runs were required.

## 5.2 Experimental Results, Analysis, and Discussion

The actual build times were calculated by using the analytical model (Eq. 4). The regression analysis and ANOVA were carried out iteratively to obtain the model. The errors were analyzed by comparing the actual and the predicted build times to identify the importance of the interactions among the four control factors. By feeding back the error analysis, the final estimation model has been obtained, as depicted in Eq. 5 where, $\varepsilon$ is the uncertainty in the actual experiments.

$$T_a = 168.33 + 23.56V + 9.44H + 160.19V\rho + 78.17H\eta + \varepsilon \qquad (5)$$

The selected analysis results are shown in Table 2, which was obtained by fitting Eq. 5. Since the *P* values of part volume, the interaction of volume and porosity, height, and intermittent factor are significantly smaller than the threshold value of 5 % in the analysis, they are of primary significance. Among them, the interaction of volume and porosity is the most significant factor, followed by part volume. With respect to the regression confidence and the adjusted regression

**Table 2** Summary of the selected regression analysis results

| Variables | Standard deviation | t-stat | *P* value | *R* square (%) | Adjusted *R* square (%) | |
|---|---|---|---|---|---|---|
| Intercept | 27.76 | 0.61 | 0.55 | | | |
| Part volume (*V*) | 0.94 | 25.07 | <0.0001 | | | Significant |
| Part height (*H*) | 8.35 | 1.13 | 0.03 | | | |
| $V \times \rho$ | 0.50 | 318.60 | <0.0001 | | | Significant |
| $H \times \eta$ | 17.08 | 4.58 | <0.0001 | | | Significant |
| Regression model | | | | 99.981 | 99.980 | |

confidence, $R^2$, $(R^2)_{adj}$ and the difference between them indicates that the regression model is satisfactory.

The residual analysis was carried out for checking the adequacy of the developed estimation model. Figure 6a is the normal probability plot of the standardized residuals of the model. It is considered as satisfactory due to the standardized residuals that appear to fit the straight line well. Figure 6b shows the distribution of the standardized residuals versus the experiment numbers. No distinct pattern has been observed, revealing that the current model is appropriate and no further factors are required for describing the relationship between the input factors and the estimated times. Approximately 98.4 % of the standardized residuals fall in the interval (−2, +2), demonstrating that the errors are normally distributed. Nevertheless, it should also be noted that a standardized residual of 3.02 indicates the presence of an outlier. Thus, the parameters in the corresponding influential observation (experiment number 45) were traced back and the distance of the point from the average of all the points in the data set was recalculated. The results show that the outlier does not have a dramatic impact on the regression model and the error of 2.2 % in experiment 45 is acceptable. Due to the unknown reason that caused the high-standardized residual, more tests should be conducted to validate and evaluate the performance of the model, which will be presented in the next section.

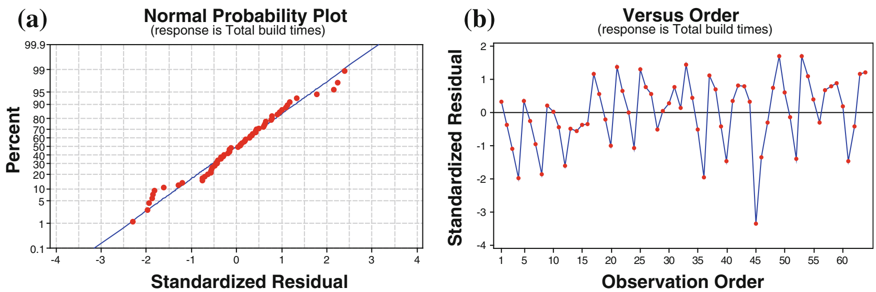


**Fig. 6** Statistical analysis plots: **a** normal probability plot of standardized residuals; (**b**) distribution of standardized residuals versus experiment number

However, it is noted that the errors tend to increase while the part volume is small (experiment 1–4, 17–20, 33–36, and 49–52). In addition, the original volumes of test part *III* and *VI* are small (less than 50 $cm^3$). As a result, the errors do not decrease significantly while the parts were scaled up 1.2 times. An exact reason cannot be provided but a possible reason is: for small parts where the volume does not exceed 100 $cm^3$, even though the number of repositioning and filament retraction times is kept unchanged, the length of repositioning toolpath is significantly shorter than that of the larger volume parts while the intermittent factors are identical. This may lead to the increase in error

## 6 Evaluation and Validation of the Build Time Estimation Model

After obtaining positive results from the previous experiments, three case studies were conducted for the evaluation and validation of the developed model. Three test parts are designed and modified, as shown in Fig. 7. Test part *VIII* and test part *IX* are modified from Kechagias et al. [5] and Zhou et al. [9], respectively, which contains nine features including planar face, boss, pocket, sphere, and chamfer. It was found that the majority of the estimation inaccuracy lies on producing parts with the volumes of less than 50 $cm^3$. Therefore, the volumes of test part *VII* and test part *IX* are specially designed to be less than 50 $cm^3$. Subsequently the three original test parts are scaled up 1.2, 1.4, and 1.6 times, generating 12 test parts with differing part volumes and heights. Due to the interaction of volume and porosity that is the most significant factor, 25, 50, 75, and 100 % levels of porosity are applied to these 12 test parts. To this end, a total of 48 test parts were defined.

The actual and estimated build times were calculated by using Eqs. 4 and 5, respectively. The percentage errors between the predicted and the actual build times are plotted in Fig. 8. The best results were obtained in the experiment runs 17–32 and there is no obvious fluctuation (less than 12 % error) in other experimental runs. The test parts in the experiments, 17–32 (test part *VIII* and variations) have low intermittent factor (less than 0.2), indicating short length of repositioning toolpath, relatively low number of repositioning and filament retraction times, as

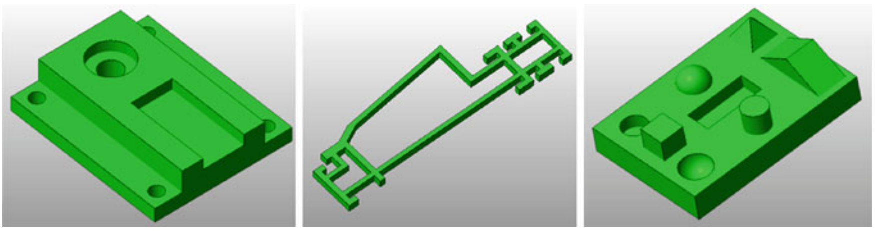

**Fig. 7** Test part *VII*, *VIII*, and *IX* (from *left* to *right*)

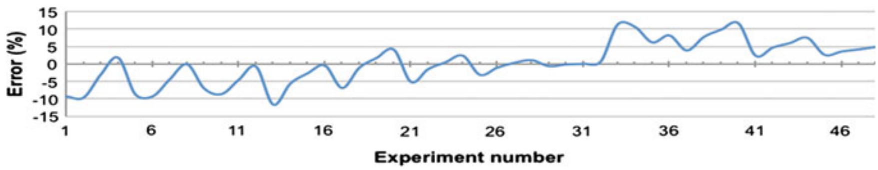


**Fig. 8** Percentage error between the estimated and actual build times

well as short resulting delay time during production. As a result, the resulting errors are reduced. In other words, the developed build time estimation model has better performance for the parts with low intermittent factor (<0.2). The predicted times tend to be longer than the actual times while the model is applied to the parts with high intermittent factor (>0.5). Paired *t*-tests were carried out for all the test parts at a 95 % confidence interval for the analysis of the differences between the estimated and actual build times. As *t*-stat is $0.748084 < t$ two-tail critical $= 2.011741$ ($\alpha = 0.05$), it can be concluded that the build time estimation model does not yield different results when compared to the actual times.

## 7 Discussion: Limitations of the Model and Future Applications

It has been identified that the proposed build time estimation model is able to predict build times and the predicted results do not have significant difference to the actual times. In comparison to other estimators [3–6], this developed build time estimation model offers a time-saving method, which only requires the dimensions of the part, i.e., 2D drawings. This eliminates considerable time used in generating 3D CAD models for each decomposed subparts, generating STL files, slicing, and post-processing them for build time calculation. Even though, the method has been applied solely to FFF/FDM process at present, the basic principle of using a 2D drawing to estimate build times is equally applicable to all additive processes.

However, certain issues should be addressed. Firstly, the model shows advantageous only for parts in which all the features involved are prismatic features. It is currently not suitable to be used for parts with sculptured surfaces because the intermittent factor cannot precisely represent the properties of such structures. As the iAtractive process is currently being developed for prismatic part production and the majority of engineering parts are prismatic or cylindrical, the estimated build times can be considered as being approximated to the actual times. In addition, a possible solution to enhance the functionality and accuracy of the model is to employ a correction factor used by Pham and Wang [4], which is partly dependent upon the ratio of the part (or parts) volume to the volume of a bounding box around the STL file.

## 8 Conclusions

This paper illustrates a methodology for developing a build time estimation model, which is used in the process planning algorithm for sequencing additive and subtractive operations in the hybrid process production. The methodology has also the potential to be used for other additive processes such as SLS and arc welding, which are two other common additive processes integrated in the hybrid processes. A theoretical model was first proposed, which was then used in the experimental design stage. Part volume, height, porosity, and intermittent factor together with their interactions have been identified as the most significant parameters that affect build times. The statistical analysis indicates that no significant difference was found between the estimated and actual build times. In addition, inaccuracy is likely to increase for parts with large intermittent factor (>0.5) or volume of less than 50 $cm^3$.

## References

1. Gibson I, Rosen DW, Stucker B (2009) Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. Springer, New York
2. Zhu Z, Dhokia V, Nassehi A, Newman ST (2013) A review of hybrid manufacturing processes—state of the art and future perspectives. Int J Comput Integr Manufact (in press)
3. Han WB, Fafari MA, Seyed K (2003) Process speeding up via deposition planning in fused deposition-based layered manufacturing processes. Rapid Prototyping J 9:212–218
4. Pham DT, Wang X (2000) Prediction and reduction of build times for the selective laser sintering process. Proc Inst Mech Eng Part B-J Eng Manuf 214:425–430
5. Kechagias J, Maropoulos S, Karagiannis S (2004) Process build-time estimator algorithm for laminated object manufacturing. Rapid Prototyping J 10:297–304
6. Campbell I, Combrinck J, de Beer D, Barnard L (2008) Stereolithography build time estimation based on volumetric calculations. Rapid Prototyping J 14:271–279
7. Zhu Z, Dhokia VG, Newman ST (2012) A novel process planning approach for hybrid manufacturing consisting of additive, subtractive and inspection processes. In: Proceedings of 2012 IEEE international conference on industrial engineering and engineering management (IEEM2012), Hong Kong, China, pp 1617–1621
8. Maropoulos PG, Baker RP, Paramor KYG (2000) Integration of tool selection with design—Part 2: aggregate machining time estimation. J Mater Process Technol 107:135–142
9. Zhou JG, Herscovici D, Chen CC (2000) Parametric process optimization to improve the accuracy of rapid prototyped stereolithography parts. Int J Mach Tools Manuf 40:363–379

# Capability-Based Approach for Evaluating the Impact of Product Requirement Changes on the Production System

**Eeva Järvenpää and Seppo Torvinen**

**Abstract** Change in the order requirements usually leads to changes in the production system that tries to meet these requirements. As changes always incur costs and take time, it would be important to be able to estimate the impact of the order requirement changes on the production system. This would facilitate the estimation of the effort and cost needed to accommodate these changes. This paper presents a preliminary method for evaluating the impact of change. The approach utilizes the previously developed capability model and capability matching framework, in order to define, how well the current production system satisfies the new requirements and what needs to be changed. The approach examines the topic from three aspects: the compatibility of the existing production system to the new requirements; the relative effort entailed in making the needed modifications to the system and; the utilization (re-usability) of the existing system for the new requirements. The aim of the approach is to help the decision maker in choosing and prioritizing between different product scenarios, which require changes to the system.

## 1 Introduction

The operation environment of today's production systems is highly volatile and rapidly changing. Change in the order requirements usually leads to changes in the system that tries to meet these requirements. One thing is evident: changes incur costs and take time. Therefore, it would be important to be able to estimate the impact of the change, in order to facilitate the estimation of the effort and cost needed to accommodate the changes. It would also help in choosing and

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prioritizing between different product scenarios which require changes. Eckert et al. [1] studied the impact of engineering design changes on the overall product design. They stated that in complex products with closely linked parts, changes to one part of the product often cause changes to another part, which in turn can propagate further change. Similarly, these product changes can impact on the production system components, which can in turn affect other system components. A change that may initially seem small and simple can cause complex modifications to other parts of the system.

There are many different methodologies for evaluating the impact of changes. Often though, these view the topic from the product development perspective, and evaluate the effects of engineering changes during the product's lifecycle or the propagation of changes within the product structure, as in Eckert et al. [1]. Other viewpoints taken by researchers are, for example, the impact of engineering changes on material planning, cf. Wanström and Jonsson [2], the impact on costs, cf. Oduguwa et al. [3], and the impact on the design process, cf. Terwiesch and Loch [4]. Attempts have also been made to evaluate and control the impact of product design changes on the production system using, for example, Design for Assembly (DFA) and Design for Manufacturing (DFM) methodologies [5]. Tolio et al. [6] presented an extensive review of approaches which try to tackle the co-evolution of products, processes, and systems from different perspectives. Lohtander and Varis [7] concentrated on global distributed manufacturing environments and highlighted the importance of knowing the manufacturing capabilities of available suppliers when making product design decisions.

This paper presents a preliminary method for evaluating the impact of product requirement changes on the production system. The approach utilizes the previously developed capability model and capability matching framework [8], in order to define, how well the current production system satisfies the new requirements and what needs to be changed. The approach is able to recognize the needed adaptation to the system in terms of the capabilities that needs to be added to the system in order to make it fully compatible with the new, changed, requirements. With this approach, it is possible to evaluate the impact of change from the technical point of view. Cost evaluations and investment calculations are not covered by this approach, yet the compatibility domain approach does provide valuable input data for such analysis. This is because, as stated by Eckert et al. [1], it is only after the impact of change has been evaluated that the time, cost, and resources can be allocated.

The paper is organized as follows. In Sect. 2 a short introduction to the capability-based adaptation is given to explain the background for the approach. Section 3 will then present the developed compatibility domain approach and apply it to a small case study. Finally, Sect. 4 will discuss the approach and conclude the paper.

## 2 Introduction to Capability-Based Adaptation

In the context of this paper, adaptation refers to changes the production system goes through during its lifecycle. The adaptation can be either physical (e.g., changing the layout of the system, adding or removing machines or machine elements), logical (e.g., changing the process sequence, re-routing or re-scheduling production) or parametric (changing the adjustable machine parameters, e.g., speed of a conveyor line) [8].

In capability-based adaptation, the product requirements are matched against the system capabilities and the system is adapted, until it satisfies the requirements of the product, i.e., until it is compatible with the new product requirements. Capabilities are functionalities of resources, such as drilling, milling, moving, and grasping. Capabilities have parameters, which present the technical properties and constraints of resources, such as speed, torque, payload, and so on. For example capability with concept name 'moving,' has parameters 'velocity' and 'acceleration.' The capability parameters allow determining which resource has the capability that best fits to the given product or production requirement. Capabilities are divided into simple capabilities and combined capabilities, where the combined capabilities are combinations of simple capabilities, usually formed by combinations of devices. Formal ontology (Core Ontology) [9] and a Knowledge Base (KB) [10] are used to model and manage this capability information, as well as the product related information. For more information about the capability model and combined capabilities, please refer to [11] and [8].

The core of the developed adaptation methodology lies in the capability-based matching of product requirements and system capabilities. The product requirements can be extracted from a 3D product model with a feature recognition and pre-process planning software [12], or they can be formulated manually, and then saved to the KB. The matching is performed according to the capability taxonomy and capability matching rules which connect the product and resource domains to each other. The taxonomy, included in the Core Ontology, is used to make a crude search that maps the resources with the required capabilities at a high level (capability concept name level), whereas the detailed reasoning with the capability parameters and combined capabilities is based on rule-based reasoning. This automatic matching procedure allows to filter the resource information and to aid the human designer by providing solution alternatives from vast amount of resource information. More details about the capability matching can be found from [13] and [8].

## 3 Compatibility Domain Approach: Evaluating the Compatibility, Effort, and Utilization

The compatibility domain approach concentrates on evaluating the impact of changes in the product requirements on the production system in terms of the new capabilities that need to be acquired to the system. The Venn diagrams in Fig. 1a show an example of the requirements for manufacturing different products (A1 and A2 are variants of the same product, while B is a completely different product). When shifting from the manufacture of one product to another, the size of the common requirements zone, or actually the area left out from the common requirements zone, gives an indication of the size of the needed change to the system. For example, it can often be assumed that the larger the requirement area of product B which does not intersect with the requirement area of product A1, the larger is the size of the needed change to the system, and the less compatible is the current system with the new requirements (Fig. 1b). This relation is not, however, directly proportional. It is close in case in which the original production system is designed and fixed for the original product, no flexibility (additional capabilities) is incorporated to the system, and the system has not undergone any changes from its original configuration. In this kind of situation the requirement area of the product A1 can be considered to represent the capabilities of the current system. However, if the system has more capabilities than are needed to manufacture the product A1 (e.g., a flexible or multifunctional system), it may be able to manufacture the next product without any physical changes, even if the product requirements have changed. Therefore, when considering the system compatibility to certain product requirements, the analysis can not rely on the comparison between the requirements of the subsequent products.

The compatibility domain approach examines the impact of change from three aspects: the compatibility of the existing production system to the new requirements; the relative effort entailed in making the needed modifications to the system; the utilization (re-usability) of the existing system for the new requirements. The definitions and details of these perspectives is given in the following sections.

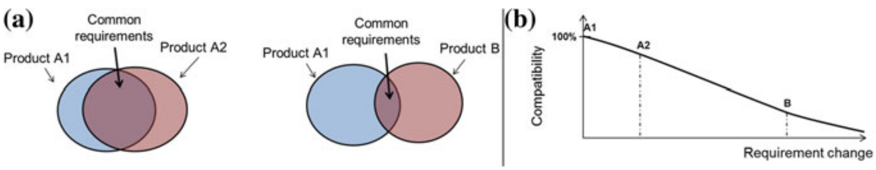



**Fig. 1** **a** Change in the product requirements causes change to the requirements targeted to the system; **b** Conceptual view of the compatibility versus requirement change [8]

## 3.1 Compatibility

Compatibility aims to present how compatible the current production system is with the new product requirements in terms of its capabilities. It represents the relative amount (in %) of the given product requirements that can be satisfied with the existing system in its current configuration. The configuration consists of physical, logical, and parametric aspects. The term "compatibility" doesn't refer to an optimal solution for the given requirement, but to an intersection, where the requirements and capabilities match in a technical sense and the system can continue its operation. If the system can satisfy all the capability requirements without any modifications, the compatibility is 100 %.

In order to visualize the compatibility domain concept and allow rough quantitative comparison of different product scenarios, a highly simplified mathematical formulation of the compatibility domain concept is constructed. The following factors defined in Table 1 and used in formulas (1–5) are considered.

The "PhysicModifCaps" and "ParamModifCaps" are included in the formulas in order to enable small adaptation actions, such as changing a tool or program to be taken into account. The coefficients 0.5 and 0.75 are adopted for capabilities requiring small physical changes or parametric changes, respectively, in order to consider, at a high-level, the fact that such capability modifications are less cumbersome than large physical adaptations, like changing complete machines. They allow differentiating the different types of adaptation in automatic analysis, which can be done based on the capability matching results and rules. In other words, they aim to give a very much simplified, rough estimate of the ease of the adaptation action in question. Other than that, the formula doesn't distinguish the

**Table 1** Factors used in the compatibility domain formulas [8]

| Factor | Definition |
|---|---|
| *ReqCaps(x)* | Number of capabilities required by the product *x* (1 capability = 1 point) |
| *ExistCaps(x, y)* | Number of existing capabilities in system *y* that fulfill some of the capability requirements of product *x* and are useable in the given situation (1 capability = 1 point) |
| *AllSystemCaps(y)* | Number of all the capabilities that exist in system *y* (1 capability = 1 point) |
| *PhysicModifCaps (x, y)* | Number of existing capabilities in system *y* that can be modified by small physical changes to be compatible with the requirements of product *x*, i.e., changing the simple capabilities it is composed of. These include only small changes, like changing the tool in the lathe. If the main device in the combination (lathe) needs to be changed, this won't apply. (1 capability = 0.5 × 1 point) |
| *ParamModifCaps (x, y)* | Number of existing capabilities in system *y* that can be modified by parametric or logical changes to be compatible with the requirements of product *x*, e.g., changing the speed of the robot. (1 capability = 0.75 × 1 point) |
| *NewReqCaps(x, y)* | Number of capabilities required by product *x* that don't exist in the system *y* (1 capability = 1 point) |

different capabilities that need to be adapted, but they all have the same value, regardless of their importance, size, price or any other parameter. Therefore all the changes have the same value in the graph, even though, in reality, some changes are more difficult, time consuming, and costly than others. Because these are impossible to estimate without real measured values and experiences, as noted in the industrial reconfiguration and re-use scenarios, the proposed compatibility domain approach only takes into account the ratio between the amount of required and provided capabilities. If more educated evaluations about the relative ease of the required capability adaptation are available, other coefficients than 1, 0.75, and 0.5 can be used in the formulas.

The compatibility of system y for the product x is calculated by the following formula:

$$Compatibility(x,y) = \frac{ExistCaps(x,y) + 0.5 * PhysicModifCaps(x,y) + 0.75 * ParamModifCaps(x,y)}{ReqCaps} * 100\,\% \quad (1)$$

Figure 1b shows an example of a "compatibility—requirement change" graph. The graph represents a conceptual view of the compatibility of the system to the requirements as changes in the requirements grow. In the graph the x-axis represents the change in the product requirements targeted at the production system. In the Venn diagrams, seen in Fig. 1a, the requirement change is represented by those areas which are outside the intersection of the two compared product requirements. The requirement change between two subsequent products, product A and B, is calculated as shown by the formula (2).

$$\mathrm{Re}quurementChange(A,B) = ReqCaps(A)not(B) + \mathrm{Re}qCaps(B)not(A) \quad (2)$$

The graph is drawn with an assumption that the system is fully compatible with the requirements set by product A1, and that it has no extra capabilities, i.e., the system was originally developed for product A1. In principle, the compatibility graph is a descending curve when the subsequent products are relatively similar, i.e., have similar amounts of required capabilities. However, the shape of the curve should not be generalized as it is easy to come up with special cases which won't fit this descending curve.

The greater the compatibility, the more requirements can be satisfied with the current system and the fewer the changes which are needed to the existing system. However, again, this comparison is valid only with very similar products, i.e., products having similar amounts of required capabilities. For example, two products may have the same compatibility, but completely different effort to modify the system to be able to produce the whole part. This is the case, for example, when product B has 20 required capabilities, of which 10 are satisfied, versus product C, with 2 required capabilities of which 1 is satisfied. In both cases the compatibility is 50 %, but the first one needs much more adaptation effort to be actually able to produce the product (10 new capabilities to be acquired for product B versus 1 capability for product C). The "compatibility—requirement change" graph is therefore only able to analyze what proportion of the product requirements can be satisfied in different cases, but not the actual effort of adapting the system to be fully compatible with the product requirements. Therefore the magnitude of the required change is formulated in Sect. 3.2.

If the new product has fewer requirements, none of which are additional to those needed for the original product, and the remaining requirements have similar capability parameters, the system is definitely able to cope with those new requirements and the compatibility is 100 %. However, it needs to be noted that even if the compatibility of the system is 100 %, it may not be an optimal way to produce the product. For example, if the production volume of this new, simpler product is high, it may not be cost efficient to occupy the whole system with excess capability in order to manufacture that product. This utilization aspect is considered in Sect. 3.3.

### 3.2 Effort: Magnitude of the Required Change to the System

The relative effort of an adaptation is here estimated as the relation between the missing capabilities (capabilities to be acquired) and all the existing capabilities in the system. Effort defines the relative amount of new capabilities (compared to all the existing system capabilities) that must be added to the current system in order to be able to produce the new product. It only considers the effort of making the system compatible with the new requirements, not removing the unused capabilities. In other words the effort is defined purely based on the new capabilities that need to be added to the system, i.e., the magnitude of the required change, and no other factors, such as ramp-up time and cost, are taken into account. Effort of making the current system y compatible with the new capability requirements of product B is calculated as shown by the formulas (3) and (4).

In which,

$$Effort(B, y) = \frac{NewReqCaps(B, y)}{AllSystemCaps(y)} * 100\,\% \tag{3}$$

$$\begin{aligned} NewReqCaps(B, y) = ReqCaps(B) - (&ExistCaps(B, y) + 0.5 * PhysicModifCaps(B, y) \\ &+ 0.75 * ParamModifCaps(B, y)) \end{aligned} \tag{4}$$

The procedure and complexity of an adaptation are not only strongly dependent on the type of change in the product requirements, but also on the type, architecture (e.g., line-type production or production cells) and degree of automation of the current system. For example, dealing with machining systems or automatic assembly systems are two completely different issues. For instance, if the product dimensions or geometry change, in machining it may just mean that the amount of material to be removed changes and all the resources are still compatible with the requirements, whereas in automatic assembly system it may affect to all the resources, such as robots, grippers, feeders, pallets, and trays. Therefore, when formulating the graphs and defining the new requirements, the propagation of the changes to the system requirements have to be taken into account. The value of new requirements cannot, therefore, be defined purely by the differences in the product characteristics, but the current system architecture also needs to be taken into account. For example, if a new process is required in addition to the old ones, new technology needs to be integrated into the existing system. Depending on the system architecture, this may result in more or less other requirements being placed on the system, which affects the overall magnitude of the required change. By determining the changes in requirements in relation to the existing system, the propagation of these changes can be taken into account.

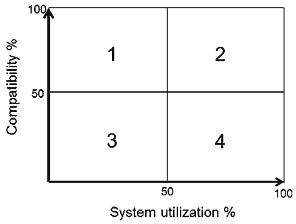
The effort is determined without considering the removal of unused capabilities. This is because the aim is to serve situations where the next order (the product to be produced and the required quantity) is unknown. Therefore, it is not necessarily wise to remove the unused capabilities from the system, because they may be needed for the next order. This is especially the case when the order sizes are small. Basically, the cost of occupying the unneeded capabilities depends on the lot size, the product manufacturing time, the situation, the order book and so on. How long will the system be occupied? What products need to be produced next? Do they need the capabilities that are about to be removed from the system? Could the unneeded devices be used in other stations at the same time? The incorporation of such factors into the method should be considered in the future in order to allow the knowledge or assumptions regarding future product scenarios to be taken into account during the adaptation planning.

## 3.3 Utilization of the Current System

Utilization of the current system shows what proportion of the current system's capabilities (in %) can be utilized (re-used) for producing the new product. Utilization of the current system y for producing product B is calculated as follows:

$$Utilization(B,y) = \frac{ExistCaps(B,y) + 0.5 * PhysicModifCaps(B,y) + 0.75 * ParamModifCaps(B,y)}{AllSystemCaps(y)} * 100\,\% \tag{5}$$

Based on the previous results, a "compatibility versus system utilization" graph can be drawn, as shown in Fig. 2. It allows the simultaneous estimation of how much of the product requirements can be satisfied with the current system, and how much of the current system's capabilities can be re-used without any modifications, in different product scenarios. Considering the system utilization is especially important if large volumes are produced. For example, it would be wasteful to occupy the whole system for a long period of time if only a few of the




The product scenarios analysed with this graph can be compared based on the four quadrants drawn on the graph:

1) Those product scenarios falling into quadrant 1 have strong compatibility with the current system, but the system has a lot of capabilities that are not utilized. Therefore these scenarios may be costly.
2) Products in quadrant 2 have strong compatibility with the current system and most of the system capabilities are utilized. This gives a rough indication that these products are the most feasible ones.
3) Product scenarios falling into quadrant 3 exhibit both weak compatibility and weak utilization and therefore they don't show much potential for re-using and adapting the existing system.
4) Product scenarios falling into quadrant 4 have weak compatibility with the existing system, but the system utilization would be strong. This in dicates that the existing system could be extended to meet the new requirements by adding new resources.

**Fig. 2** Compatibility versus system utilization graph and explanation of the quadrants

system's capabilities are being utilized. On the other hand, the profitability of the currently unneeded flexibility depends on the future product scenarios.

## *3.4 Case Study*

The following case study aims to demonstrate the use of the compatibility domain approach in a real production context. The original case product A is a cell phone, where four screws are to be screwed. The current production system is a flexible screwing system implemented in a TUT-microfactory module [12]. The change scenarios include situations in which the requirements targeted at the production system change. The original cell phone scenario is referred to as "product A," and the subsequent scenarios are named "product B," "product C," and so on. The change scenarios handled here include: Product C—Change in the screw size; Product E—New different parts added to the product; Product F—Screws replaced with new parts; Product G—A completely different product, Product H—Finishing pre-ready product. Table 2 presents first of all the components of the current production system and its capabilities. Secondly, it displays the capability requirements of the different selected product scenarios, from A to H, at the capability concept name level. The numbering after the required capabilities indicates the existing capability that fulfills the requirement. Required capabilities which don't exist in the current system or which need some change are written in *italics and underlined*. Figure 3a will then display the capability requirements of the product scenarios B, C, and D compared to product A in the form of Venn diagrams. The figure shows the common requirements zone, which represent similar capability requirements in the two products under comparison. The size of this zone is determined by the factors discussed in the previous sections.

In order to compare the relative effort of the needed adaptation between different product scenarios, the "compatibility—effort" graph was drawn, as shown in Fig. 3b. This graph clearly shows that the compatibility itself doesn't reveal much about the effort needed to modify the system when comparing very different

**Table 2** Existing system capabilities and capability requirements of different product scenarios

| System | Capabilities | Product A requirements | Product C requirements | Product E requirements | Product F requirements | Product G requirements | Product H requirements |
|---|---|---|---|---|---|---|---|
| TUT-micro-factory frame | attachmentFrame (1) | Module frame (1) | Module frame (1) | Module frame (1) | Module frame (1) | *Heating material* | Module frame (1) |
| | | Transporting (7) | Transporting (7) | Transporting (7) | Transporting (7) | *Injecting material* | *Transporting (7)* |
| Screwing robot | screwing (2), pickingUp (3), transporting (4), inserting (5) | Bulk feeding (6) | Bulk feeding (6) | Bulk feeding (6) | *Feeding* (*physicModif 6*) | *Molding* | ObjectRecognition (8) |
| Feeding system | plateFeeding (6) | PickingUp (3) (objectRecognition (10), orienting (12), positioning (11)) | PickingUp (3) (objectRecognition (10), orienting (12), positioning (11)) | PickingUp (3) (ObjectRecognition (10), Orienting (12), Positioning (11)) | *Disensing glue* (transporting (4), objectRecognition (8), positioning (9)) | *Cooling* | |
| | | | | | *PickingUp* | *Opening the mould* | |
| Belt conveyor | Transporting (7) | Inserting (5) (object recognition (8), positioning (9), transporting (4)) | Inserting (5) (object recognition (8), positioning (9), transporting (4)) | Inserting (5) (object Recognition (8), positioning (9), transporting (4)) | | *Releasing the part* | |
| Machine vision system 1 | ObjectRecognition (8), positioning (9) | Screwing (2) | *Screwing* (*physicModif 2*) | Screwing (2)<br>*Module frame* | Inserting (5) | *Transporting* | |
| Machine vision system 2 | ObjectRecognition (10), positioning (11), orienting (12) | | | *Transporting*<br>*Disensing glue (transporting, objectRecognition, positioning)*<br>*Feeding*<br>*Picking up*<br>*Inserting* | | | |

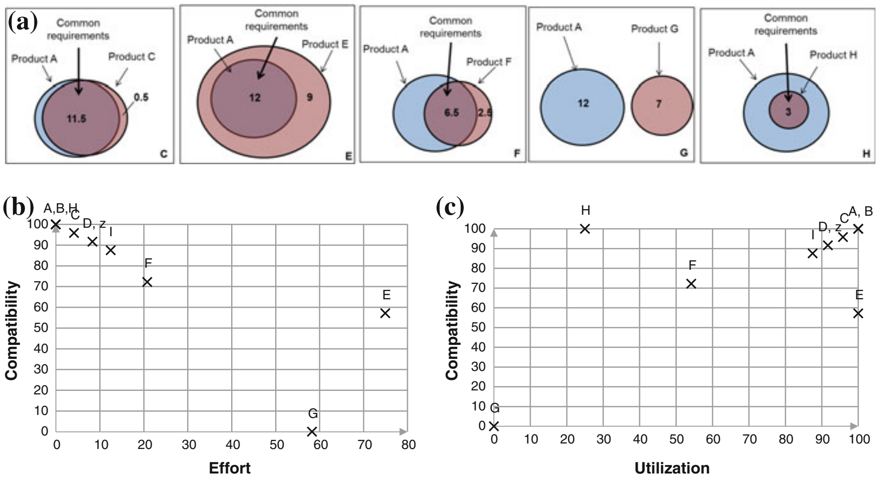



**Fig. 3** Compatibility domain approach applied to a case study. **a** Common requirement zone of different products with the product A; **b** Compatibility versus effort; **c** Compatibility versus utilization

products, i.e., products having different amounts of capability requirements. Examples of this are the products F, E, and G, whose amounts of required capabilities differ notably. The "compatibility—utilization" graph was drawn to be able to compare the product scenarios based on their compatibility and the re-usability of the existing system. The scenarios falling into the upper right corner represent "good cases," for which the compatibility is good and most of the system capabilities can be utilized. On the other hand, the scenarios in the lower left hand corner represent the "worst cases," for which no capability requirements can be satisfied with the current system and therefore the current system cannot be utilized. Scenario H represents a case where all the required capabilities exist in the current system, but only small number of all the capabilities offered by the system is utilized. The rest of the capabilities are "wasted." In contrast, scenario E represents a case where all the offered capabilities can be utilized, but more capabilities need to be acquired in order to satisfy all the requirements.

## 4 Discussion and Conclusions

The presented compatibility domain approach views the impact of product requirement changes on production system from three viewpoints, namely compatibility, effort, and utilization. The first views the problem more from the product perspective, whereas the latter two view it from the system perspective. The last two diagrams facilitate the comparison of different product scenarios in regard to the needed adaptation effort and the re-usability of the system. The approach utilizes the existing resource capability descriptions and the capability matching framework, in order to identify those resources or points in the system where adaptation activities are needed. The emphasis has been on finding the intersection where the product requirements and the current system capabilities match, and evaluating any differences. Although the developed methodology concentrates only on defining the required changes to the system hardware, it also opens up the possibility to roughly estimate the time and money that need to be invested by providing the required input information in terms of new capabilities that need to be added to the system. Therefore, it facilitates further calculations and decision-making regarding the production system adaptation.

The presented approach is an initial attempt to try to model the impact on product requirement changes on production system, and it is built to complement the capability-based adaptation methodology developed earlier. Therefore it has some restrictions and limitations that need to be taken into account. First of all, the values given by the presented formulas of compatibility, effort, and utilization by no means represent absolute values for these three concepts. Instead they provide an estimate of the relative effects of change, and are intended to facilitate a rough comparison between different product scenarios especially during automatic analysis, which is done based on the capability matching results. They help to evaluate the effect of different product decisions on a system within a product family. In order to evaluate the real effort and cost of the required adaptation, the nature of the specific adaptation activities needs to be considered. For example, the number of required changes may be similar in two completely different cases, one requiring the replacement of devices, and the other requiring the addition of new devices. In the latter case, it is also likely that there is a requirement for additional space, which may need to be acquired. Therefore, in the latter case, the effort and cost incurred by the change may be greater. Currently, this approach evaluates only the relative amount of the required adaptation activities, differentiated through both the large and small physical changes, as well as the logical and parametric adaptation actions. The required effort is defined based on the new capabilities that need to be added to the system, and no other factors, such as system ramp-up time and cost, are taken into account at present. Also it doesn't take into consideration that some capabilities may be acquired by changing only one resource of the whole system (in very rare case).

One major issue at the start of the compatibility formulation is the granularity (i.e., level of detail) of the representation of the required and existing capabilities. It is important that the granularity of the capabilities is similar in the scenarios under comparison, in order to insure the validity of the comparison. In the presented case study, the application of the compatibility domain approach is fully controlled by human designer, and is therefore highly subjective. Thus, even though the graphs give quantitative estimates of the compatibility, effort, and utilization, the estimates should be considered more as qualitative than quantitative analyses. They don't provide absolute values for the impact of the changes, but they do enable relative comparisons between similar cases. The reliability of the proposed method should be analyzed by testing it with multiple real industrial case studies.

## References


1. Eckert C, Clarkson PJ, Zanker W (2004) Change and customisation in complex engineering domains. Res Eng Des 15(1):1–21
2. Wänström C, Jonsson P (2006) The impact of engineering changes on materials planning. J Manuf Technol Manag 17(5):561–584
3. Oduguwa PA, Roy R, Sackett PJ (2006) Cost impact analysis of requirement changes in the automotive industry: a case study. Proc Inst Mech Eng, Part B: J Eng Manuf 220(9):1509–1525
4. Terwiesch C, Loch CH (1999) Managing the Process of Engineering Change Orders: The Case of the Climate Control System in Automobile Development. J Prod Innov Manage 16(2):160–172
5. Boothroyd G, Dewhurst P, Knight W (2002) Product design for manufacture and assembly, 2nd edn. CRC Press, Boca Raton, p 720
6. Tolio T, Ceglarek D, ElMaraghy HA, Fischer A, Hu SJ, Laperrière L, Newman ST, Váncza J (2010) SPECIES—co-evolution of products, processes and production systems. CIRP Ann Manuf Technol 59(2):672–693
7. Lohtander M, Varis J (2012) Collecting manufacturing information in a global distributed manufacturing environment. Mechanika 18(1):84–88
8. Järvenpää E (2012) Capability-based adaptation of production systems in a changing environment. PhD thesis, Tampere University of Technology, Tampere
9. Lanz M, Kallela T, Velez G, Tuokko R (2008) Product, process and system ontologies and knowledge base for managing knowledge between different clients. IEEE Int Conf Distrib Human-Mach Syst 2008:508–513
10. Lanz M, Rodriguez R, Luostarinen P, Tuokko R (2010) Neutral interface for assembly and manufacturing related knowledge exchange in heterogeneous design environment. In: Ratchev S (ed) Precision assembly technologies and systems. Springer, New York, pp 21–29
11. Järvenpää E, Luostarinen P, Lanz M, Tuokko R (2011) Presenting capabilities of resources and resource combinations to support production system adaptation. IEEE Int Symp Assembly Manuf (ISAM) 6
12. Garcia F, Lanz M, Järvenpää E, Tuokko R (2011) Process planning based on feature recognition method. IEEE Int Symp Assembly Manuf (ISAM), p 5
13. Järvenpää E, Luostarinen P, Lanz M, Tuokko R (2012) Development of a rule-base for matching product requirements against resource capabilities in an adaptive production system. The 22nd international conference on flexible automation and intelligent manufacturing, FAIM 2012, 10–13 June 2012, Helsinki, Finland, pp 449–456

# Manufacturing Processes Design with UML and ERP Standard: A Case Study

**Agnieszka Stachowiak, Izabela Kudelska and Adam Radecki**

**Abstract** The following paper is to introduce an approach to production process design based on Enterprise Resource Planning (ERP) standard and benefiting from UML (Unified Modeling Language) standard. The goal of the paper is to present methodology and tools for designing, optimization and implementation of manufacturing and service processes with unified language UML and ERP standards. The paper is organized in two main sections. In the first one MRP/ERP standard is briefly described and OMG-UML/RUP (Object Management Group-Unified Modeling Language/Rational Unified Process) is introduced. In the second a case study on company representing food industry is developed to present some examples of object-oriented modeling based on UML standard. The case study object is a company representing food industry, which makes manufacturing processes it performs really sensitive for health, safety and hygiene issues on one hand and cost efficiency on the other, resulting in necessity of holistic and multi criteria approach, provided by ERP standard application, necessary.

## 1 Introduction

Companies may differ with scope of activities, providing services, manufacturing or combining these actions, as well as with advance in technology, starting with basic computer support or High-Tech solutions and working on Virtual Enterprises bases. Requirements toward design, optimization and implementation of processes depend on the type of a company and its technological level. The requirements generate numerous decision problems referring to costs area and including application costs, development and implementation of "zero costs" approach, Intelligent Manufacturing System application for modeler development to

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guarantee fast reaction of the system to changes in environment of small and medium enterprises, ERP (Enterprise Resource Planning) standard development, upgrading ITIL/ITSM (Information Technology Infrastructure Library/IT Service Management) to IT systems etc. [1]

Processes of analysis, design and programing to be used and presented in the following paper are supported with CASE methods which enable automated support within the entire cycle of system development: starting with analysis, through design and programing and finishing with implementation and exploitation supervision. The important element of CASE tools is the procedure of model examination that provides early errors detection.

There are numerous CASE packages available on the market. They differ with notation and partially with description of meanings and actions—generally with package semantics. These products can be divided into three groups:

- Upper Case
- Lower Case
- I-Case—Integrated Case

Processes mutually cooperating and modeled with unified methodology can be referred to as integrated processes. Integration is generally multi-directional and can follow various routines, namely:

- integration of manufacturing processes for both discrete and continuous production,
- integration of processes concerning mapping of core processes, HRM (Human Resource Management) systems modeling and Work Flow systems.

Realization of integration approaches presented above will be executed with integrated processes methodology OMG-UML/RUP (Object Management Group-Unified Modeling Language/Rational Unified Process) presented in the paper.

The goal of the paper is to present methodology and tools for designing, optimization and implementation of manufacturing and service processes with unified language UML and ERP standards. The paper is organized in two main sections. In the first one well-known MRP/ERP standard is briefly described and OMG-UML/RUP is introduced. In the second a case study on company representing food industry is developed to present some examples of object-oriented modeling based on Unified Modeling Language (UML) standard.

## 2 Material Requirements Planning and OMG-UML/RUP Standard

Material Requirements Planning (MRP) is formal and computerized approach to stock planning, manufacturing and purchasing scheduling and to general planning in enterprises. Thanks to the system, users are equipped with information on timing and quantities of requirements which enables generation of orders and re-planning of requirements already satisfied. Opposite to traditional control systems, MRP reacts to problems or difficulties earlier—basing on historical data on requirements for parts or components at higher assembly level. MRP methodology is known for over sixty years, as it was developed in fifties of XX century, but it was popularized in 80s and upgraded to MRPII—Manufacturing Resource Planning [2].

Basic functions MRPII standards include these of MRP and others to enlarge its scope from materials to manufacturing resources, i.e.: sales planning, production planning at minimum stock possible, orders receiving, control of material and technical inputs, stock management and management at minimum cost possible and finances management in terms of continuous providing information on production costs per unit. Because of successful use of the approach and increasing complexity of organizations and business the need to increase capabilities of MRPII appeared. Hence, the next upgrade developed was Enterprise Resource Planning (ERP) standard, which includes holistic approach to finance management, introduction of quality management issues, tooling management elements, maintenance aspects. What is more the system of multi facilities management was developed with introduction of Supply Chain Management Issues (SCM) [3]. Nowadays in Poland MRPII/ERP standard is successfully implemented in small and medium enterprises using internet services. Its functional range is increasing and more attention is paid to services management.

Development of methods and tools of object-oriented modeling, their osmosis, has led to necessity of standardization of processes supporting computer systems modeling. Perfect solution would be elimination from modeling process a semantic gap between organization and information system and OMG-UML/RUP standard is believed to be the solution closest to this problem elimination [4].

The abbreviation refers to the following aspects:

Object Management Group was developed by three methodologists who accepted UML as unified language of modeling and system's lifecycle management method called RUP (Rational Modeling Language).

Unified Modeling Language is a language for IT systems modeling. Using this graphic language for visualization it is possible to develop and document IT systems. Symbols are dedicated to elements and connected in diagrams, enabling description of general models as well as detailed ones. UML diagrams can be used for developing models of the designed system at various levels of complexity and for efficient communication and mutual comprehension of experts from numerous fields.

Rational Unified Process (RUP) is a process that manages modeled system's lifecycle. It is based on iterative and incrementing system's lifecycle. It is two dimensional: in horizontal position it includes phases, iterations and check points (this is how time factor is reflected), while in vertical position is presents statistical aspects of IT system development process [3, 4]

OMG-UML/RUP standard introduces four methods for description of system behavior in four orientation platforms including time, message, event and activity.

The first diagrams presenting time orientation are referred to as sequence diagrams, cooperation diagrams represent message orientation, while state diagrams represent orientation to events. Activities are presented in action diagrams.

## 3 Company and Market Analysis

The enterprise in a producer of sweets in podkarpackie voivodship.

Environment significantly influences company's performance. One of the methods to analyze company's performance is analysis of five Porter's forces (check Fig. 1).

The market environment in which company is working is very competitive, companies aiming to attract and keep the largest number of customers possible manufacture products of high quality or sophisticated taste to meet customers' needs and expectations. What is more, manufacturers often compete with prices even though it is harmful for the entire sector.

High entrance barriers are of mostly economic character—founding a new company is a cost-consuming project, cost of purchasing innovative technologies is high, as well as cost of machinery modernization or access to functioning distribution channels. All these factors make entering to any market difficult to new producers. Economic factors are reinforced with diversity of products available on the market and recognizable and well –established brands appreciated by customers.

Wholesalers are a strong group of customers as they order large quantities of product at the same time striving for the best conditions of contracts concerning prices decrease with simultaneous increase of either service level or quality of products. Additionally customers have large choice of potential suppliers as there are many producers of chocolate sweets competing against each other and cost of changing supplier is small or none.

The sweets market the company is operating on is composed of numerous potential suppliers who can provide manufacturers with all the components

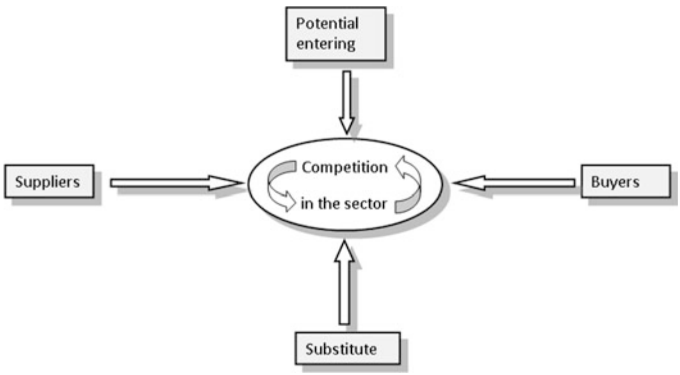


**Fig. 1** Sector driving forces. *Source* own work

necessary to execute production of chocolate products (including powder milk, sugar, nuts etc.). The large number of suppliers results in decrease of market force of individual suppliers and makes the producer quite demanding concerning quality, prices and logistics issues. The very important element of company's strategy is not making long-term contracts with their suppliers, which makes the company relatively independent from suppliers and able to choose partners meeting all the criteria and requirements defined.

The market of sweets is attractive which can contribute to increased risk of introduction of substitutes—products which are to some extent similar to these manufactured by the company presented and discussed in the paper.

### *3.1 Production*

Chocolate manufacturing process is multi stage and time consuming, it takes usually several days. It starts with cleaning and drying cocoa seeds to decrease their humidity. The next stage is selection, which is simply removing seeds that do not qualify for further processing. Selected seeds are roasted which is short (max 30 min) explosion to high temperature to eliminate water and increase aroma. Roasted seeds are rapidly cooled to avoid their spontaneous roasting. To take the seeds out of shells it is necessary to peel them. The next stage is separation—seeds are grinded at the temperature of 70 °C. the output of this process is fluid cocoa substance which is pressed to obtain fat called cocoa butter. At this stage of chocolate production the most important resource is a machine—so called melanger, responsible for blending components until they are homogenous. The next stage is pressing—chocolate mass is pressed with couple of presses, one rotating faster than the previous, which makes structure more homogenous as well. After that chocolate mass is mixed at high temperature for couple of days. This process leads to improvement of taste and aroma. The next stage is cooling, necessary to form chocolate products. Forming is the last stage of chocolate productions.

## 4 Case Study—Model of Processes in Company

The case study introduced presents the example of modeling processes developed for a company representing food industry. The case study is focused on presentation of key processes of the company with diagrams of use case. The second area of modeling is behavior of the system which is reflected with system dynamics and introduced with diagrams of activities and diagrams of sequence. Notation and presentation of modeled structures is prepared according to OMG-UML/RUP standard.

CASE Study Standard is presented in the development of a set of mutually integrated drawing tools made using Visio Professional.

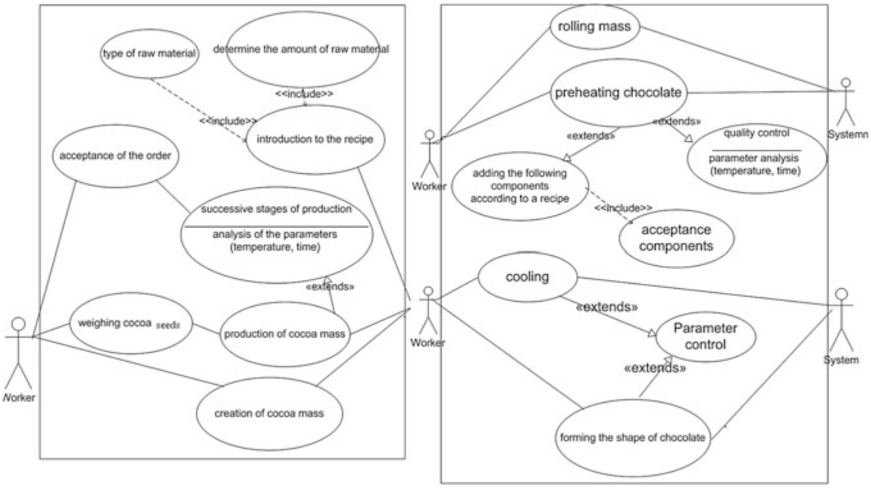


**Fig. 2** Diagram of use case. *Source* own work

## *4.1 Modeling Processes with UML*

The first diagram presents behavior of the system from user's point of view. It shows interactions between the system and external units (check Fig. 2).

The next diagram is a diagram of sequence presenting cooperation between objects and messages sent between them (check Fig. 3). The diagram used to model dynamic aspects of the system is diagram of activities (check Fig. 4).

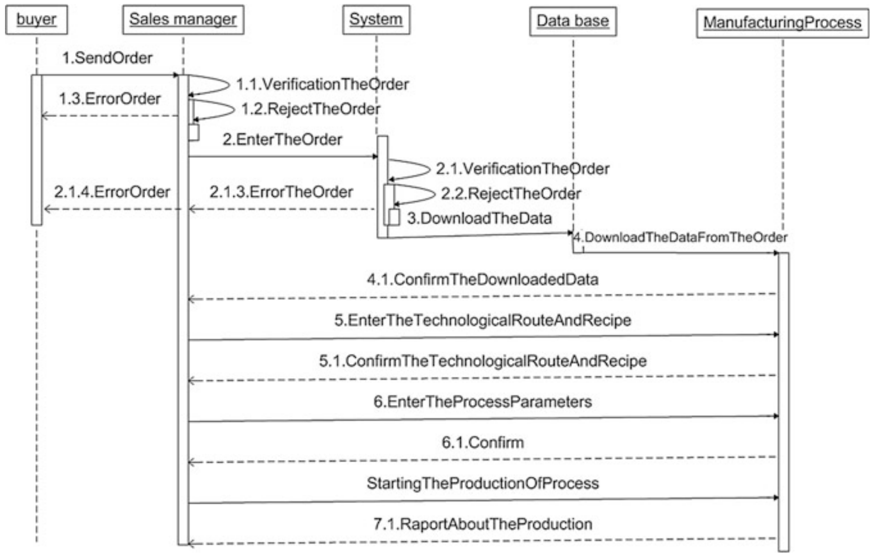


**Fig. 3** Diagram of sequences. *Source* own work

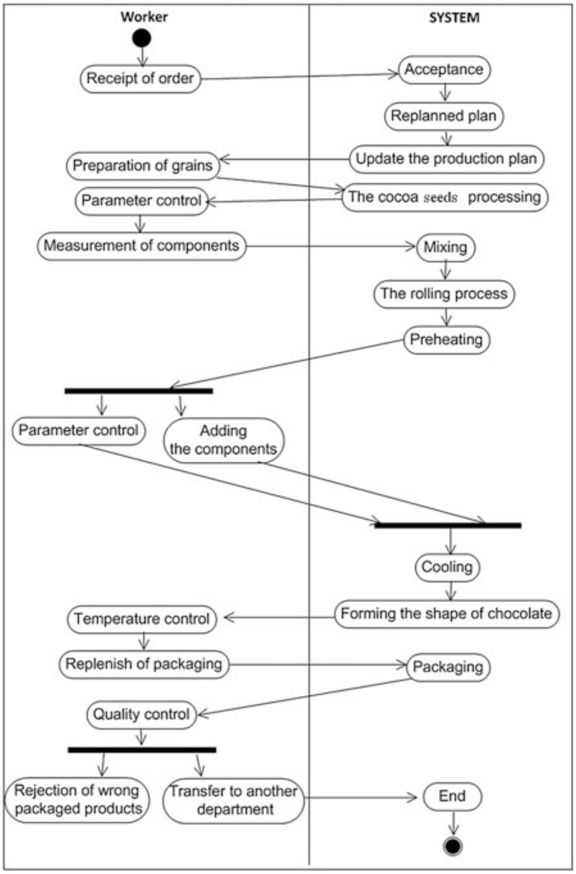


**Fig. 4** Diagram of activities. *Source* own work

## *4.2 Processes in ERP System*

The model of processes is defined with object-oriented methodology. It presents the map of processes while the net of processes is referred to requirements of the real system. Requirements are rekorder with Visio Profesional [1].

The simulation presented includes the set of processes of reference model of an ERP system referred to the company mentioned above and diagrams modeled (Figs. 5, 6).

# 5 Summary

The important characteristics of each IT system is its efficient performance, however, this is not the only issue that should be considered. Adaptability which is simply ability to adjust to unavoidable changes in business functioning seems to be

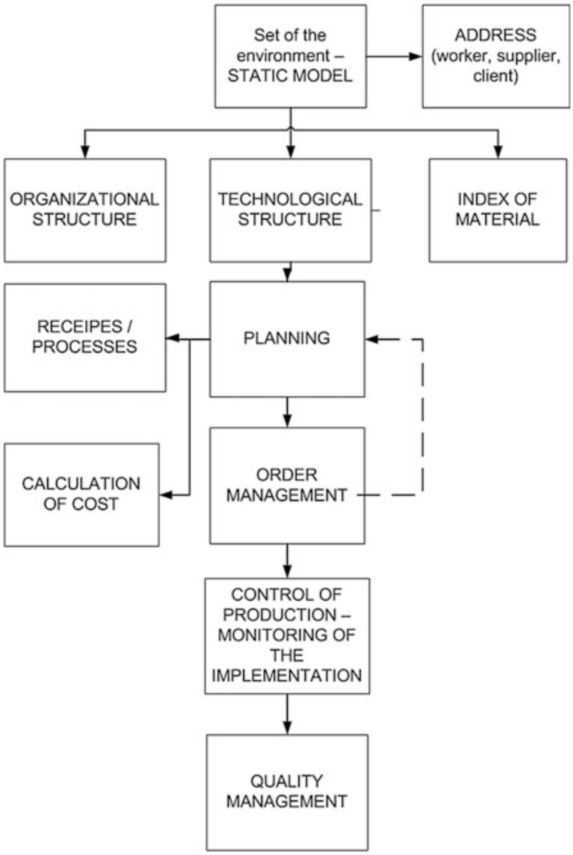


**Fig. 5** ERP structure in production management—reference models. *Source* own work

crucial as well. Some time, i.e. two years after launching the system and its implementation it is necessary to assess its performance, usability and usefulness. The questions to be answered include identification of the level in which the system supports goals defined at the very beginning of the implementation process. The outcome of the assessment is simply definition of further changes and improvements of the IT system to be introduced, analyzed and applied.

An important feature of the use of UML is definitely visualization and animation work the design of computer system. Construction of a computer system should be made only after a thorough analysis of requirements and verification of UML models prepared.

The company analyzed in the paper implemented ERP class system to improve its processes, mostly those of planning, production performance and costs calculation. Clear definition of materials to be used in production, warehousing and opportunity to check stock levels at any time allows the company to forecast material requirements for each production task and make purchases when necessary. The result is decreased amount of money frozen in stocked assortment.

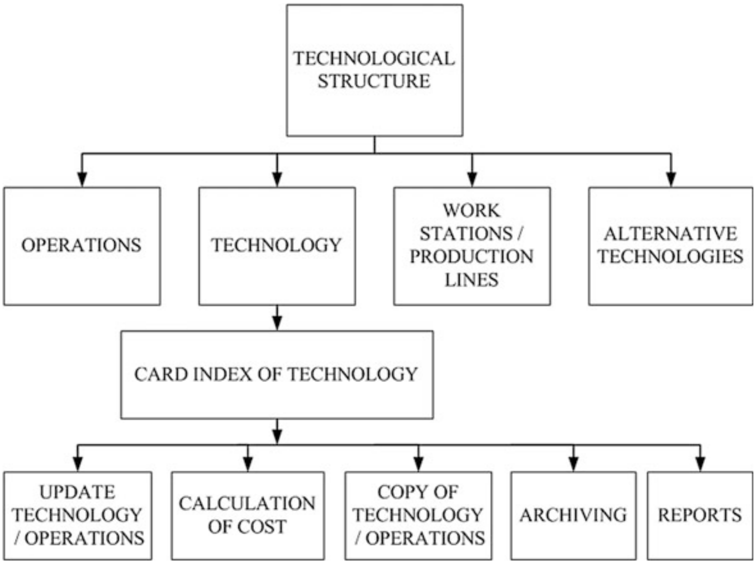


**Fig. 6** Manufacturing reference models—technological structure. *Source* own work

Benefits of ERP implementation in the area of production and warehouse:

- Fast data exchange.
- Coordination of all means of production, including machine and equipment.
- Continuity of production.
- Reducing stock levels to a minimum.
- Full transparency of production costs.

What is more, the company implemented human resources management mode, stock management mode and payroll mode which enabled integration of processes within company. Hence, processes previously supported with various IT solutions now are integrated.

Authors are aware that the area of designing processes with UML and ERP standard is a large one and it is not and cannot be fully described in hereby paper, however, they believe that the case study introduced presents both UML and ERP. The issue discuss is a vast one, hence only small part of material flows was analyzed in predefined company but the idea was to choose the subject of the case so that it could present range, scope and benefits from the tools used in the best way possible.

## References


1. Schneider G, Winters JP (2001) Applying use cases a practical guide, 2nd edn. Addison-Wesley, Reading
2. Oleśków Szłapka J, Pawlewski P, Fertsch M Limitations and performance of MRPII/ERP systems—significant contribution of AI technoloques. 19th international conference on production research
3. Yourdon E, Argila C (2000) Analiza obiektowa I projektowanie. Wydawnictwo Naukowo Techniczne, Warszawa
4. Szumański Zb (2010) Projektowanie i wdrażanie procesów produkcyjnych I usługowych z zastosowaniem języka UML oraz standardu ERP. Oficyna Wydawnicza Politechniki Warszawskiej,Warszawa
5. Henderson-Sellers B, Collins G, Graham I (2001) UML-compatible processes. In: Proceedings of the 34th Hawaii international conference on system sciences—2001, IEEE Computer Society, Hawaii
6. Dąbrowski W, Stasiak A, Wolski M (2007) Modelowanie systemów informatycznych w języku UML 2.1. Wydawnictwo Naukowe PWN SA, Warszawa
7. Kudelska I (2011) RUP methodology and UML language in the creation of computer system in food—agricultural enterprise. In: Jałowiecki P, Orłowski A (eds) Information system in management computer aided logistics, Warsaw University of Life Sciences Press (SGGW), Department of Informatics, Warsaw, pp 57–67
8. Orlicky J (1981) Planowanie Potrzeb Materiałowych. Państwowe Wydawnictwo Ekonomiczne, Warszawa
9. Wight O (1984) Manufacturing resource planning: MRP II. Oliver Wight Limited Publications

# FMEA as Applied to Electronic Manufacturing: A Revised Approach to Develop a More Robust and Optimized Solution

J. Enright, H. Lewis and A. Ryan

**Abstract** Failure Mode and Effect Analysis (FMEA) is a proactive tool used to identify, evaluate and prioritize potential weakness or failure modes in a given system. As with any methodology, familiarity leads to scrutiny. The more a particular method is utilized, the more questions are asked and inevitably the more weaknesses are found. The FMEA is no different. From its early stages of development with NASA, the FMEA has evolved into an industry accepted methodology used across varied fields from pharmaceutical, to militarily to automotive. It is this widespread use which has exposed the FMEA to various questions and critics. This paper will discuss a body of research which aims to dissect the FMEA process with particular focus on the perceived weaknesses documented in the available literature. Following a full and detailed literature review, the next phase of this research work will be to identify an optimum FMEA solution for use in the Electronics Manufacturing industry. All findings, recommendations and modifications will be trialed and proven in a high volume automotive electronic manufacturing environment across a number of global manufacturing sites.

## 1 Introduction

Before any attempts can be made to mitigate or control a failure mode, it is imperative that the risk is thoroughly assessed. Assuming the risk analysis methods were sound and comprehensive in identifying all relevant failure modes, the next,

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and perhaps most critical step in any risk management procedure is to assess the potential risk of each failure mode. As discussed by Pollock [1], the two critical elements to be considered as part of any risk assessment process are the probabilities of the risk occurring and the severity of the risk should it occur. Armed with accurate detail on both these elements an organization can make an informed decision on what steps to take next.

As a risk assessor it is imperative to appreciate not only the importance of these two elements but also their interdependency. The assessor must be in a position to recommend where best to spend an organizations resources with regard to risk mitigation. Consideration must be given as to the importance of spending vast amounts of time and money trying to prevent a defect which, if it happens, may result in serious consequences at the end customer but has of yet as never or at worse very rarely happens, or is it more appropriate to spend the resource on smaller issues which regularly impact on the customer and causes continued annoyance?

Before the assessor can make these critical decisions, he/she needs to accurately evaluate and prioritize all potential risks. Failure Mode Effect Analysis (FMEA) is an industry accepted methodology [2] specifically developed for the purpose of risk assessment.

FMEA is a methodology or tool used to drive and document the evaluation of potential failure modes based on three criteria: the severity of a risk should it occur, the frequency which the identified failure mode is likely to occur, and the systems or controls which are in place to detect the risk should it occur. Using predefined rankings, quantitative values can be assigned to each of the three decision criteria enabling an overall sore, or risk priority number (RPN) to be applied to each identified failure mode. Using the RPN all potential failure modes can be prioritized according to the level of risk to which they expose the user or organization. Armed with this information, risk control measures, be they risk avoidance, risk mitigation or risk acceptance, can be put in place.

Like any improvement activity, FMEA should be applied as early in a given process as possible. While the methodology can certainly be successfully employed at any maturity level, the advantage of starting at the earliest possible stage is that the user or organization will not have to commit resources, be they time, money or personnel, to a process or product with will later be found to be potentially flawed resulting is the requirement for costly rework, redesign or reprocessing.

Figure 1 shows a typical product/process development life cycle from concept through to the full scale production/operations. Where possible the FMEA process should be employed from phase 1 of the above cycle. The purpose of the FMEA is to optimize the product or process at as early a stage as possible. Being a proactive tool, the FMEA aims to review where potential problems may be encountered and put the relevant containments/redesigns in place before the event. This vision or philosophy must be instilled from the very beginning. Inevitably not all failure modes will be visible from the conceptual stage which means the FMEA must be

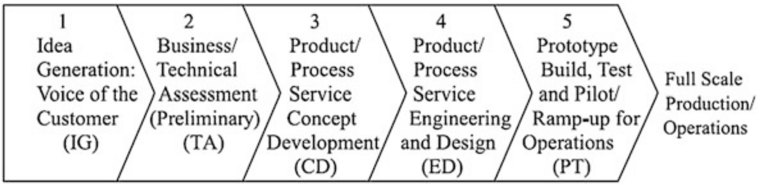


**Fig. 1** Product/process development cycle [21]

**Table 1** Different types of FMEA

| FMEA type | Where applicable |
|---|---|
| System FMEA | Sometimes referred to as a concept FMEA, this is applied at the very early design stages concentrating failure modes between the functions of the systems and the sub-systems [22] |
| Design/product FMEA | Applied at the design stage of a product life cycle, the design FMEA reviews the system at a component level for design characteristics which may later cause issue for product performance [23] |
| Process FMEA | The process FMEA is applied to the manufacturing process as opposed to the product. Typically the PFMEA will review the key parameters in accessing the risk involved in the manufacturing process [24] |
| Service FMEA | Service FMEA focuses on field service after sales. Areas like after sales service, spare parts, etc. [25] |
| Software FMEA | Software FMEA is essentially a Deign FMEA for reviewing the functionality of software modules |

revised at each stage of the development process and, periodically during full scale production/operations.

Further to "when to apply the FMEA", there is also the consideration as to what type of FMEA to apply. While the fundamental structures and approach remain constant, the review scope or the review field will determine the type of FMEA employed. Table 1 gives and overview of the available FMEA types.

As with any methodology, familiarity leads to scrutiny. The more a particular method is utilized, the more questions are asked and inevitably the more weaknesses are found. The FMEA is no different. From it's early stages of development with NASA, the FMEA has evolved into an industry accepted methodology used across varied fields from pharmaceutical, to militarily and automotive. It is this widespread use which has exposed the FMEA to various questions and critics.

## 2 FMEA Weaknesses

In his 1993 article Gilchrist [3] presented a critical review of the FMEA and in particular the use of the RPN to rank failures. He points out that using the product of the three attributes, severity, occurrence and detection to calculate a ranking

**Fig. 2** Combination of S, O, and D yielding an RPN of 64

| Severity | Occurrence | Detection |
|---|---|---|
| 1 | 8 | 8 |
| 2 | 4 | 8 |
| 2 | 8 | 4 |
| 4 | 2 | 8 |
| 4 | 4 | 4 |
| 4 | 8 | 2 |
| 8 | 1 | 8 |
| 8 | 2 | 4 |
| 8 | 4 | 2 |
| 8 | 8 | 1 |

score for a given failure mode is inaccurate due to the non-linear method of scoring the occurrence element of the equation and the linear method of scoring the detection element. Further more, he points out that different failure modes, having very different characteristics and different impacts on the three attributes making up the RPN, can mathematically be expressed as the same RPN value (See Fig. 2). For example, consider failure mode A with a severity score of 2, an occurrence rating of 6 and a detection rating of 5. This gives a RPN rating of 60 to failure mode A. Now consider failure mode B. This failure mode has a severity score of 5, occurrence score of 3 and a detection score of 4. Like failure mode A, failure mode B also has a RPN rating of 60 despite the significant difference in attribute scores. The Ford FMEA handbook [4] define a severity score of 2 as a slight annoyance, where as a score of 5 is classified as customer dissatisfaction. Gilchrist argues that a system which considered failure mode A and failure B as equals, is a flawed system.

While the limitation of the RPN as a prioritization method has been documented by Carmignani [5–7], Bowles in his 2003 [8] review perhaps best describes the pitfalls of the RPN from a numerical view point. Starting by defining the four different measurement scales, Nominal, Ordinal, Equal Interval and Ratio measurements, Bowles continues to segregate the three RPN attributes of severity, occurrence and detection into their respective properties. He proposes that severity is at most an Ordinal scale based on a subjective judgement and assigned a ranking 1–10. The occurrence scale provides an Interval measure for the lower scales but then changes to an Ordinal measure toward the top end of the scale. While detection can be classified as an ordinal measurement, it is again extremely subjective relying heavily on the expertise of the assessment team members. Respective of the fact that almost all of the three measurements can be described as Ordinal measurements, Bowles proposes that applying a multiplication operation to a set of Ordinal values is essentially meaningless as it cannot be assumed that they all have the same interval value. Ultimately he hypothesizes that the RPN formula is incorrect and not a reliable source for prioritization failure modes.

A review of the RPN scale by Sankar and Prabhu [9] highlight some fundamental problems which further expose the RPN ranking system as a flawed system. The conventional approach assumes a linear evenly distributed numeric scale.

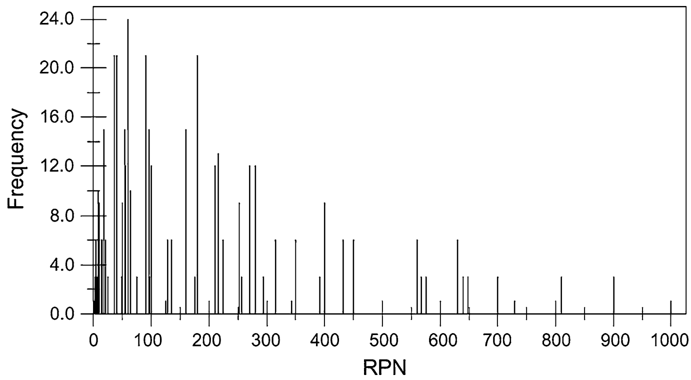


**Fig. 3** Histogram of RPN numbers generated from all possible combinations of severity, occurrence, and detection [22]

Sankar and Prabhu aside from discussing some of issues previously pointed out by Gilchrist et al. such as failure modes with different attributes having the same RPN value, explore the scale of possibilities suggested by the RPN scale of 1—1,000. Rational thinking would lend to the belief that the closer you get to an RPN value of 1,000, the greater the risk factor. Similar thinking would suggest that a RPN rating of 800 would be worse than a rating of 400 by a factor of 2. Sankar and Prabhu prove this not to be the case. An analysis of the scale shows that of the various resulting outcomes from the RPN equation, there are only 120 unique outcomes possible, certain outcomes can be repeated up to 24 times and the mean value attainable is 166. Figure 3 shows a pareto distribution of all possible RPN results. This graphical representation further illustrates the inaccuracies in using the current RPN method as a failure mode prioritization method.

The proposed alternative by Sankar and Prabhu is a risk priority rank (RPR) to represent the increasing risk associated with the severity, occurrence and detection combinations. This proposed alternative still assigns an integer from 1 to 1000 to each failure mode to indicate priority, but instead of relying on the sum of the three attributes, numbers are assigned based on expert knowledge and the application of a series of conditional If/Then rules.

Bowles, based on his findings suggests that at minimum the RPN value should be viewed as an ordinal measurement and to discard any analysis which tries to compare failure modes based on their corresponding RPN value. Additionally, in Bowles's view, the Detection attribute should be removed from the RPN calculation because of it subjectiveness and the fact that it can be a misleading function which can be misinterpreted leading to a false sense of security. Further to this Bowles believes that using the RPN simply as an ordinal measurement but in conjunction with a cost factor (ratio measurement) would make it a far more usable function.

Culminating the above points and the fact that the FMEA and corresponding RPN views a failure mode as a singular event as opposed to the potential of a singular failure mode causing multiple failures at the customer, Gilchrist defines an alternative, and in his view, a more accurate FMEA model which he expresses as the expected cost (EC).

$$\mathrm{EC} = \mathrm{CnP_f P_d}$$

The expected cost model considers the probability of the customer receiving a defective unit as $P_f P_d$, the product of $P_f$, the probability of the failure occurring and $P_d$, the probability of the failure occurring and not being detected. To address some of his concerns with regard to the conventional RPN, Gilchrist includes a cost per failure (C) and the number of items produced (n) to complete his model.

Ben-Daya and Abdul Raouf [10] while acknowledging Gilchrist's observations and proposal, suggested that the expected cost model was itself flawed. Yes it addressed a number of issues with the conventional RPN, but it fails to consider what Ben-Daya and Abdul Raouf consider to be one of the major drawbacks of the RPN, the weightings associated with severity, occurrence and detection. They suggest that the occurrence factor determines the likelihood of a defect escaping to the customer and as such should be awarded a higher weighting. Their proposed solution is to rate occurrence using a larger interval. The rating scale in the interval (0–9) helps identify the chance of the defect occurring, however, the scores that goes toward the PRN calculation is a power of 2 in the interval (1–512).

Wang et al. [11] proposes the application of fuzzy logic to formulize the linguistic terms used in the classification of severity, occurrence and detection. While the RPN is a very crisp numerical value assigned to a failure mode, the accuracy of this value can be questioned considering the individual scorings may have been more qualitative than quantitative. Bowles and Pelaez [12] among others have presented fuzzy logic as a valuable tool to over come the gap between qualitative and quantitative, thus allowing accurate evaluations.

The concept of fuzzy logic has been successfully used as a foundation in the attempts to improve the current FMEA methodology [13]. Braglia et al. [14] proposed a multi attribute decision making approach called fuzzy TOPSIS (Technique Ordered Preference by Similarity to the Ideal Solution). Their fuzzy version of TOPSIS allows for the weightings of severity, occurrence and detection to be evaluated using triangular fuzzy numbers. Chang et al. [15] used fuzzy linguistic terms to evaluate severity, occurrence and detect before using the Gray theory to determine the risk priorities of potential causes.

From reviewing the available literature, the applicable of fuzzy logic to complex FMEAs is a process which demands high expertise and experience in developing the required fuzzy rule set. The more complex the system under review the more rules required and hence the more complex fuzzy system. Like the FMEA itself, a fuzzy logic system demanding large rule bases can become a drain on resources and as a result fail. Wang et al. [11] proposed a solution to this by replacing the required rule knowledge base, and even the reduced rule knowledge base as proposed by some fuzzy logic FMEA approaches, and replacing it with a fuzzy weighted geometric mean (FWGM) for risk evaluation and prioritization of failure modes.

Like Wang et al.; Gracia et al. [16] put forward a fuzzy logic proposal to accommodate the linguistic terms favored by consulting experts when assessing failure modes as part of the FMEA process. Further more, they also acknowledge the short comings of the fuzzy logic system when considering the effort required to generate a complete set of rules necessary to evaluate the combinations of fuzzy inputs. To address this, their proposal combines the techniques of fuzzy logic and Data Envelopment Analysis (DEA) to establish a new failure mode ranking. To further emphasis the relevance for DEA, Chin et al. [17] proposed DEA for prioritizing failure modes (albeit with fuzzy logic).

Chin et al. [18] suggests that little or no attention is paid to the diversity and uncertainly of the assessment information used to complete the FMEA. If the assessment information is incorrect or inaccurate, all resulting decisions and actions will be jeopardized. While best practice when completing FMEAs is to employ cross function, inter departmental teams to ensure the participation of a wide knowledge base of experience and skill, this in itself can introduce concerns. Different team members will invariability bring different opinions and agendas, possibility providing different or even conflicting views on the same issue based on their unique experience and background [19]. Chin et al. propose using group evidential reasoning (ER) to develop a new FMEA model based on belief structures.

Continuing on the theme of human participation and the inherent limitation which this introduces, Bluvband and Grabov [20] put forward a number observations. They propose that the common practice of brain storming is not the most effective method of identifying all relevant failure modes. As a solution they suggest a 10-point check list to prompt an FMEA team to ask the right questions. Having accurately identified failure modes, the next concern for Bluvband and Grabov was the process of ranking severity, occurrence and detection on a team bases. Inevitably, with a group or team of people there will be difference of opinion with regard to ranks. Again the authors suggest a series of guidelines to aid the FMEA team in coming to an accurate agreement.

## 3 Proposed Research Questions

Of the available literature, the vast majority of critiques and commentators focus on the limitations and draw backs associated with the front end process or the process of identifying, assessing and prioritizing the various failures modes. As already discussed in detail, yes there are limitations to most methods of identifying failure modes, be they check lists, brain storming sessions or expert knowledge. Similarly, the current RPN prioritizing process is flawed both as a numerical exercise and as a subjective analysis approach.

While this research acknowledges and concurs with the findings of the literature review, the author proposes taking a different view of the FMEA process. Yes, it is important to correctly identify all relevant failures modes and equally important to attempt to rank them in some form of ordered fashion, but ultimately this is a administrative exercise. For an organization to gain benefit from the FMEA process real actions need to be put in place to address real issues causing problem for both the organization internally through costly rework and/or downtime, and at the customer through potential business losing warranty returns.

As such this research will propose utilizing the existing assessment and prioritization approach as simply a method of identifying and documenting all failures modes and their associated risks. The author will focus on the latter stage FMEA activity associated with corrective actions and explore two hypotheses:

- Corrective Action Prioritization as a result of economic factors
- Corrective Action Feedback Loop with a view to linking the existing RPN number to both an upper and lower Key Risk Indicator.

While it is accepted and acknowledged that the FMEA is a worth while exercise, the documented drawback, limitations and preconceptions do manifest themselves in practical applications of the FMEA. This fact is further supported from the results of an internal training questionnaire issued by the author where 83 % of participants believed that the FMEA is a time consuming and unwieldy exercise, and 66 % were concerned that there is no structure in place to manage the mitigating actions. Now more so than ever because of the economic climate, the resistance to FMEAs will be heightened meaning alternatives approaches need to be considered to convince management of the true benefits. Based on industry experience and following a detailed review of the available literature, alternative methods of prioritizing corrective actions are required. Yes in an ideal world with limitless resources all failure modes should have a corrective action applied to them, however, when each corrective action costs money or places further demands on already limited recourses, management will need to consider what are the benefits, the pay backs and the long term strategies associated with each corrective action.

This research will review what if any options are available from current literature before introducing and trialling various alternatives with regard to resource costing, probability of success based on corrective actions, interdependency of corrective actions, cost to the customer etc. The proposed outcome of this research will be a mathematical formula which can be applied to a given corrective action to determine its viability. This proposed formula will then be proven across multiple automotive electronic manufacturing sites.

Justifying the application of corrective actions is necessary, but ultimately is a further resource drain unless combined with a dynamic and live FMEA process. This research body will propose and trial a means of linking the initial process FMEA RPN scores to a defined set of process key risk indicators (KPI). By outlining a range, defined by both an upper and lower KPI value, for which the current corrective action is keeping the process at an acceptable performance level, any deviation outside of the defined KPI levels will trigger a requirement to review and potentially update the relevant FMEA.

## 4 Summary

While the FMEA as a risk assessment tool is proven and utilized across multi-disciplinary fields over a range of industrial sectors, it is not without it's critiques. A literature review will uncover a comprehensive body of research documenting flaws in the FMEA process from the methods of identifying failure modes, to the methods documenting the severity and impact of the said failure modes. Perhaps the most debated element of the FMEA process in the development and application of the Risk Priority Number (RPN). While acknowledging the research work done to date, the author believes that while the accuracy of the FMEA process in prioritizing failure modes is important, the application of the relevant corrective actions is more important and more beneficial to the organization employing the FMEA. As such the author is proposing a body of research where two hypotheses are explored; Corrective Action Prioritization as a result of economic factors, and Corrective Action Feedback Loop with a view to linking the existing RPN number to both an upper and lower Key Risk Indicator. Both will be trialling in electronic manufacturing sites to validate their merits.

## References


1. Pollock S (2005) Create a simply framework to validate FMEA performance. ASQ Six Sigma Forum Mag 4(4):27–34
2. Deepti V, Ramanamurthy N, Balasubramanian KU (2004) Effective risk management: risk analysis using an enhanced FMEA technique. In: Proceedings of annual project management leadership conference, India
3. Gilchrist W (1993) Modelling failure modes and effects analysis. Int J Qual Reliab Manag 10(5):16–23
4. Ford Motor Company (2004) FMEA handbook, Version 4.1
5. Carmignani G An integrated structural framework to cost-based FMECA: the priority-cost FMECA. Reliab Eng Syst Safety 94(4):861–871
6. Chen JK (2007) Utility priority number evaluation for FMEA. J Fail Anal Prev 7(5):321–328
7. Narayanagounder S, Gurusami K (2009) A new approach for prioritization of failure modes in design FMEA using ANOVA. In: Proceedings of world academy of science: engineering and technology, vol 49, pp 524–531
8. Bowles JB (2003) An assessment of RPN prioritization in a failure modes effects and criticality analysis. Reliab Maintainability Symp 380–386
9. Sankar NR, Prabhu BS (2001) Modified approach for prioritization of failures in a system failure mode and effects analysis. Int J Qual Reliab Manag 18(3):324–335
10. Ben-Daya M, Raouf A (1996) A revised failure mode and effects analysis model. Int J Qual Reliab Manag 13(1):43–47

11. Wang YM, Chin KS, Kwai Poon GK, Yang JB (2009) Risk evaluation in failure mode and effects analysis using fuzzy weighted geometric mean. Expert Syst Appl 36:1195–1207
12. Bowles JB, Pelaez CE (1995) Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. Reliab Eng Syst Saf 50:203–213
13. Kieselbach R (1997) Systematic failure analysis using fault tree and fuzzy logic. Technol, Law Insur 2:13–20
14. Braglia M, Frosolini M, Montanari R (2003) Fuzzy TOPSIS approach for failure mode, effects and criticality analysis. Qual Reliab Eng Int 19:425–443
15. Chang CL, Wei CC, Lee YH (1999) Failure mode and effects analysis using fuzzy method and grey theory. Kybernetes 28:1072–1080
16. Garcia P, Schirru R, Frutuoso E, Melo P (2005) A fuzzy data envelopment analysis approach for FMEA. Prog Nucl Energy 46(3–4):359–373
17. Chin KS, Wang YM, Poon G, Yang JB (2009) Failure mode and effects analysis by data envelopment analysis. Decis Support Syst 48:246–256
18. Chin KS, Wang YM, Poon G, Yang JB (2009) Failure mode and effects analysis using a group-based evidential reasoning approach. Comput Oper Res 36:1768–1779
19. Naude P, Lockett G, Holmes K (1997) A case study of strategic engineering decision making using judgmental modeling and psychological profiling. IEEE Trans Eng Manag 44(3):237–244
20. Bluvband Z, Grabov P (2009) Failure analysis of FMEA. Reliability and maintainability symposium, pp 344–347
21. Yang J, Yu L (2005) Electronic new product development—a conceptual framework. Ind Manag Data Syst 102(3):218–225
22. Stamatis DH (2003) Failure mode and effect analysis: FMEA from theory to execution. ASQ Quality Press
23. Naagarazan RS, Arivalagan AA (2005) Total quality management. New Age International Publisher, New Delhi
24. Perry RC, Bacon DW (2007) Commercializing great products with design for six sigma. Prentice-Hall, Englewood Cliffs
25. Dyadem Press (2003) Guideline for failure mode and effect analysis, for automotive, aerospace and general manufacturing industries, Dyadem Press

# Simulation of the Pneumatic Behavior in the Virtual Commissioning of Automated Assembly Systems

**Anton Strahilov, Dennis Effmert and A. N. Other**

**Abstract** Currently, the development of complex automated production stations will almost be impossible without the use of computer aided simulation. So as to increase the reliability of such simulations, the simulation models must depict the reality as much as possible. Including the physical properties of the elements in the models allows for an increase in realism of the simulation. One of the aspects in this field is the pneumatic behavior of pneumatic drives. Using physics based simulation approaches of the video game industry, a real-time assembly station simulation for the virtual commissioning considering the pneumatic behavior of the pneumatic drive was developed. This paper presents how the underlying model was developed and the extent to which different simulation factors have an influence on the pneumatic behavior.

## 1 Introduction

The automated realization of assembly processes is becoming more important for the cost effective production of a company [1]. For these companies the increasing amount of new product variants [2] which are produced at the same time as the existing product variants by the same automated assembly station, represents a new challenge in which the quality of the produced goods needs to be guaranteed at all times [2]. In order to be able to manage this challenge, companies rely on simulation models which make it possible to validate the functions of an automated assembly station on an early development stage [2] (Fig. 1).

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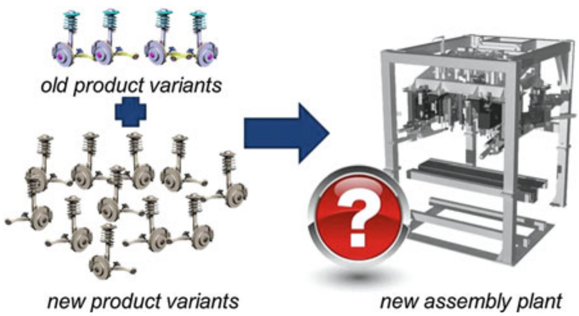



**Fig. 1** Production of old and new product variants at a new product station

One of the methods to accomplish this is virtual commissioning. In order to be able to increase the use of this simulation method, the applied simulation models need to resemble reality to the greatest possible extent [3]. One possibility for doing so is offered by the inclusion of physical characteristics in these simulation models. Several approaches demonstrate how the physical characteristics can be included when analyzing the physical behavior of assembly components [4, 5]. Kinematics, dynamics, and the station components' forces rank among these. The physical behavior of actuators is, among others, of main interest for the virtual commissioning. In general, these actuators are used to accomplish well-directed movements of the assembly components. For doing so the dynamics of the assembly components is monitored through the actuators, e.g., power and moments. Both electrical and pneumatic actuators are usually used, e.g., servo motors or pneumatic cylinders. For the scope of this paper the pneumatic actuators are of special interest. Furthermore the difficulty when operating these pneumatic actuators is explained in detail. The pneumatic model which has been developed for the virtual commissioning will also be introduced. Based on this model, a prototypical implementation is presented, where physics engines typically used in the computer game industry are used.

## 2 Motivation

Generally for the movement in automated assembly stations pneumatic actuators are used. The reasons for this are, among others, the simple realization of linear movements [6]. Through the well-directed injection of transmission fluid (air) in the pneumatic actuator, dynamics and kinematics of the actuator are controlled, such as, e.g., power and speed of the piston. Forces and moments originating in the assembly components also influence the physical behavior of pneumatic actuators. As a consequence the assembly components' forces and moments considerably influence the speed of the pneumatic actuator and hereby also the duration of the assembly process. Figure 2 shows the forces of a pneumatic actuator in a schematic manner.

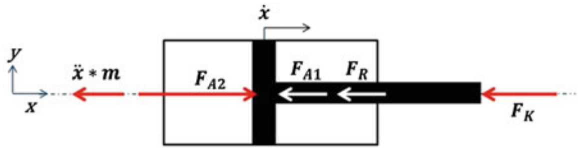



**Fig. 2** Forces which act upon the piston

When solving the equilibrium equation of the forces which act along the x-axis the acceleration $\ddot{x}$ against the extrinsic power $F_K$ can be determined.

$$\ddot{x} = \frac{F_{A2} - F_{A1} - F_k - F_R}{m} \tag{1}$$

In order to be able to move the piston to the right side, the condition $F_{A2} > F_{A1} + F_K + F_R$ needs to be fulfilled. Let us assume that the extrinsic power $F_K$ would increase, provided that $F_{A2}, F_{A1}$ and $F_R$ stay the same, the acceleration $\ddot{x}$ of the piston and therefore its speed $\dot{x}$ would be reduced (1). The actual difficulty during virtual commissioning is to consider the extrinsic power which depends on the dynamics of the assembly components. Moreover the duration of the piston movement depends directly from its speed.

Usually, the forces $F_{A1}$ and $F_{A2}$ are assumed to remain constant, the reality though is that these forces depend on the chamber pressure [7]. Furthermore the air in the chambers is compressible, thus the pressure in the chamber cannot be constant [6, 7]. The extrinsic force hereby plays a fundamental role on the chamber pressure. Based on this the forces during virtual commissioning would also need to be considered. In order to be able to do so, the physical behavior of the assembly components needs to be considered.

In the virtual commissioning of automated assembly stations these influencing factors are currently not considered. Usually a constant speed is assumed and therefore the duration of the movement is pre-defined. This assumption limits the validity of the simulation model and hinders the early detection of mistakes which can be traced back to the physical behavior of the pneumatics actuators. For instance, a typical mistake is a position that cannot be reached by a pneumatic actuator, due to unforeseen changes in the extrinsic force.

## 3 Basics

### *3.1 Fluid Mechanics*

Fluid mechanics deal with the behavior of fluids, i.e., liquids and gases. Fluid mechanics can be classified into hydromechanics (fluids) and pneumatics (gases) [8]. For the scope of this work the basics of pneumatics are defined, as these are important when describing the pneumatic behavior of pneumatic actuators (Fig. 3).

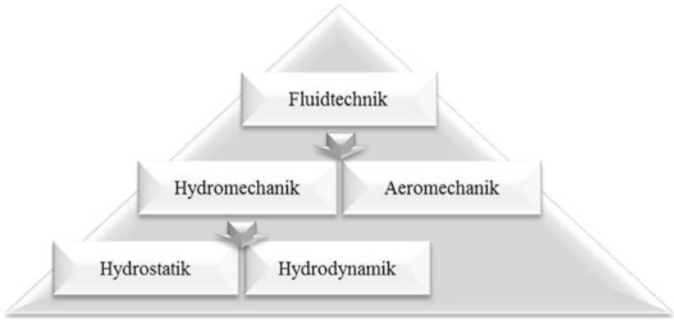



**Fig. 3** Classification of fluid technology

## *3.2 Equation of State of an Ideal Gas*

With the help of this equation of state and under the assumption that the system is closed the dependency between the parameters pressure p, volume V and temperature T can be determined [6].

$$p \cdot V = m \cdot R \cdot T \tag{2}$$

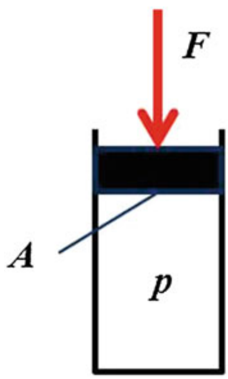
where $m$ is the mass and $R$ the universal gas constant

## *3.3 Pressure in a Closed System*

In Fig. 4 a closed system is depicted. The pressure exerted on the system depends on the ratio of the applied force to the piston area [6–8].

$$p = \frac{F}{A} \tag{3}$$

**Fig. 4** Pressure in a closed system



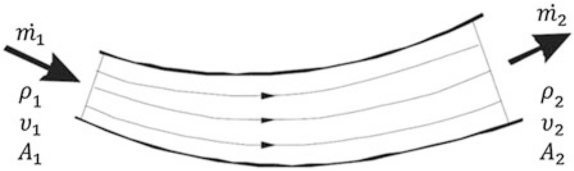



**Fig. 5** Stationary flow system [6]

## 3.4 *Law of Conversation of Mass*

The Law of conversation of mass states that the mass which enters the system minus the mass leaving it is equal to the mass which is inside the system at any given point [7].

$$\int_A \rho \cdot v \cdot dA + \frac{d}{dt} \int_V \rho \cdot dV = 0 \tag{4}$$

Figure 5 illustrates a stationary flow system.

The mass $m_1$ which flows into the system can be expressed by:

$$\dot{m}_1 = \rho_1 \cdot v_1 \cdot A_1 \tag{5}$$

And the escaping mass $m_2$ by:

$$\dot{m}_2 = \rho_2 \cdot v_2 \cdot A_2 \tag{6}$$

where $\rho$ is the mass density and $v$ is the gas' speed over the cross section $A$. Assuming that no mass can accumulate inside the system the Eq. (4) can be simplified as follows:

$$\dot{m}_1 - \dot{m}_2 = 0 \tag{7}$$

Hereby the mass density $\rho$ of the gas proportionally depends on the pressure inside the system [6].

$$\rho = \frac{p}{R \cdot T} \tag{8}$$

## 3.5 *Pneumatic Actuators*

Pneumatic actuators are designed to convert the performance gathered from the compressed air reservoir into a mechanic one [6, 9, 10] (Fig. 7). In general pneumatic actuators are used for rotary and linear motions. Typical example of this is the linear pneumatic actuators, also known as pneumatic cylinders. A simple representation of such a pneumatic cylinder is shown in Fig. 6.

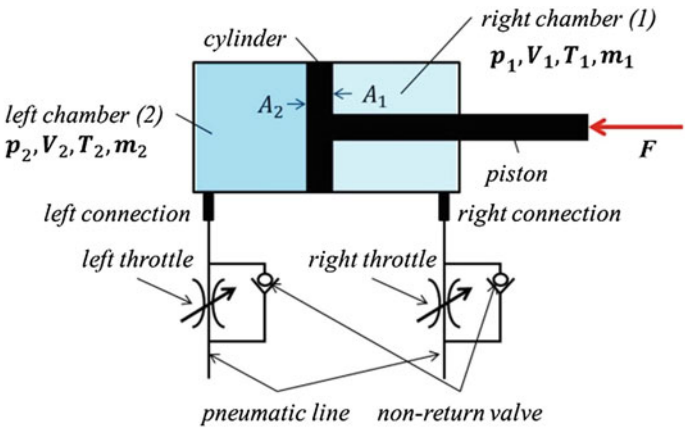



**Fig. 6** Representation of a pneumatic cylinder [6]

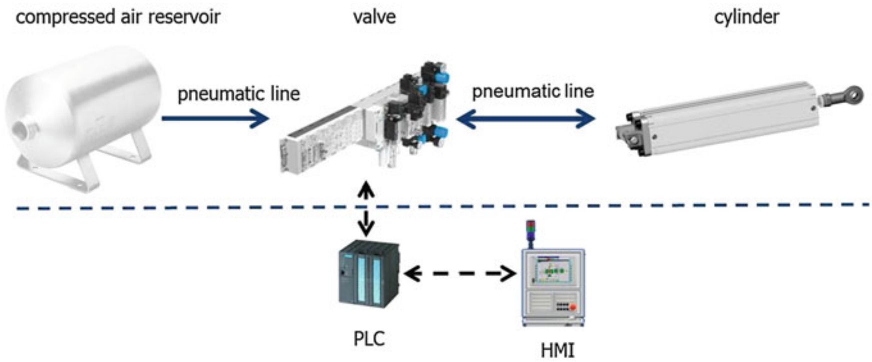



**Fig. 7** Architecture of a pneumatic cylinder, regulated through PLC

Pneumatic cylinders generally consist of a rigid cylinder and a mobile piston. Between cylinder and piston two chambers are formed—one left chamber and one right chamber. By means of non-return valves the gas is delivered into these chambers and conducted away from them. The speed is regulated by the so-called throttle valve. For the left and the right chamber the throttle and the non-return valves are connected in series (see Fig. 6). It is their task to limit the flow stream which is delivered to and taken away from the chambers. This way the speed of the piston is determined. The actual controlling of the individual chamber is realized through the valves, so that the air supply to the chambers is switched on or off. The transmission of the gas from the valve to the connections occurs with the help of pneumatic lines [1] (Fig. 7).

The gas flowing into the chamber is gathered from a compressed air reservoir with the help of a valve. The air is already compressed to a certain pressure $p_A$ $(6 - 10\ bar)$ [6]. This pressure is relative to the atmospheric pressure $p_U(1\ bar)$

and is called operating pressure. Furthermore it is assumed that the operating pressure is constant.

Due to the throttle valve a certain time is needed before the pressure in the chamber reaches the operating pressure. The piston only starts moving when the force which is originated by the operating pressure overcomes the external forces, such as for example friction forces, weight, etc.

# 4 State of the Art

## *4.1 Physics Engines*

Physics engines are software libraries which provide various functions in order to simulate the physical behavior of objects [4, 11]. They have been developed for the computer game industry in order to increase the realistic approach of the games [12]. For doing so, algorithms have been developed which detect collisions between two bodies in real-time and treat them according to physical laws [4, 11]. In order to enable real-time capability during this process, simplified convex, i.e., non-concave, collision bodies are generated from the geometric models. This simplification is accomplished by the physics-engines [11, 12]. In this way the geometry and the mass of the object as well as its friction coefficient can be considered [12]. Based on this it is possible to use functions that make possible to simulate the kinematics of the objects.

Successful applications of these physics-engines for the mechatronical validation of production lines are presented in [4, 13] and [5]. IT tools have also been developed which make it possible to use the functions of the physics-engines for industry. Some of them also offer the possibility to be used for virtual commissioning (e.g., IndustrialPhysics). Real-time collision detection and management are of special interest for this paper. This is important because during virtual commissioning the behavior of pneumatic actuators under the influence of external forces needs to be correctly depicted.

## *4.2 Virtual Commissioning*

In [14] virtual commissioning is presented as a method of validation of the PLC program even before the real commissioning takes place. When using virtual commissioning a model of the plant, the so-called mechatronic plant model is needed. This model is classified into the expanded 3D geometry model and the behavior model. The expanded 3D geometry model thereby serves for the motion visualization of the plant components without considering their physical behavior. An expansion of the mechanic model by adding the collision model is presented in [4], the so-called physics-based plant model. With the help of this model collision detection and management under consideration of the physical characteristics becomes possible. This is based on the 3D geometry of the expanded 3D geometry model.

There are also other IT tools which have been developed particularly for the simulation of fluid systems, e.g., DHSPlus [15]. Among other things they offer the possibility to simulate the physical behavior of pneumatic-actuators during virtual commissioning. For doing this an additional IT tool for the 3D visualization of the movements and the forces which act on the actuators is needed (e.g., SimPack). This tool exchanges information such as position, speed, and force through a defined interface. There is also the possibility to model the exterior forces within the same IT tool, although with additional effort and considerable simplification.

## 5 Pneumatic Model

To handle pneumatics in a physic based simulation it is necessary to sum up the theoretical basics in an algorithm. This algorithm has to be adapted to meet specific demands imposed by the physic engine. As this paper handles pneumatic cylinder systems the algorithm covers the behavior of a cylinder.

Basic components to build up a cylinder are rigid bodies. In a first step, by using the ability of a physic engine to depict density and friction, a geometry representation of the cylinder is used. The second step covers the simulation of the travel. It can be simulated via prismatic joints which are limited in translatory direction.

The geometry representation of the cylinder is simplified with respect to the original CAD model (Fig. 8), because convex geometries are much easier to simulate and perform much better during simulation. Furthermore some tiny structures, which are not relevant for the simulation, like grooves or screws, are deleted so as to allow for real time simulation. In the same way, the internal structures of the cylinder are neglected. The piston and the housing are ignored as a collision pair. Therefore the stick–slip-effect cannot be simulated at this time.

It is possible to construct the entire cylinder by single convex geometries and link them to one physical body, but this will bring up a higher effort in modeling. Since virtual commissioning is used to reduce development complexity, accepting this extra effort will be contradictory. On the other hand this will increase the computational cost of the simulation and will hardly fulfill the real-time simulation requirement.

So far the mechanical modeling has been described. For pneumatic simulation the use a fluid system, as provided by the PhysX engine, would usually be the first choice. However, at this point the physical simulation was expanded by an algorithm which transfers the pressure computation to the physic model. The algorithm uses the displacement of the piston relatively to the cylinder housing to derive the current lifting to pressure ratio.

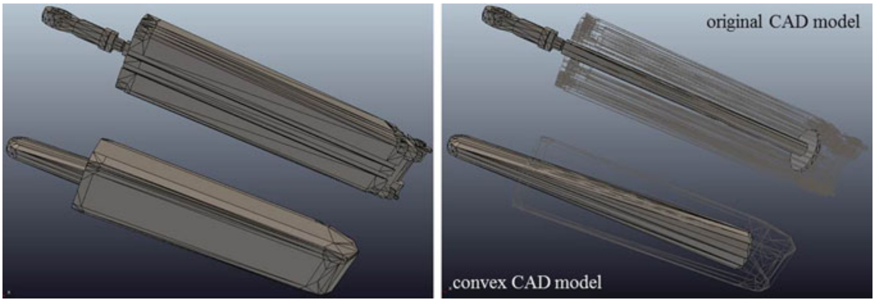



**Fig. 8** The original and convex CAD model from the cylinder

The pressure conditions in the cylinder are used to calculate acting forces to both, the piston and the housing. These forces are transferred back to the engine. This leads to a classical closed loop. In combination with the scene feedback the piston displacement is determined, which is the input for the next simulation step. In addition advanced technical data of the cylinder is relevant. An important component is the shaft seal which is, among others, the reason for the stick–slip-effect.

## 6 Pneumatics Integration into the Physic Engine

Based on the above consideration, the algorithm and its integration in the physical computation are described in this section. The algorithm used to build up a pneumatic expansion is shown below in C++ pseudo-code notation. The entire algorithm is based on the *equation of state of an ideal gas*.

```
simulateCylinder(float timestep)
{               //First get the piston lifting from the physic engine
                currentLifting = getPistonLifting();
                //Calculate the pressure for each chamber
                for (int i = 0; i < 2; i++)
                {
                //Calculate the chamber volume from the current lifting and the
                cylinder characteristics
                currentChamberVolume = calculateChamberVolume(i,
                currentLifting);
                //Get current pressure difference between the chamber and the
                environment
```

```
        currentPressureDifference = getPressureDifference(chamberPressure[i]);
        //Depending on the air restrictor parameters a specific volume of gas (air)
        diffuses
        gasVolumeDifference = timestep * restrictorConstant[i] * current
        PressureDifference;
        //Now the pressure can be calculated
        pressure = max(chamberPressure[i], environmentPressure);
        //The gas mass in the chamber is updated
        gasMass[i] - = pressure * currentChamberVolume/(specificGasConstant
        * temperature);
        //The chamber pressure is determined with the equation of state of an ideal
        gas
        chamberPressure[i] = gasMass[i] * specificGasConstant * temperature/
        currentChamberVolume;
    }
    /* Now we got the pressure values for both chambers we can calculate the acting
    force depending on the cylinders characteristics like cross section area and
    shaft seal parameters.*/
    actingForce = calculateForce();
    /* Caused by the shaft seal there is also a friction force acting on the piston.
    With respect to the pistons linear velocity the friction will modify the acting
    force. This is a great benefit, due the piston and housing do not need to be
    treated as a collision pair. The calculation of the friction is reduced to a min-
    imum of cost.*/
    applyShaftSealFriction(actingForce).
    /* Finally the acting force has to be transferred to the engine. This means the
    force has to be applied to the piston body and inverted to the housing to
    guarantee equilibrium of forces. Therefor the force is multiplied to the vector in
    piston orientation.*/
    addForce(actingForce);

}
```

This algorithm is executed before every physic simulation step. The resulting force acts in the physic simulation and will determine a new piston position. Since the *compressed air reservoir* provides a constant pressure, the outer pressure support (such as lines or valves) does not need to be simulated. In Fig. 9 the piston lifting of a cylinder simulated by the algorithm is plotted against the simulation steps ($t = 1$ ms). The diagram shows the influence of the stick–slip-effect.

Figure 10 shows the linear velocity magnitude of the piston.

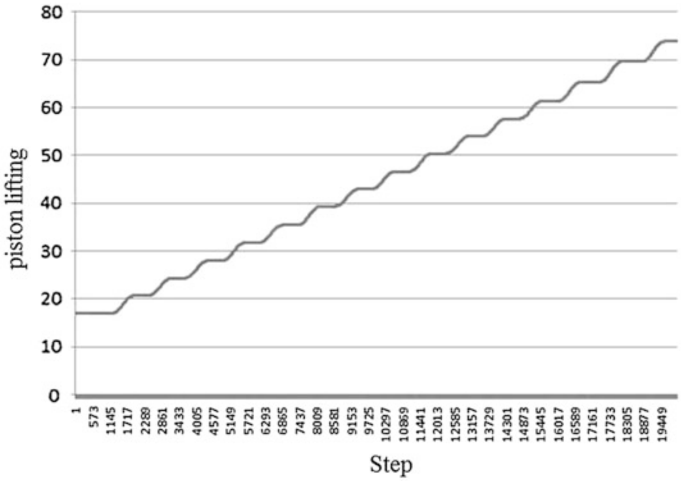



**Fig. 9** The piston lifting of a cylinder

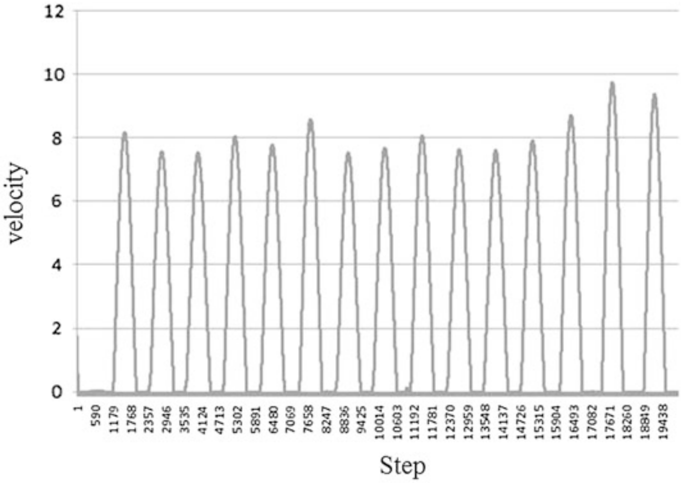



**Fig. 10** The linear velocity magnitude of the piston

## 7 Summary

This paper presented how physic-based approaches from the video game industry can be used to create a real-time capable simulation model of an assembly production station for virtual commissioning. One of the aspects not considered in current methodologies is the behavior of pneumatic drives. This behavior strongly depends on the dynamic, i.e., forces and moments, of the assembly station. This paper focuses on the modeling of the pneumatic drive To accomplish this, the mechanics of the assembly are modeled in real-time using a physics engine, which takes into account the behavior of the pneumatic drive. The relevant basics of pneumatic drives as well as the dependencies between the mechanics of the drive and the pneumatic are presented. Based on these basics, a detailed model is presented and its plausibility shown through an exemplary implementation. Important aspects like the accuracy or the scalability of the model and the simulation, which are relevant to establish the validity of the virtual commissioning, fall out of the scope of this paper, but will be addressed in the future.

## References


1. Roscher J (2008) Bewertung von Flexibilitätsstrategien für die Endmontage in der Automobilindustrie Institut für industrielle Fertigung und Fabrikbetrieb. Dissertation, Stuttgart
2. Bracht U (2002) Ansätze und Methoden der Digitalen Fabrik. TU Clausthal, IMAB, Anlagenprojektierung und Materialflusslogistik
3. Strahilov A (2012) Development of the physics-based assembly system model for the mechatronic validation of automated assembly systems. Winter simulation conference (WSC), Berlin
4. Spitzweg M (2009) Methode und Konzept für den Einsatz eines physikalischen Modells in der Entwicklung von Produktionsanlagen. Dissertation
5. Strahilov A (2012) Mechanische Absicherung automatisierter Montageanlagen mit physikbasierten Simulationen. Design for X, Bamberg
6. Geimer M (2009) Vorlesung Fluidtechnik. KIT, Karlsruhe
7. Baehr HD (2005) Thermodynamik. Springer, Bochum
8. Gebhardt N (2010) Fluidtechnik in Kraftfahrzeugen. Springer, Dresden
9. Parr A (2011) Hydraulics and pneumatics. Elsevier, Oxford
10. Esposito A (2009) Fluid power. Pearson, Ohio
11. Coumans E (2012) Bullet 2.80 physics SDK manual. Manual
12. Eberly DH (2004) Game physics. Morgan Kaufmann Publishers, Los Altos
13. Reinhart G, Lacour FF (2010) Design metaphors for physically based virtual commissioning. Paper
14. Kiefer J, Bergert M, Rossdeutscher M (2011) Mechatronic objects in production engineering: a key enabler in automotive industry. In: atpedition, Dec 2010, pp 36–44, ISSN 2190-4111
15. FLUIDON: http://www.fluidon.com/index.php?id=144, am 17 Dec 2012 um 11:42 Uhr
16. Boeing A, Bräunl T (2007) Evaluation of real-time physics simulation systems. School of Electrical, Electronic and Computer Engineering University of Western Australia. In: Proceedings of the 5th international conference on computer graphics and interactive techniques in Australia and Southeast Asia
17. Song P (2002) Modeling, analysis and simulation of multibody systems with contact and friction. Dissertation in mechanical engineering and applied mechanics, University of Pennsylvania
18. Lee SH, Terzopoulos D (2008) Spline joints for multibody dynamics. ACM Trans

# An Innovative Framework for the Simulation of Manufacturing Systems: An Application to the Footwear Industry

**Alexandra F. Marques, Miguel Mujica, Jorge Pinho de Sousa, Paulo Sá Marques, Rui Rebelo and António C. Alves**

**Abstract** Simulation in industrial environments has been recognized as a valuable approach for capturing the different characteristics and complexity of the dynamics in industrial processes. However, there is a clear need for spreading the use of simulation tools in manufacturing companies and for simplifying the simulation modeling process. In fact this process is still highly demanding in terms of the specific skills of the modelers and in terms of the time needed to develop models that are effectively useful in actual manufacturing systems. The slow modeling process often precludes the use of simulation for facing the operational problems that rise in the day-to-day operations. This paper presents a brief overview of the use of simulation tools in manufacturing, and focus on the development of an innovative simulation framework based on libraries of components and modules. This framework will contribute for reducing the learning curve in developing simulation models for manufacturing and logistics systems. The requirements and advantages of this novel modular modeling approach are presented and discussed in the context of a case study that uses the SIMIO software for simulating the production and logistics systems of a generic footwear manufacturing system in Portugal.

## 1 Introduction

Simulation is becoming more and more important for engineering complex production and logistics systems. Although simulation models started to be developed in the 60's for virtually representing and emulating the dynamics of real-size

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industrial environments [1], efforts are still needed for spreading its utilization by manufacturing companies.

Over the years, simulation models evolved to cope with the increasing complexity of manufacturing systems, that may include many components (operations, facilities, equipment, workers), complex relations among the components, and may further address multi-products or several production lines. Most of the simulation models tackle uncertainty and risk in product demand and in the duration of the operations (e.g., [2]). Recent developments in simulation tools take advantage of optimization routines to assure the best use of production resources, or to reduce costs or delays [1].

Simulation models have been used for many purposes including facilities planning, supporting product design, diagnosing the performance of a production process and identifying bottlenecks, performing lab tests on potential improvement ideas (e.g., expected results of the application of *lean* techniques), conducting stress tests to the system for scaling the production capacity and logistics, ergonomics and training (e.g., [3, 4, 5]). Consequently, simulation tools may help to improve the design and analysis of manufacturing systems and may also support scheduling, production planning, and decision-making [6]. The contribution of these tools toward the increase of efficiency and competitiveness of manufacturing companies is well established in some key policies and strategic documents such as the Future of Manufacturing in Europe 2015–2020 of the EU [7] and the Visionary Manufacturing Challenges for 2020 of the Board on Manufacturing and Engineering Design in the USA [8].

In practice, different simulation approaches can be taken, including system dynamics (e.g., [9, 10]), agent-based modeling [11], and discrete event systems (DES) [12], although the latter seams to be the mostly used for industrial environments. In general terms, DES models represent the dynamics of the production and logistics systems over time as a sequence of events. A set of variables is used to describe the "state" of the system at a given instant. The state of the system changes only when an "event" occurs in a discrete instant of time. The event may possibly have a continuous evolution once it starts, but this is not what one is interested in: the primary focus is on the beginning and the end of the event, since the end of an event can cause the beginning of another [12, 13, 14].

DES models may be built with programming languages for simulation (such as SIMULA) or with the help of specific software tools called Visual Interactive Modelling Systems (VIMS). There are an increasing number of commercial off-the-shelf VIMS solutions available for specific as well as for generic applications [1]. VIMS are more easily used than programming languages as they provide many features for simulation modeling and restrict programming to the event coding that configures the behavior of objects in response to given events.

Regardless of the approach in use, the processes of building and maintaining simulation models are often unique and tailored to a specific industry or company and to a particular simulation purpose. The modeling process is still highly demanding in terms of the specific skills of the modelers and in terms of the time needed to develop simulation models that are effectively useful in actual manufacturing systems. A DES model resulting from such a process represents in detail the complex structure and interactions of a given manufacturing system and can hardly be reused even for handling other systems of the same industrial sector. Furthermore, the models need to be continuously updated to keep up with the changes of the manufacturing systems (e.g., new production processes, new products, changes in the industry layout).

The limitations in the modeling process, among others described in [5], have prevented a wide use of simulation tools in manufacturing companies and particularly preclude their use for handling the operational problems that rise in the day-to-day operations.

Recent developments in modeling and programming paradigms, with an emphasis on reusability and object oriented programming, aim at significantly reducing the efforts for developing simulation models (e.g., [15]). The new generation of VIMS built according to these paradigms, already provide the modeler with reusable standard objects and many features that aim at facilitating the construction of the simulation model, including the possibility of using existing models as "black-box" modules in complex simulation models or even reusing them as templates for new simulation models. Further advances in VIMS address the integration with the company information systems, as a way to provide information required for automatically maintaining the simulation models.

However no such generic library of components or modules was found specifically for manufacturing systems. The literature is scarce both on conceptual frameworks and on applications of VIMS that accomplish reusability of objects and enhance the simulation modeling process. The framework for Extended Digital Manufacturing Systems [16] provides an integrated environment for products, production systems, and business processes that may be used for the purpose of simulation. However, the detailed simulation objects and the simulation modeling process are not described in that framework. Recent work on ontology models for equipment (e.g., [17, 18]) as well as existing standards initiatives such as the ISO 15531-MANDATE [19] for manufacturing data and ISA 95 [20] for the integration of enterprise and control systems, may further contribute for establishing common concepts and definitions in this domain. The Core Manufacturing Simulation Data (CMSD) Standard developed in 2010 [21, 22] and already applied in the car manufacturing industry [23, 24] may be quite useful for integrating simulation systems with other manufacturing applications.

This paper aims at contributing to the development of simpler and faster simulation modeling processes through an innovative framework for simulating manufacturing systems, enhancing modularity, and reusability. Such framework will hopefully contribute to a significant reduction of the learning curve for developing new simulation models. The paper describes the framework concepts and its application in the creation of new simulation models with SIMIO. The paper further presents some preliminary results on the application of this approach for simulating a production and logistics system in footwear manufacturing.

## 2 A Framework for the Simulation of Manufacturing Systems

The framework encompasses the definition of concepts, relevant information, and libraries of simulation objects that can be used within a VIMS, for quickly creating simulation models for any manufacturing system. So far, the framework also includes a library of modules that may be used for simulating the production and logistics processes of footwear manufacturing companies. Such framework promotes the use of new standard and simplified simulation modeling processes, especially for companies with a library of modules available. The framework may further contribute for adopting new system architectures that enhance automatic data collection from the company information systems, guaranteeing a continuous update of the simulation model, thus making a better use of the enhanced features of commercial VIMS.

The framework was developed under the scope of the PRODUTECH-PTI Project representing join efforts of the national industry of manufacturing technologies toward the increase of its productivity and competitiveness. The work-plan for the development the framework encompassed a specification phase and an implementation phase for producing prototypes for several types of industrial sectors. The specification of the framework was built upon a comprehensive literature review on the simulation of manufacturing processes and on a survey of manufacturing equipment used and produced by the industrial sectors that take part in the PRODUTECH initiative. A group of experts in simulation from Portuguese research centers and consultancy companies met regularly during the specification phase for drawing an initial concept map for simulating manufacturing systems independently from the VIMS platform. Although SIMIO (www.simio.org) was selected for the prototype implementations.

Several other researchers and users of VIMS from the manufacturing companies in PRODUTECH also met in full day workshops for discussing concepts and procedures, setting the type of problems to be addressed by the library, and identifying and characterizing the main attributes of its components. During these workshops, the users have assured that all the manufacturing equipment identified in the initial survey could be mapped into objects of the general library. The group of experts agreed upon some premises about the processes for quickly developing and updating simulation models, which were then refined and improved during the implementation phase.

The group of experts further recognized that relevant modules for the manufacturing systems should be case-specific. Therefore, despite some general definitions and a common working procedure, the group split into smaller working groups for separately approaching several industrial sectors. The group that focused on the footwear manufacturing companies in Portugal conducted several internal workshops during the modules specification. Regular development meetings during the implementation phase assured the compliance with common developing procedures.

The domain of the framework is the **concepts and information for the simulation of manufacturing systems**, encompassing three main groups of concepts: structure of a simulation model, library of components for the simulation of manufacturing systems, and required information (see Fig. 1).

The group of concepts related with the *simulation model* may be common to all industrial sectors. In general terms, any DES model within a VIMS represents a system composed by *entities* that are progressively handled by *components* representing equipment and/or workers linked by physical or logical connectors. The state of a model changes only when a discrete set of events occur [13, 14]. The *event code,* the decisions, and business logic that guide the entity flows across the system are built using a simulation language or alternatively using graphical flowcharts that sequence a set of elementary routines. In SIMIO these routines are called Processes and Steps [25]. Such programming structures use as input the information for simulation, which is imported to specific tables of the VIMS. Each execution of the simulation model is a *simulation run*. During the simulation, the VIMS compute a set of relevant indicators that depend on the simulation goal. The evolution of the indicators during the simulation is displayed in dashboards or results tables.

Simulation models focus on the whole or parts of the production and logistics processes. Consequently, the generic library for simulating manufacturing systems is built around the concept of component or resource. The sub-components that may constitute the equipment are not considered in this work.

The *component* or *resource* represents one equipment, machinery, and/or worker that performs nuclear operations of the manufacturing system. The component can also be composed by a set of complementary equipment and workers that can only be used as a group. An example is a functional group of shoe sewing machines that execute the same task but any single shoe is only handled by one of the machines. The total capacity of this pool or resources is the sum of the capacity of each machine.

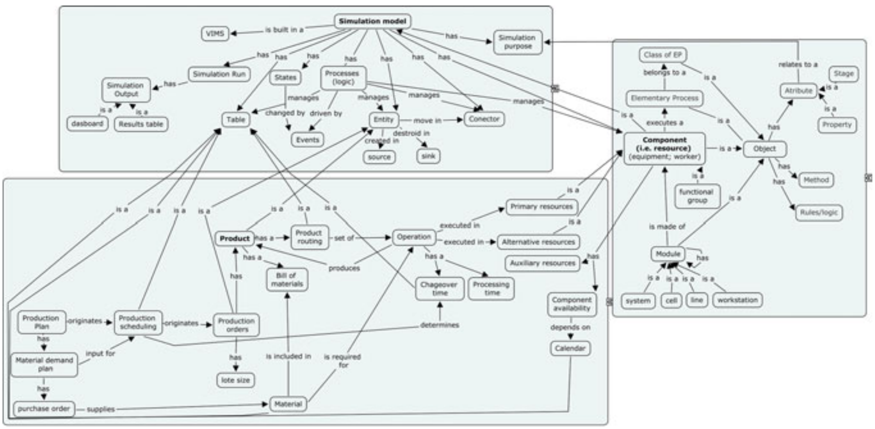


**Fig. 1** Concept map of the framework for simulating manufacturing systems

For the purpose of simulation, each component has a generic behavior that is modeled with an elementary process (EP) (as discussed in Sect. 2.2). EPs are hierarchically classified in classes and can be included in more complex models, called modules. Like in [17, 19] a *module* represents a logic association of components and/or other elementary modules that for the purpose of simulating complex systems may be considered a unique object with inputs and outputs. Any module is defined by a sequence and number of components and/or modules and the logic that links those objects within the module. An example is a shoe sewing line with many distinct sewing machines. Each type of shoe is processed by several of these machines in a unique sequence.

Both components and modules firstly developed may be encapsulated and added to a library for re-utilization. The utilization of a module may require adaptations of the inherent logic routines (i.e., processes) for each application.

A component is characterized by a set of properties, states, methods, and rules. Properties are intrinsic characteristics such as its maximum working velocity, power autonomy, and maximum capacity. A state is a characteristic of the object whose value changes during the simulation, such as its instance velocity or used capacity. A method is an action or function executed by the component in response to events. Generic methods that may be considered for a manufacturing equipment can be: “putting the product in a queue when it arrives to the equipment,” “stop processing if a required worker is not available,” “stop processing during setup and changeover or at the beginning or end of the day.” A rule is a logical, physical, or business-related condition that must be verified during the simulation. Examples include axioms, such as “the maximum velocity cannot be exceeded” but also other rules such as “the need to stop processing when a malfunction occurs.” A module may be characterized by its own set of properties, states, and methods, whose values may be computed directly from the values of the attributes of its components.

Finally the information required for the simulation of manufacturing systems is depicted in the conceptual map of Fig. 1, built upon the existing ISO 15531-Mandate and CMSD standards. Accordingly, in general the simulation considers a production plan for a given period that can be a day or a week. The plan includes the list and amount of products to be produced, leading to a required material demand plan: purchase orders to the suppliers, and production orders for the components to be produced internally by the company. Following the plan, the production scheduling establishes the sequence in which the products will be produced and in which equipment, thus creating the production orders that are the main input for the simulation. Each product is manufactured according to a receipt or product routing that is also an input for the simulation, including the list and sequence of the core production operations, and the processing times for each unit of product in primary or alternative resources.

The **generic library of Components for the simulation of manufacturing systems**, developed in the context of the framework, group elementary processes into 3 classes: Manufacturing, Storing, and Movement (see Fig. 2).

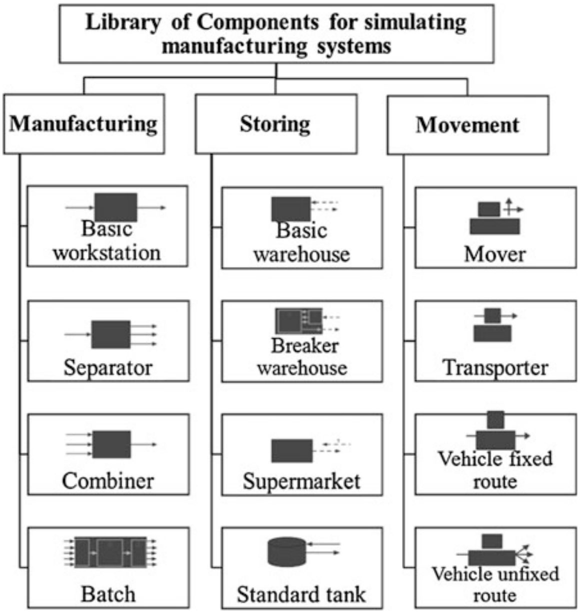


**Fig. 2** Generic library of components for the simulation of manufacturing systems

The *Manufacturing* class includes the resources that perform operations that modify the nature of the product. The resources of this class are mainly represented by the types and amounts of products that get in (b) and out (c) of an elementary process (see Fig. 3). There may be a unique product flow coming into the resource through an entering node (a) or the different types of products may have distinct flows with origin in other different resources, but just having a single entering node. Similarly, there may be one or several exiting nodes (d). The resource representation further includes entrance and exit buffers for queuing the products before and after transformation.

In general terms, the component may behave as a basic *workstation*, whenever the units of a single product lot are simultaneously received and transformed into a single product lot that leaves the resource as a whole, for further handling. In this case $b = c = 1$ and usually $a = d = 1$. In this approach, the focus is the "changes" introduced in the product flow, and therefore the consumables and the possible by-products are usually not considered.

The component behaves as a *separator* by splitting a single product lot into distinct types of product lots that, from that point on, will have separate handling. In this case $b = 1$, $c > 1$ and usually $a = 1$, $d > 1$. The *combiner* has the inverse


**Fig. 3** General representation of the elementary processes of the manufacturing class

behavior by merging distinct types of products, usually coming from distinct entry nodes, into a single product type that, from that point on, will constitute a unique flow ($b > 1$, $c = 1$ and usually $a > 1$, $d = 1$). The resources that perform packing (and unpacking) operations are considered a special case of combiner (separator) since they combine several units of one or several types of products into a container (that may be considered a different type of product) and, from that moment on, the full container may be viewed as a new product. The component behaves as a *batch station* whenever received products are clustered into buffers according to their size or other specific processing requirements, and are then processed as a lot when a buffer reaches a minimum dimension. Afterward, the processing lot is split and the different product types follow distinct product flows ($b = 1$, $c = 1$ *and* $a > 1$, $d > 1$).

Exceptional situations may occur in the classification of these elementary processes. Examples include the basic workstation with more than one exit node ($a = 1$, $d > 1$) for splitting the resulting product among the principal and alternative resources, according to some pre-defined rule. The separator may have a unique exit node ($a = 1$, $b = 1$), whenever the distinct types of products follow a unique flow but, by some reason, the types of products need to be kept differentiated. These exceptional situations may be discussed case-by-case taking into account the use of the resources in a given industrial sector.

The *storing class* includes the components that are mainly devoted to the temporary retention of products. The equipment in this class accepts a limited amount of products and product types, store them for a period of time (that may or may not be previously established), and then releases them whenever necessary, often taking into account the products entering sequence, and their entrance and due dates. This class applies to both raw materials, work-in-progress and finished products, here considered as variants of the product entity. The typical elementary processes of the *storing class* are the *basic warehouse* for discrete products, and the *standard tank* for continuous products. Other elementary processes include the *breaker* that, besides storing, may also break the incoming product lot into smaller lots to be separately released. The *supermarket* is often used in *lean* engineering is a particular case of the basic warehouse with normalized stocks and products being restocked in the same amount they are released to the production process.

The components included in the *movement class* are devoted exclusively to the physical handling of products. An equipment that simultaneously moves and transforms should be included in the previous class of *transformation*. Within the *movement class*, the equipment behaves as a *mover* whenever the whole or parts of the equipment move with the product. In the *transporter* products are moved along the equipment. Vehicles move products across trajectories that may be complex but predicable—*vehicle with fixed route*—or with random components—*vehicle with unfixed route.*

It should be noted that in the generic library designed in this work, resources are fully characterized in terms of properties, states, methods, and rules that are relevant for simulating their behavior for the set of goals previously established.

The framework further includes **libraries of models for an industrial sector.** Such libraries should approach the main stages of the generic production and logistics systems. The modules are instantiated and parameterized by the modeler during the process of creating a simulation model for the specific case under study. Modules are characterized according to the number and type of components, number and type of modules, rules for sharing workers and consumables among the resources of the modules, performance indicators for the module, and rules for setting the product flow within the model. The latter may include the rules for selecting the pieces of equipment to use in case of alternative resources, as well as tables for establishing the production routing.

Up to now, modules are identified through an in-depth analysis of existing manufacturing systems and their simulation models, this process involving both the modelers and the business experts. A general module identification process may emerge in a bottom-up approach driven from the experience of modules identification in each sector. Such process may further benefit from the results of recent work in prototyping virtual factories developed under the scope of EU projects such as VFF (see e.g., [18]) and COPERNICO [26].

The framework will lead to a new **simulation modeling process** that actually reduces the work of the modeler through the use of reusable components and models. This process should involve the "customer" and possibly the suppliers of production and logistics equipment, in the simplified approach of collecting information for the simulation. It should also guarantee that part of the work may be conducted independently from the selected VIMS. All these features will hopefully contribute for shortening and simplifying the simulation modeling process.

## 3 Case Study: Production and Logistics Systems of the Footwear Industry in Portugal

The footwear industry has an important impact in the Portuguese economy, representing 8 % of national exports. Employs approximately 33 thousand employments for producing around 62 million pairs of shoes, 95 % of which are exported for more than 130 countries [27]. The traditional footwear manufacturing system encompasses cutting, stitching, assembly, finishing, and packing. These production stages are often physically separated and create considerable intermediate stocks leading to long production lead-times. Over the years, the traditional industry units have been specializing in producing high value-added leather footwear. The footwear manufacturing systems tend to become more and more flexible and integrated, enabling the production of small quantities of highly diverse models tailored to customer specifications.

To assess the advantages and limitations of the proposed approach to the simulation of footwear manufacturing systems, the project focused on three generic footwear manufacturing systems provided by the CTCP [28] for producing

200 pairs, 500 pairs, and 1,000 pairs per day. According to the Framework, an exhaustive list of the equipment used in each of manufacturing system was firstly compiled and each equipment mapped into the proposed standard elementary processes. Then, the manufacturing process was scrutinized for identifying modules that may simplify the simulation modeling process. The One Step transporter prototype developed by Inesc Porto was one of the first modules identified. This module is particularly relevant as it contributes for the current specialization trend of the sector by integrating traditionally independent stages of the process such as the assembly and finishing.

## 4 Preliminary Results

Preliminary results suggest that the 62 production and logistics equipment listed for the cases were successfully mapped into the elementary processes of the library of components (Table 1). The proposed framework proved to be adequate to model the behavior of all the equipment for the purpose of simulating the systems behavior. Results showed that the Sewing stage has the highest number of types of equipment, most of them behaving as basic workstations.

The elementary processes of the library were successfully built from objects of the standard library of the SIMIO. As an example, the basic workstation was implemented using a Workstation. Other elementary processes such as the basic warehouse are implemented as combinations of standard objects and require significant modeling efforts.

The ongoing work in identifying the modules for the footwear industry suggests that there will be at least one module for each stage of the manufacturing process and for each of the target shoe production level. The preliminary results with the 1 step transporter show that it may be implemented using a set of transporter elementary processes. Significant modeling efforts are used to configure the logic of the product flow in the system (see Fig. 4). Further conceptualization work is needed to create a general 1 step transporter module that can be easily parameterized by the user to fit to a specific manufacturing process.

**Table 1** Number of types of equipment used in the footwear manufacturing systems in Portugal

| Stages of the footwear manufacturing system | Elementary processes | | | | | |
|---|---|---|---|---|---|---|
| | Basic workstation | Separator | Combiner | Basic warehouse | Transporter | Total |
| Cutting | 1 | 3 | | 3 | 1 | 8 |
| Pre-stitching | 6 | 1 | | | | 7 |
| Stitching | 19 | | 1 | 2 | 1 | 23 |
| Assembling | 11 | 1 | 5 | | 1 | 18 |
| Finishing and packing | 2 | | 1 | | 3 | 6 |
| *Total* | *39* | *5* | *7* | *5* | *6* | *62* |

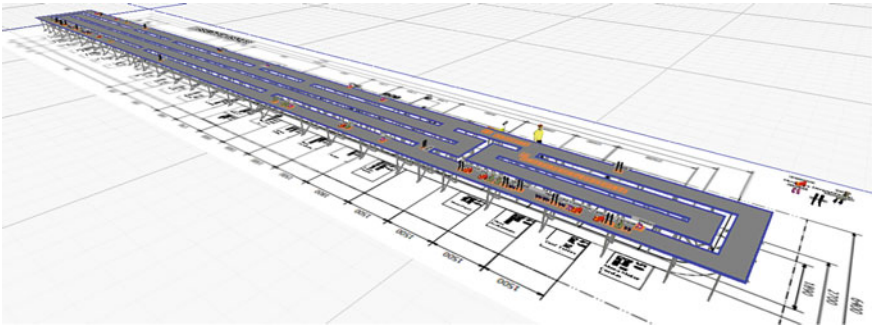

**Fig. 4** Simulation model for the 1 step transporter prototype

At this stage, the information used for simulation was randomly generated and imported from text files built for research purposes. Future work will foresee the direct integration with a footwear manufacturing company. Preliminary results further show that the simulation modeling process is significantly simplified although the modelers experience in using the commercial solution and his background in manufacturing systems are still of great relevance.

## 5 Concluding Remarks

The key elements of the framework for the simulation of manufacturing systems are described. Preliminary results in the footwear industry are presented. Future work will complete these results by implementing in SIMIO all the elementary processes. Specific resource components for the footwear industry will be developed in SIMIO. Additional research will lead to new modules for the footwear industry. Other lines of work will foresee the application of the proposed framework for other industry sectors, including the textile manufacturing and metal works.

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## References

1. Swain J (2011) Software survey: simulation-back to the future. ORMS-Today 38(5). http://informs.org/ORMS-Today
2. Wenzel S, Boyaci P, Jessen U (2010) Simulation in production and logistics: trends, solutions and applications, advanced manufacturing and sustainable logistics, lecture notes in business information processing, 46, Part 1, pp 73–84

3. Fowler JW, Rose O (2004) Grand challenges in modeling and simulation of complex manufacturing systems. Simulation 80(9):469–476
4. Kuehn W (2006) Digital factory: integration of simulation enhancing the product and production process towards operative control and optimization. Int J Simul 7(7):27–29
5. McLean C, Leong S (2001) The expanding role of simulation in future manufacturing. In: Proceedings of the 2001 winter simulation conference, pp 1478–1486
6. Mujica MA, Piera MA (2011) A compact timed state space approach for the analysis of manufacturing systems: key algorithmic improvements. Int J Comput Integr Manuf 24(2):135–153. Taylor & Francis
7. Geyer A, Scapolo F, Boden M, Dory T, Ducatel K (2003) The future of manufacturing in Europe 2015–2020: the challenge for sustainability. IPTS-EU. 2003. http://foresight.jrc.ec.europa.eu/documents/eur20705en.pdf
8. National Research Council (NRC)/Board on Manufacturing and Engineering Design (BMED) (1998) Visionary manufacturing challenges for 2020. National Academy Press, Washington, D.C
9. Sterman J (2000) Business dynamics: systems thinking and modeling for a complex world. Irwin/McGraw-Hill, Boston
10. Wakeland WW, Gallaher EJ, Macovsky LM, Aktipis CA (2004) A comparison of system dynamics and agent-based simulation applied to the study of cellular receptor dynamics. In: Proceedings of the 37th annual Hawaii, international conference on system sciences
11. North MJ, Macal CM (2007) Managing business complexity discovering strategic solutions with agent-based modelling and simulation. Oxford University Press, Oxford
12. Banks J, Carson J, Nelson B, Nicol D (2005) Discrete-event system simulation, 4th edn. Pearson
13. Schriber TJ, Brunner DT (2010) Inside discrete-event simulation software: how it works and why it matters. In: Proceedings of the 2010 winter simulation conference, pp 216–229
14. Schriber TJ, Brunner DT (1997) Inside discrete-event simulation software: how it works and why it matters. In: Proceedings of the 1997 winter simulation conference, pp 14–22
15. Herrmann JW, Lin E, Ram B, Sarin S (2000) Adaptable simulation models for manufacturing. In: Proceedings of the 10th international conference on flexible automation and intelligent manufacturing, vol 2. College Park, USA, pp 989–995
16. Nylund H, Salminen K, Andersson P (2011) Framework for extended digital manufacturing systems. Int J Comput Integr Manuf 24(5):446–456
17. Lohse N, Hirani H, Ratchev S, Turitto M (2006) An ontology for the definition and validation of assembly processes for evolvable assembly systems (ISATP 2005). The 6th IEEE international symposium on assembly and task planning: from nano to macro assembly and manufacturing, pp 242–247
18. Terkaj W, Pedrielli G, Sacco M (2012) Virtual factory data model. In: Proceedings of OSEMA 2012 workshop, 7th international conference on formal ontology in information systems, Graz, Austria, 24–27 July 2012. http://www.vff-project.eu/
19. Cutting-Decelle AF, Michel JJ (2003) ISO 15531 MANDATE: a standardised data model for manufacturing management. Int J Comput Appl Technol 18(1/2/3/4):43–61
20. Scholten B (2007) The roadmap to integration: A guide to applying the ISA-95 standard in manufacturing. ISA
21. Core Manufacturing Simulation Data Product Development Group (2010) SISO-STD-008-2010 standard for: core manufacturing simulation data–UML model. http://www.sisostds.org/
22. Leong SK, Lee YT, Riddick FH (2006) A core manufacturing simulation data information model for manufacturing applications. In: Proceedings of the systems interoperability standards organization 2006 fall simulation interoperability workshop
23. Leong SK, Johansson M, Johansson B, Lee T, Riddick FH (2008) A real world pilot implementation of the core manufacturing simulation information model. In: Proceedings of the simulation interoperability standards organization (SISO) spring 2008 SIW workshop, p 11

24. Johansson M, Johansson B, Skoogh A, Leong S, Riddick F, Lee YT, Shao G, Klingstam P (2007) A test implementation of the core manufacturing simulation data specification. In: Proceedings of the 2007 winter simulation conference, pp 1673–1681
25. Kelton W, Jeffrey Smith J, David Sturrock D (2011) Simio and simulation: modeling, analysis, applications, 2nd edn. Simio LLC, p 400
26. Rose-Anderssen C, Baldwin JS, Ridgway K, Boettinger F, Agyapong-Kodua K, Brencsics I, Nemeth I (2012) Application of production system classification in rapid design and virtual prototyping. In: Proceedings of the 14th international conference on modern information technology in the innovation processes of the industrial enterprises, Budapest, Hungary, 24–26 Oct 2012
27. APICCAPS (1993) Statistical study on footwear, components and leather goods-2011. p 237
28. CTCP (1993) Manual Prático de Novas Tecnologias de Produção e Organização do Sector do Calçado". p 237

# Multi-Agent Simulation for Concept of Cellular Transport System in Intralogistics

**Mustafa Güller, Yılmaz Uygun and E. Karakaya**

**Abstract** In recent years, the importance of flexible solutions and new challenging requirements in the field of intralogistics has increased because of changeability in dynamic and uncertain environment. The Cellular Transport System that aims to cope with these new requirements provides an efficient way to increase the flexibility and changeability of intralogistics. In this paper, we propose a multi-agent simulation framework for Cellular Transport Systems that is an application of Swarm Intelligence to control the autonomous vehicles' behavior. The paper discusses how we apply situated agent-based simulation as a tool for modeling and implementing a decentralized control of vehicle swarm. Furthermore, we aim to optimize the suitable number of vehicles used within a warehouse system. The simulated model provides an environment in order to study problems and performance issues of the vehicle operations.

## 1 Introduction

Intralogistics concept is defined as a combination of organization, controlling, execution, and optimization of the in-house material and information flow as well as handling in industry [1]. Flexibility, responsiveness, reconfigurability, and high availability in the field of intralogistics are key challenges for industries, especially in dynamic and uncertain environment. This dynamic environment is characterized by a wide variety of products, fluctuations in demand, and increased customer expectations in terms of quality and delivery time. In particular, autonomous vehicles have been widely adopted as a key component to intralogistics systems in order to improve capability to respond in real-time to any disturbance and

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reconfigurability in reaction to dynamic environment. Traditionally, the automation of vehicles is centrally organized and hierarchically structured. However, modifications are very costly and time consuming since hierarchical systems are rigid and static, and hierarchical systems cannot cope effectively with disturbances [2]. To deal with dynamic and changing operating conditions, interest in decentralized control of automated intralogistics systems has grown in both academicians and the practitioners over the last decades. In the decentralized solution, there is no central knowledge base about the state of the system and there is no central manager allocating vehicles to their missions [3]. The basic idea of these concepts is to put more autonomy in vehicles which make decisions based on their local and random information. According to Wagner and Hausner [4], the advantages of decentralized control are: (1) Increase of the flexibility and improvement of the adaptability of the automation system, (2) Higher efficiency (throughput, use of resources, degree of automation), (3) Reduction of communication effort, (4) Increased robustness and reliability by local troubleshooting, (5) Reduction of complexity for integration of resources/machines, and (6) Faster setup and reconfiguration.

The vast majority of decentralized material flow projects have focused on automated storage and retrieval system (AS/RS) and static conveyor systems in which unit loads are forced to use given paths and routes through the system [5]. Although AS/RS technology can achieve high throughput and fast response times in many material handling applications, AS/RS and classic conveyor system have limitations, such as limited flexibility and autonomy by the physical build-up of the system. Since it is a very rigid design, it cannot enable fast responsiveness and rapid adaptation to changes encountered in warehouse operations [6]. In order to cope with rigid design limitations, a group of dynamic, flexible mobile vehicles which have open path navigation and enable adaptability during runtime of a system is replaced inflexible continuous conveyor system. As a result, an alternative system that has been proposed is Cellular Transport System (CTS) developed by Fraunhofer Institute for Material Flow and Logistics. Cellular Transport System consists of a number of small, efficient, and autonomous transport vehicles which are called Multishuttle Move (MSM). MSM is a novel fusion of conventional shuttle and automated guided vehicle system [5]. In this system, MSMs are required to pick-up the requested orders from rack system and autonomously deliver them to order picking stations. Thus the vehicles can move on rack levels as well as freely within the warehouse. This allows the Cellular Transport System to be easily expanded and to modify the system configuration depending upon the system requirements. In this concept, the necessity to improve the flexibility and adaptability, such as providing additional storage capacity, supporting the storage and transport of new products, introducing new storage and picking strategies, including new sources and destinations in the transportation system, is provided by using a swarm of vehicles. In other words, CTS is a self-managing system adopted by Swarm Intelligence to control the autonomous vehicles' behavior.

Automated intralogistics systems consist of many constraints due to the layout of facility, the type of material handling system, the shapes and properties of packages, storage and picking policies [7]. The optimization of their performances requires the formulation of a model. However, dynamic elements cannot be easily translated into mathematical terms. A better way to cope with this problem is to develop a simulation model. Nowadays, simulations are intensively used for applications in logistics as a decision support tool that enable to model the complex and dynamic situations of the real-world problems without the limiting assumptions. Moreover, a simulation model allows to measure the performance of the existing systems for different structural scenarios as well as to evaluate the impact of different operative conditions to the existing system.

In this paper, we develop a multi-agent simulation model to evaluate the performance of the Cellular Transport System situated in a specific environment and to optimize the suitable number of Multishuttle used for moving goods within a distribution center. The remainder of this paper is organized as follows. In Sect. 2 the architecture of cellular transport system and its components is presented. We describe the multi-agent simulation model of distribution center environment that was developed to represent the real system in Sect. 3. Finally, details of the implementation and evaluation results are given in Sect. 4.

## 2 Architecture Description of Cellular Transport System

The main components of Cellular Transport System are autonomous vehicles, lifts, and a system of rails in the rack area. An MSM is a rail-guided in the racking system or lift and able to leave the rail system to operate as an Autonomous Transport Vehicles (ATV) with the open path navigation [5]. This navigation is based on sensor fusion of range measurements using an IEEE 802.15.4a wireless network. In Fig. 1, an MSM is depicted. The vehicles move their loads with a speed of 1 m/s on the floor and 2 m/s in the rack system. An MSM uses a battery as its energy source. An intelligent, battery-based energy concept allows each vehicle continuous operation of 4.5 h without recharging.

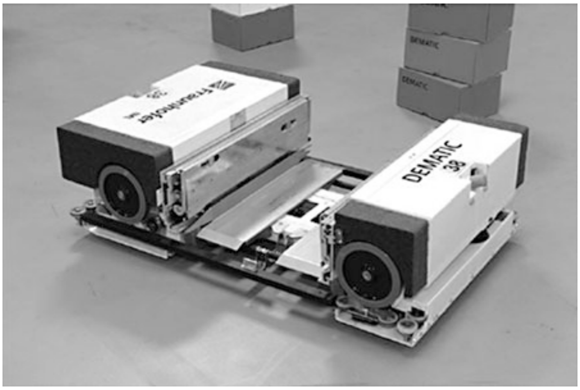


**Fig. 1** Multishuttle move system

The control architecture of the MSM has three different layers: sensor and actuator layer, operational layer, and strategic layer ([5, 8, 9]). Figure 2 shows a schematic of the control architecture.

The sensor and actuator layer (SA layer) of the control at the lowest level performs for all short-term tasks. This layer is mainly used for local navigation. Typical functionality which is located in this layer is to encapsulate individual controllers like fieldbus communication, sensor data acquisition, and the closed-loop drive control for vehicle positioning. The operational layer is located between SA layer and strategic layer. This layer implements the mid-term tasks of a MSM

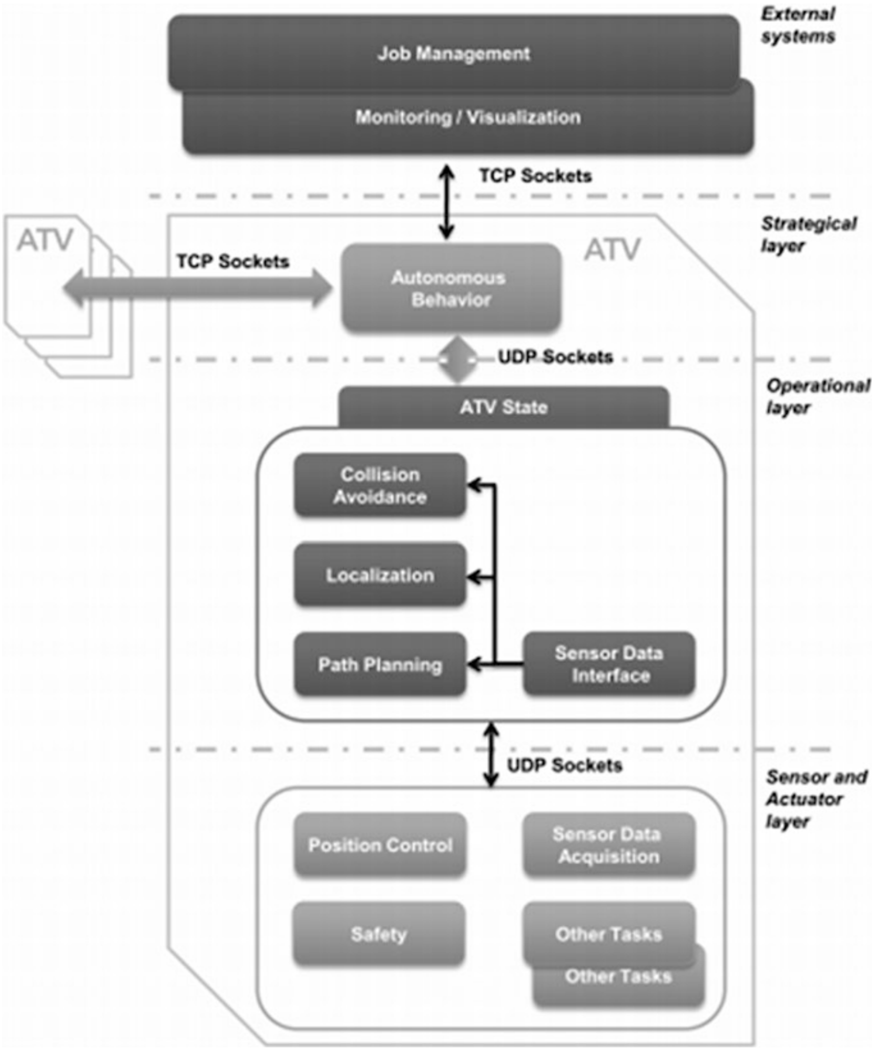


**Fig. 2** Control architecture overview [5]

like, e.g., basic movement primitives, collision and obstacle avoidance, localization, and path planning. With the help of the sensor data from the SA layer, MSMs cope with potential collisions with each other or obstacles in the warehouse environment. The general behavioral control paradigm in this layer identifies possible obstacles and initiates a redesign of the actual path or a reduction of the velocity depending on the actual situation. This layer also consists of all information to describe the actual state of charge, the actual position, velocity of the vehicle, and the load condition. The strategic layer has a global view on the MSMs and its environment and it is responsible for the creation of an autonomous behavior realized via Software Agents in order to achieve a given goal. The Software Agent has a communication interface to all tasks of the operational layer and is able to communicate with other agents as well as external systems.

For a corresponding practice test, a trial hall with a Multishuttle shelving system and pick stations for the application in smaller and medium-sized distribution centers were installed at Fraunhofer IML in 2011. In this distribution center, MSMs transport bins with Euro footprint (600 × 400 mm) from a high bay racking to order picking stations and back to the racking [10]. Order pickers collect the orders from Euro-bins and pack them into custom bins. Figure 3 shows the target application of the proposed decentralized MSM system.

The distribution center layout typically contains following locations:

- A set of workstations where it is possible the order picking operations which consists of retrieving individual items from storage on the basis of customers' orders;
- A set of recharging area where MSM can recharge their batteries;
- Storage area where products are stored;
- Transportation area between storage area and workstations.

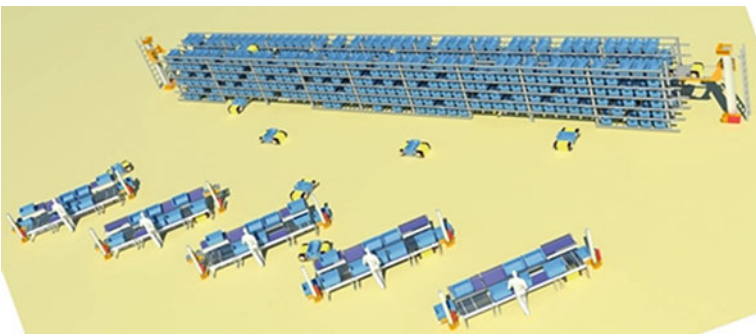

**Fig. 3** The trial hall of cellular transport system with MSM © Fraunhofer IML

## 3 Agent-Based Simulation for Cellular Transport System

In recent years, the agent-based simulation concept (ABS) has been used as an effective way to build and control complex systems [11]. In ABS, the model consists of a set of agents that are autonomous and self-directed. Due to the ABS structure, agents interact with other agents and each of the agents has its own strategy in order to achieve its goal [12]. The main features of agents are the capability to make independent decisions, their ability to perform flexible actions in a dynamic and unpredictable environment, and their pro-activeness depending on motivations generated from their internal states [13]. In order to manage the complexity of autonomous operations of Cellular Transport System, we have developed a simulation environment using agent-based modeling that enables dynamic objects such as MSMs.

Our simulation has been implemented in AnyLogic™, which is Java based simulation software that support discrete event, system dynamic, and agent-based modeling approaches [14]. The developed simulation model is composed of a set of agents that communicate with each other and with environment via messages. The different developed agents that are captured to model consist of MSM agent, Lift agents, Enter-Exit agents, and Workstation agents. All these agents have their own characteristics and logic of behavior. In order to design of agents and specification of their behaviors, we use the statecharts that are basically directed graphs where different kinds of nodes represent states and edges stand for transitions as shown in Fig. 4 [15]. A state can be considered as a set of reactions to external events that determine the object's situation. The transitions within the state charts are triggered by certain events, such as a message, arrival, a condition, or a timeout. When a transition is triggered, the agent leaves its current state, initiates the actions specified for that transition, and enters a new state [16].

Figure 5 depicts a screenshot of the MSM agent state chart for a single command cycles, where only one operation (storage or retrieval) is performed at a time. Boxes show the possible states and arrows the possible transitions. The square shapes in the chart represent branches (decision nodes). The MSM agents start at their home location. While in state *idle*, the MSM agent waits for a new order request. If there is a request, they change their state to the *move to enter* state

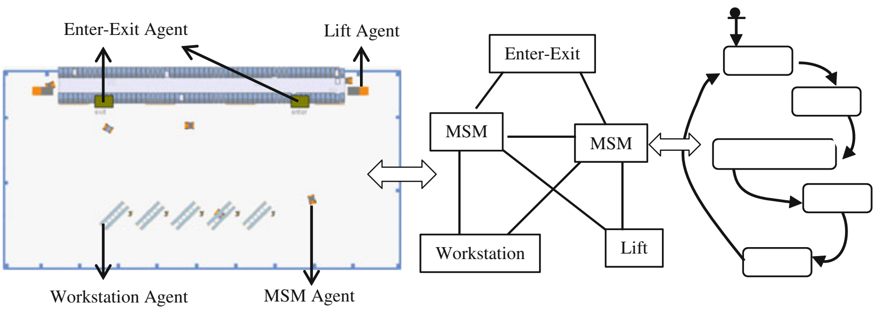


**Fig. 4** Agent-based simulation of cellular transport system

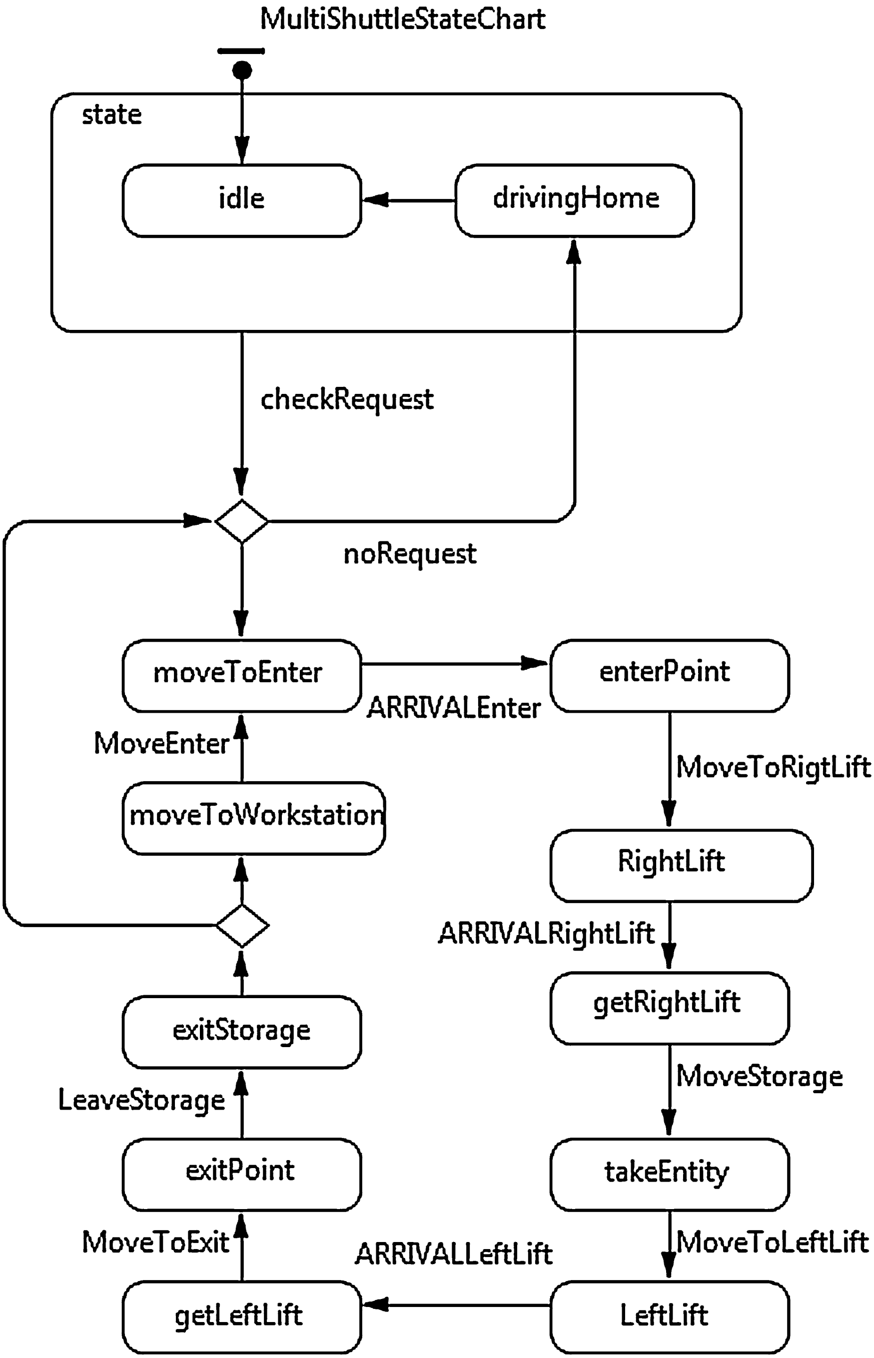


**Fig. 5** State transition model of MSM agent

and then they move through storage enter point to pick requested order. The decision of where to drive next is made when the current task is completed and next state is triggered by arrival transition. Some of the state changes are connected by passing messages. After arriving the enter point of storage area, the enter point agent communicates with the MSM agent by sending a "Move to Right Lift" message. The "Arrival Right Lift" event triggers the transition from *right lift* to the *get right lift* state and the agent moves to the destination tier vertically. The state of MSM agent is changed to *take entity* state with the message "Move Storage" received from lift agent. Once the requested order is picked from storage area, the agent executes the *left lift* state modeled in same way with *right lift* state and MSM agent moves to exit point of storage area. As soon as the MSM reaches its target, it changes its state and moves to a workstation according to the order. After retrieval transaction, a similar process is also executed for storage transaction. When the agent finishes the storage-retrieval transactions, the MSM executes the *driving home* state and moves back to his base (home location). While going home location or charge area, each MSM agent checks the order pool of the distribution center with the "Check Request" timeout transition.

Figure 6 shows the statecharts modeling respectively the behaviors of lift, enter-exit, and workstation agents. A queuing system has been implemented for lift agent and enter–exit agent. The lift agent is in the *empty* state by default and transitions into the *move* state when a MSM is ready to move to the destination tier. If the lift is not in the *empty* state, we add MSM to queue list of lift agent. The transition between the *agent leave* and *base position* states are triggered by timeout. After the MSM leaving period, lift agent executes *base position* state and return base location.

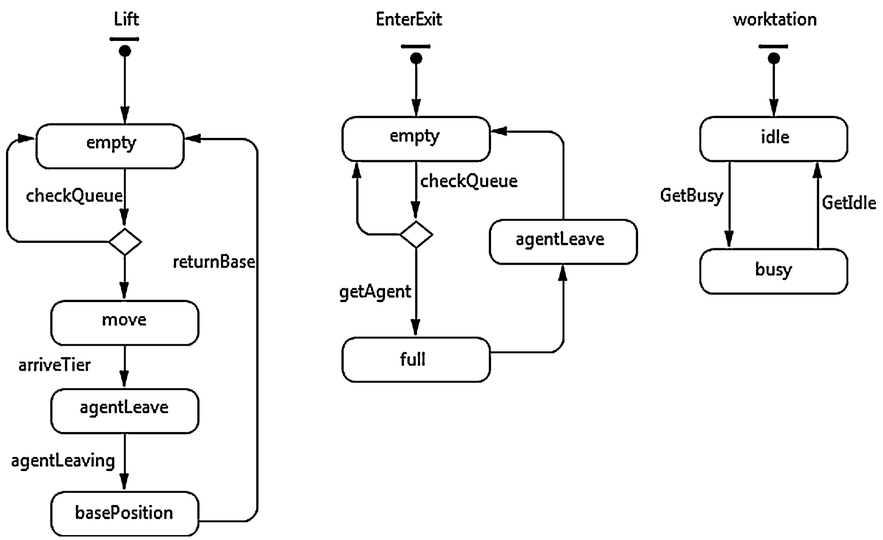


**Fig. 6** The statecharts for lift, enter–exit point, and workstation agents

The enter-exit agent can be one of three states. An *empty* state represents the state where enter-exit agent has not been assigned to any MSM. If MSM agent arrives at the storage area entrance (or exit) and if enter–exit agent is in the *empty* state, enter–exit agent communicates with the MSM by sending a message to lead to target location. The transitions between *full*, *agent leave*, and *empty* states is modeled by the timeout transitions, which models deceleration and rotation speed of MSMs. The workstation agent is idle state by default and goes into the busy state once MSM is reached at workstation. The messages "Get Busy" and "Get Idle" signify the transitions between these states.

A number of specific functionality the system must be considered during architectural design [17]:

- Order assignment: orders are generated by warehouse order scheduler and have to be assigned to MSM agents.
- Collision avoidance: safety measures are necessary when MSM agents cross the same intersection at the same moment.
- Deadlock avoidance: the system must ensure that MSM agents do not find themselves in a deadlock situation.

One of the main objectives is to efficiently transport goods to their destination. Due to dynamic environment and unsynchronized actions between agents, there is the possibility that conflicts arise between vehicles in the transportation area. In order to avoid collision with other MSMs agents, it is required that the agent has to maintain a minimal safety distance at all times. The collision is avoided by prioritization algorithm. One agent simply remains stationary for a certain amount of time according to right-of-way rule, while other agent considers it a static obstacle and resumes moving.

## 4 Experimental Results

The physical layout of the trial hall is 1,000 $m^2$ with length of 65 m. The exemplary distribution warehouse consists of a multishuttle shelving system with 5 tiers and specially developed pick stations. For simulation experiment, the sample problem is considered with approximately 600 storage positions that the storage and retrieval transactions are modeled as independent Exponential arrival processes 220 order/h. One of the main objectives of this simulation study is to understand how Cellular Transport System affects the performance of a typical distribution center. The required systems throughput can be scaled by the number of vehicles. Figures 7 and 8 show the results of experimental simulation runs.

The diagram shown in Fig. 7 displays the progress of the storage and retrieval time depending on the number of used MSMs. It can be seen that the times for average task completion decrease with the number of MSMs. However, the slope of the curve significantly decreases after 8 or 9 MSMs and increases relatively. It is expected that the likelihood of vehicle blocking at the transportation area increases

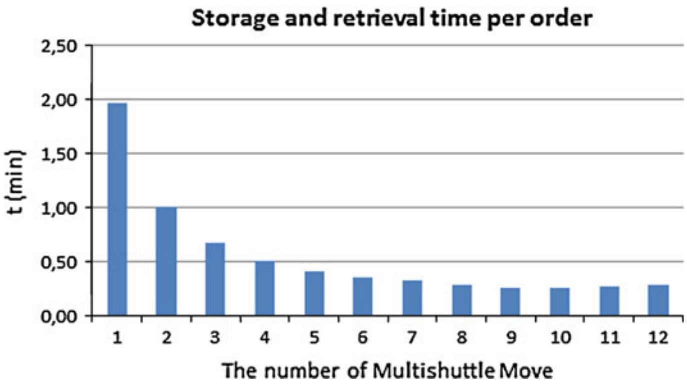


**Fig. 7** The time spent by MSMs for simultaneous loading and unloading

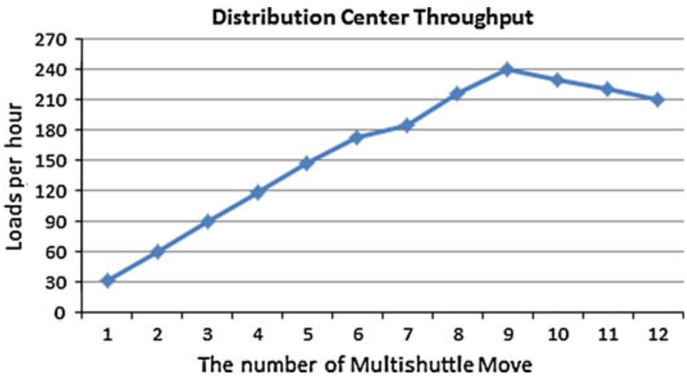


**Fig. 8** The number of orders per hour with the number of MSMs in the system

with the increase in the number of MSMs. This observation can be confirmed from the results in Fig. 7.

Figure 8 compares the throughputs of the system in terms of loads per hour related to the number of MSMs. From the figure, it can be seen that the throughput of the system reach maximum level at 8 MSMs while using more MSMs can improve the system performance only little. For double cycle (simultaneous loading and unloading), the expected throughput of a single Multishuttle Move is 31 units per hour.

## 5 Conclusion

The evolution in intralogistics systems put forward new challenging requirements. Due to dynamic changes and uncertain environment, such as order variations, changing products, load variations, vehicles must be able to adapt their behavior with changing circumstances. The Multishuttle Move (MSM) allows for a more efficient usage of available floor space and does not require any prior path definition. In this paper, we have presented an agent-based simulation approach to the control of MSM transport system that aims to cope with these new requirements. This research is an initial attempt to model MSM in Cellular Transport System. The simulation platform presented provides a basis to collisions with other vehicles in motion. Experiments have demonstrated that the relationship between throughput of the system and number of MSM in the decentralized architecture. We have pointed out that collision delays significantly impact throughput capacity and cycle times.

The presented simulation model is today limited to the trial hall installed at Fraunhofer IML. Another limitation of this study is that collisions are always solved by prioritization algorithm according to right-of-way rule. A possible solution would be the application of reducing its speed. In the near future, we are about to add architectural models to cope with order assignment and deadlock avoidance. Furthermore, we will investigate more efficient collision avoidance algorithms and integrate them with simulation model. Remaining challenge in Cellular Transport System is to optimize the physical layout of a distribution center.

## References


1. Arnold D, Furmans K (2006) Materialfluss in Logistiksystemen, Springer, Berlin
2. Versteegt C, Verbraeck A (2002) Holonic control of large-scale automated logistic systems. In: The IEEE 5th international conference on intelligent transportation systems, Singapore
3. Berman S, Edan Y (2002) Decentralized autonomous AGVs in material handling. Int J Prod Res 40(15)
4. Wagner T, Hausner C, Elger J, Lowen U, Luder A (2010) Engineering processes for decentralized factory automation systems. Factory Automation
5. Kamagaew A, Stenzel J, Nettsträter A, TenHompel M (2011) Concept of cellular transport systems in facility logistics. In: 5th international conference on automation, robots and applications (ICARA2011)
6. Heragu SS, Cai X, Krishnamurthy A (2009) Analysis of autonomous vehicle storage and retrieval system by open queueing network. In: 5th annual IEEE conference on automation science and engineering, India, 2009
7. Colla V, Nastasi G (2010) Modelling and simulation of an automated warehouse for the comparison of storage strategies. Modell Simul Optimization
8. Kamagaew A, Albrecht T (2011) Fortschritt durch Wandel. Logistik heute 4:54–55
9. Kamagaew A, Große E (2011) Zellular transportsysteme-multishuttle move. Multimodelaes Intralogistikkonzept, vol. 51
10. Röhrig CL, Lategahn J, Müller M, Telle L (2012) Global localization for a swarm of autonomous transport vehicles using IEEE 802.15.4a CSS. In: The international multiconference of engineers and computer scientists, pp 828–833
11. Murray J (2004) Specifying agent behaviors with UML Statecharts and StatEdit. RoboCup 2003: robot soccer world cup VII, vol 3020. pp 145–156
12. Weyns D, Holvoet T (2008) Architectural design of a situated multiagent system for controlling automatic guided vehicles. Int J Agent-Oriented Softw Eng 2(1)
13. Sebers P, Uwe A, Helen C, Clegg C (2007) A multi-agent simulation of retail management practices. In: Proceedings of the 2007 summer computer simulation conference

14. http://www.anylogic.com/. Accessed 14 Feb 2013
15. Alexander H, Tom H, Yolande B (2006) Testing AGVs in dynamic warehouse environments. Lecture notes in computer science, 2006
16. Glinz M (1995) An integrated formal model of scenarios based on Statecharts. Software engineering—ESEC'95. Springer, Berlin, pp 254–271
17. Danny W, Tom H (2008) Architectural design of a situated multiagent system for controlling automatic guided vehicles. Int J Agent-Oriented Softw Eng 2(1):90–128

# Modeling and Simulation of a Laser Scanner Sensor: An Industrial Application Case Study

**Jose Lima, José Gonçalves, Paulo J. Costa and A. Paulo Moreira**

**Abstract** A laser scanner is a popular sensor widely used in industry and mobile robots applications that measures the distance to the sensor on a slice of the plan. At the same time, simulation has becoming more and more used in industries and academia since it presents several advantages. It takes the building and rebuilding phase out of the loop by using the model already created in the design phase. Further, simulation time on testing is cheaper and faster than performing the multiple tests of the design each time. Besides, it is easier to measure some variables in simulation than in real scenarios. In this paper, a laser scanner sensor is modeled and implemented in a developed simulator that already has several other sensors and actuators models. The presented simulation reflects the laser model properties such as target color dependences, noise, limits, time constraints, and target angle functions. As a case study, the same scenario is assembled with real components on a conveyer belt and in simulation. Results from both approaches are compared and validate the proposed model methodology. As an example, a 3D object recognition task is addressed highlighting the developed realistic model. Further industrial and R&D implementations based on this sensor could be stressed in simulation before implementation.

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## 1 Introduction

Robot simulators are becoming more and more popular among the researchers and industry. They allow fast development and testing, that is a very important issue nowadays. The more realistic the simulator is, the easiest is to transfer code to real robots. Although the final aim is real robotics, it is often very useful to perform simulations before implementing real robots. This is because simulations are easier to setup, less expensive, faster, and more convenient to use. Building up new robot models and setting up experiments is very fast. A simulated robotics setup is less expensive than real robots and real world setups, thus allowing a better design exploration. Simulation often runs faster than real robots while all the parameters are easily debugged. Simulations make it possible to use computer expensive algorithms that run faster than in real robot microcontrollers. Finally, nowadays the simulation results are transferable onto the real robots [1]. Recently, the development of 3D modeling and digitizing technologies has made the model generating process much easier [2]. A laser scanner is a crucial element for a 3D mapping usually used in industry 3D scanning services and robotics. It allows to measure distance based on infrared beam and a rotating mirror that changes the beam direction along 240°.

The final goal of this paper is to model a laser scanner Hokuyo URG-04LX (Fig. 1) and to introduce it in the simulation environment. With this work, simulation enhances the possibility of simulating robots with a realistic laser model. Information for the model was based on some experimental setup, once the sensor specifications only provide a rough estimation of the sensor accuracy and on references [3, 4]. This paper also addresses the spectrum of laser scanner noise that is an innovative topic. Other authors [3] assume the measurement error is a

**Fig. 1** The Hokuyo URG-04LX

Gaussian noise that in a detailed approach, this noise becomes Gaussian with a low pass filter convolution.

This paper is organized as follows: After introduction, Sect. 2 presents a brief overview and some technical details of the URG—04LX. Section 3 addresses the laser scanner modeling where distance, angle, color, illumination, and noise spectrum interfere in measures. Then, Sect. 4 validates the results with a real laser application and the developed model simulation comparison. Finally, Sect. 5 concludes the paper and points out the direction of future work.

## 2 The Hokuyo URG-04LX

Measuring the depth of a scene (based on three-dimension vision hardware) is a topic that is being addressed by several developers and researchers. Examples of that is the stereo vision, time of flight (TOF) cameras, and the well-known Microsoft Kinect and the Asus Xtion based on infrared camera and an IR projector measuring two consecutive IR frames. Some of these sensors are expensive (TOF cameras) and usually present a low resolution for distant objects.

The Hokuyo URG-04LX is an LRF categorized as an Amplitude Modulated Continuous Wave (AMCW) sensor. The laser emits a laser beam and a rotating mirror changes the beam's direction. Then the laser hits the surface of an object and is reflected. The direction of reflected light is changed again by a rotating mirror, and captured by the photo diode. The phases of the emitted and received light are compared and the distance between the sensor and the object is calculated. A rotating mirror sweeps the laser beam horizontally over a range of 240°, with an angular resolution of 0.36°. As the mirror rotates at about 600 rpm, the scan rate is about 100 ms [3]. This information is summarized in Table 1.

### 2.1 *Experimental Setup*

The USB connection was used to acquire digital data from the sensor. A developed application that communicates and controls the laser scanner was developed and allows to logger the acquired data. As this application was written in Lazarus IDE,

**Table 1** Specification for the real laser

| Main specification | URG-04LX | Units |
|---|---|---|
| Measuring area | 20–5,600 | mm |
| Accuracy | 60–1,000: ± 30 mm<br>1000–4095: ± 3 % | mm |
| Angular resolution | 0.36 (360°/1,024 steps) | Deg |
| Scanning time | 100 | ms/scan |

it is possible to compile and run it on Microsoft Windows and Linux operative systems.

Measures were acquired with a white and non-reflect surface, such as paper in dark conditions at 22 °C temperature. Drift effects from the warm-up time, already analyzed in [3] and [4] were neglected for the simulation model.

## 3 Laser Scanner Modeling

A developed simulator, Simtwo [5, 6], used and tested in innumerous situations with different kind of robots (wheel, humanoid, underwater, manipulators, lighter-than-air) has already several sensors and actuators modeled from real scenarios. SimTwo uses the Open Dynamics Engine [7] to manage the dynamics of the scenario and glscene [8] to manage the 3D graphics. Examples of actuators are well known motors (propellers, solenoid, blower, pen tip) and examples of sensors are a laser beam (line), a 1D distance sensor, capacitive and inductive proximity sensors, and a floor white line sensor.

The popular laser scanner Hokuyo URG-04LX was modeled and implemented on SimTwo. With this new model, it is expected to simulate a numerous situations for automation and robotics.

The model of laser sensor was built with several variables such as distance and target angle, scene illumination, color and material of surface, and finally the noise spectrum. Next subsections present an approach for each variable with the measure and the standard deviation that gives the measure error.

### *3.1 Distance Model*

A perpendicular object was placed in front of the laser scanner for 20 known distances from 50 to 2,500 mm (50, 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,200, 1,400, 1,600, 1,800, 2,000, 2,200, 2400, and 2,500 mm). A linear function was obtained for the 20 distances and for each distance 20 measures, as presented in Fig. 2. The standard deviation is presented in Fig. 3. This laser presents an output error of 5.6 % for the 400 measures.

### *3.2 Angle Model*

An object away 530 mm from the laser was placed and the angle was changed from −80° to 80° (with an increase of 20°). For each angle 20 measures were obtained allowing to verify the effect on the measured distance of the object angle. The object (a surface with 4 mm of thickness, *d*) is tied to an axis of rotation. An

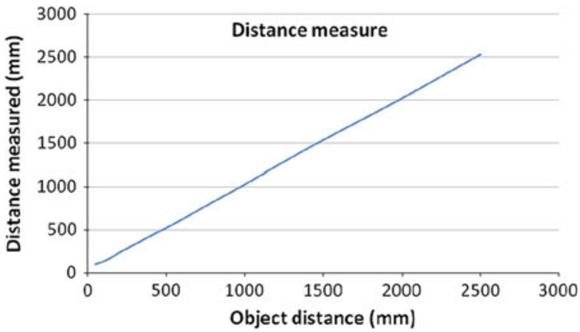


**Fig. 2** Measure distance

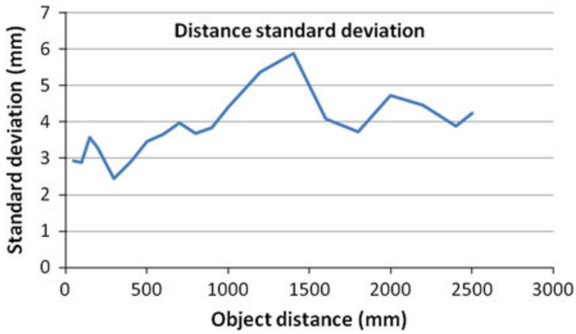


**Fig. 3** Standard deviation measure

adjustment function presented in Eq. (1) is applied once the thickness of the object introduces error, where *Dist* is the real distance from laser to the surface and DistCorr is the corrected distance (Figs. 4 and 5).

$$DistCorr = Dist - \frac{d}{2} + \frac{d}{2} \cdot \frac{1}{\cos(\alpha)} \quad (1)$$

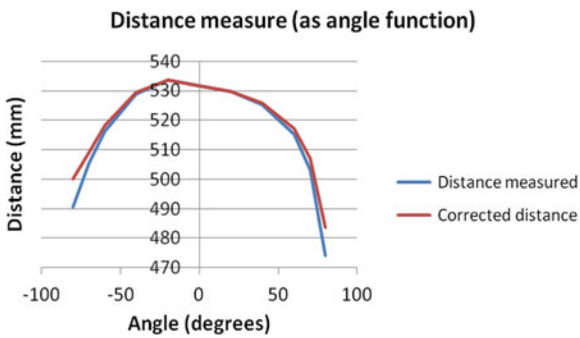


**Fig. 4** Target angle measurement

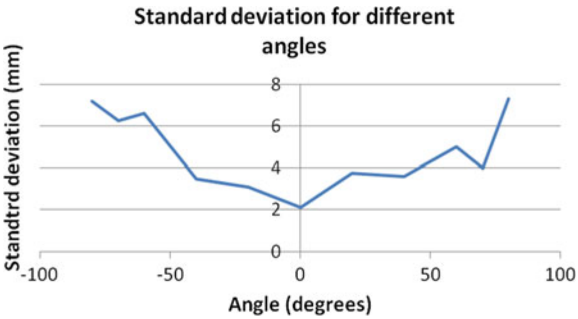


**Fig. 5** Target angle standard deviation

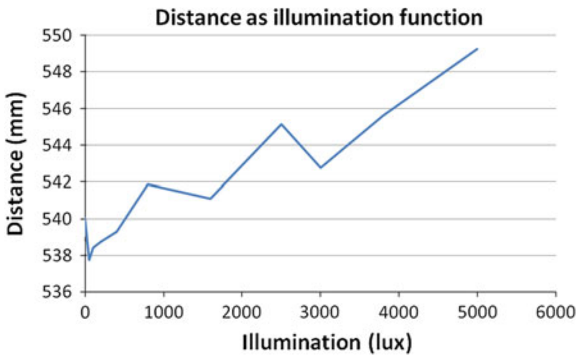


**Fig. 6** Measured distance depending on illumination

## *3.3 Illumination Model*

The effects of distance and the illumination of scenario on the final measure were studied. Sensor error remains approximately the same for different illumination (see Fig. 7) but distance measures are affected by the light present in the target. As presented in Fig. 6 the light present in the target influences the measure and shows the object further away. This topic was not implemented in simulation and it is pointed out as a future work direction.

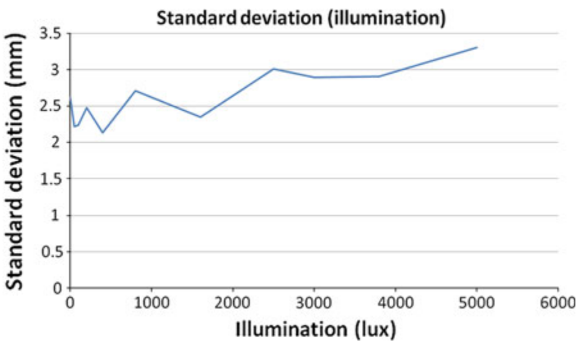


**Fig. 7** Standard deviation for different illumination

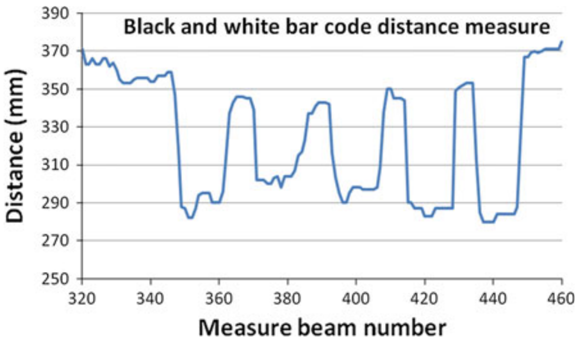


**Fig. 8** *Black* and *white* bar code distance measurement

## 3.4 Color Model

The surface color and gray levels do not significantly affect the mean value or the distribution [3]. Authors disagree with this statement in the (R = 0; G = 0; B = 0) and near RGB colors. The black surface influences the distance measure and returns a closer measure. As an experimental setup, a planar surface placed at 340 mm from the sensor with a black and white bar code was tested and the average measure of 100 distances, presented in Fig. 8, proof this dependence.

## 3.5 Surface Material

The surface of material affects the distance of the target. It depends on its roughness and reflectivity and it is difficult to establish this dependence. Since this property is not implemented in simulation (for now simulation surfaces only have visual textures) it will not be addressed in this paper.

## 3.6 Noise Spectrum

The noise presented at the output of sensor does not fulfill the white noise properties (as referred in [3]). A deep study of the noise sensor was developed based on frequency decomposition using a *Fast Fourier Transform* (FFT). Then a finite impulse response (FIR) filter was applied in the model to a white noise generator to obtain the same spectral components as the real sensor.

A block diagram of this task is presented in Fig. 9 where $x[n]$ is the Gaussian noise, $y[n]$ is the output of the FIR filter and the sum with the ideal laser scanner gives the final output of the sensor noise.

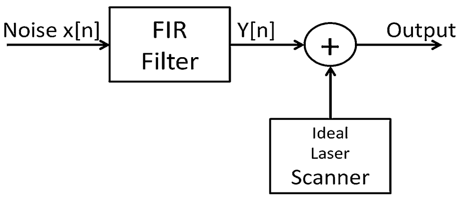


**Fig. 9** Diagram block of noise generator

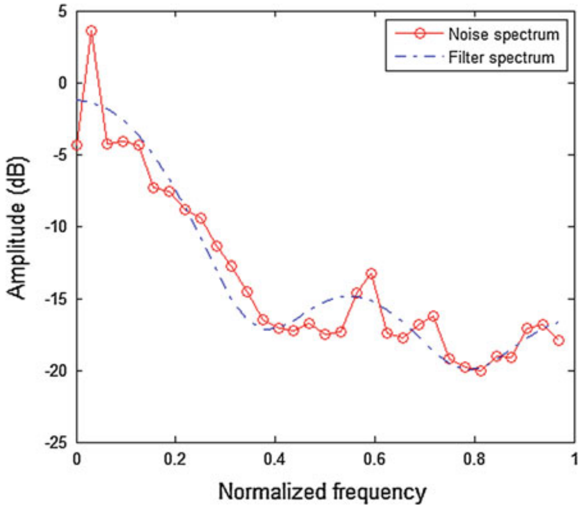


**Fig. 10** FFT of acquired noise and filter design

A planar surface was measured and the noise extracted was processed. Matlab was used to compute a FIR filter and get the impulse response coefficients $b$ (see Eq. 2). The filter and real acquired noise is shown in Fig. 10.

$$b = (0.0662\ 0.0923\ 0.1282\ 0.1770\ 0.3717\ 0.1770\ 0.1282\ 0.0923\ 0.0662) \quad (2)$$

## 4 Validation and Results

In order to validate the model of the laser sensor implemented in simulation, an object was scanned in a real conveyer belt with a speed $v_{cb}$ of 0.0664 m/s, as presented in Fig. 11 and the same scenario was implemented in simulation, as presented in Fig. 12.

In both situations a wood parallelepiped with a length of 154 mm, a width of 65 mm, and a height of 65 mm was used. The laser sensor was placed 400 mm above the conveyer belt. It is desired to get the three-dimensional information of the object. The box surface obtained by the real laser scanner can be illustrated in a 3D mesh plot, The real data can be seen in Fig. 13 while the simulated scenario

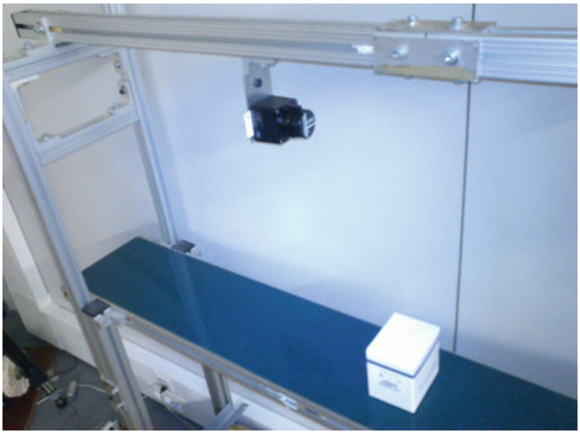

**Fig. 11** Real scenario

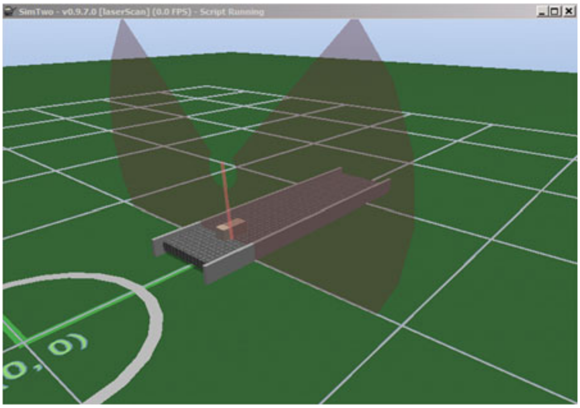


**Fig. 12** Simulated scenario

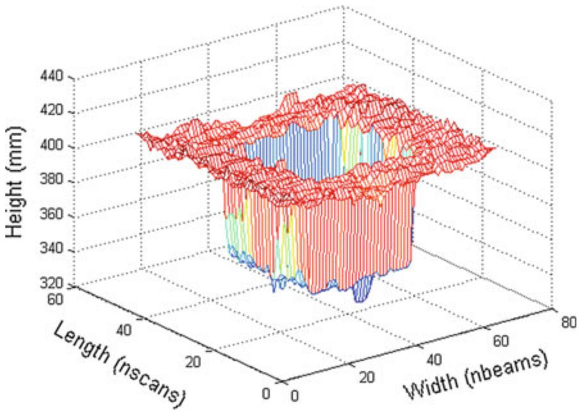


**Fig. 13** Simulated acquired data of a parallelepiped

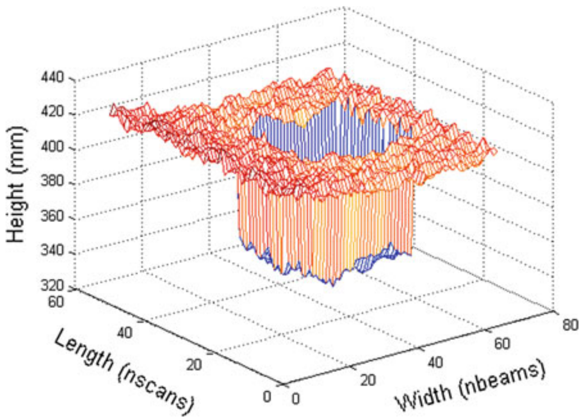


**Fig. 14** Real acquired data of a parallelepiped

results can be seen in Fig. 14. The height axis (z-axis) presents a lower distance measure when the scanned object is present.

## 4.1 Length

The length of the object ($l$) is related to the speed of the conveyer belt. Assuming 100 ms/scan, as presented by manufacturer it is possible to estimate the length based on Eq. (3) where $\Delta t$ is the time that object takes to cross the beam—Eq. (4)

$$l = v_{cb} \cdot \Delta t \tag{3}$$

where

$$\Delta t = nscans \cdot 0.1 \tag{4}$$

## 4.2 Width

The width of the object ($w$) can be estimated using the laser scanner announced angular resolution (0.36°) and the number of beams that intercept the object ($nbeams$) as presented in Eq. (5).

$$w = 2 \cdot d_b \cdot \tan\left(\frac{\alpha}{2}\right) \tag{5}$$

where $d_b$ is the distance between sensor and the box and

$$\alpha = 0.36 \cdot nbeams \tag{6}$$

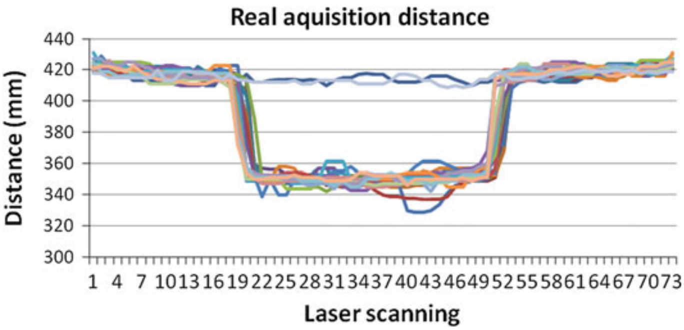


**Fig. 15** Real target acquisition distance

## *4.3 Height*

The height ($h$) can be computed as the difference between conveyer belt average distance ($d_{cb}$) and $d_b$ measured average distances as expressed in Eq. (7). This measure is dependent of the object material type and color.

$$h = \tilde{d}_{cb} - \tilde{d}_b \quad (7)$$

## *4.4 Real and Simulation Comparison*

The measurement of the parallelepiped was based on the acquisition data from the sensor. Figures 15 and 16 present the 25 scan measures for real and simulated scenarios respectively.

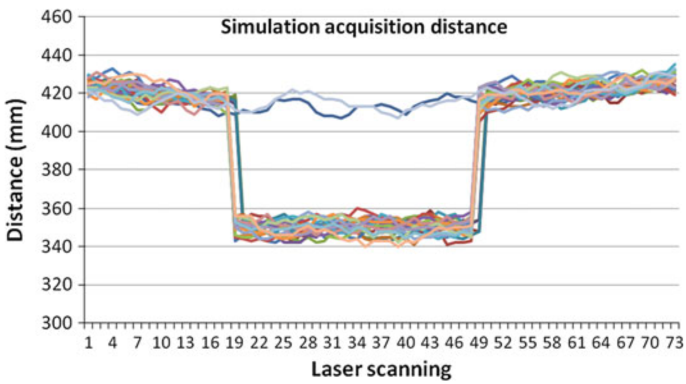


**Fig. 16** Simulated acquisition distance

**Table 2** Statistical main indexes for real and simulation comparison

| Statistical index | Real measurement | Simulator measurement |
|---|---|---|
| Average of conveyer belt distance (without objects) | 418.16 | 419.21 |
| Standard deviation of the conveyer belt distance | 3.89 | 4.01 |
| Average of parallelepiped distance | 351.38 | 350.30 |
| Standard deviation of parallelepiped distance | 4.25 | 3.60 |

**Table 3** Numerical results of real and simulation data

| Values in mm | Real measures | Real estimated dimension (mm) | Simulation measures | Simulation estimated dimension (mm) | Real measure (mm) |
|---|---|---|---|---|---|
| Length | nscans = 23 | 152 | nscans = 23 | 152 | 154 |
| Width | nbeams = 32<br>$d_b = 351$ | 70 | nbeams = 31<br>$d_b = 352$ | 69 | 65 |
| Height | $d_{cb} = 418$<br>$d_b = 351$ | 67 | $d_{cb} = 420$<br>$d_b = 352$ | 68 | 65 |

A statistical data analysis for both situations brings up a measurement of simulator realism where the average and standard deviation show the accuracy of simulation (see Table 2).

Measurements for the parallelepiped were obtained for real and for simulation scenarios based on *nscans* and *nbeams*. It is possible to observe (Table 3) that both measures are almost the same. These results validate the implemented SimTwo model.

### *4.5 Noise Spectrum Measurement*

The final comparison between real and simulation model is presented in the FFT of Fig. 17. It shows the spectrum of the real noise (gathered from laser sensor)—red circles, the simulated noise—blue cross line and the filter design—blue dotted line spectrums. It is possible to notice the proximity between the responses that validates the proposed noise spectrum method.

## 5 Conclusions

Simulation is a tool used by researchers and industry development departments that allows to reduce time and materials consumption once environments can be easily tested in a virtual scene. A very important goal of the simulator results is its

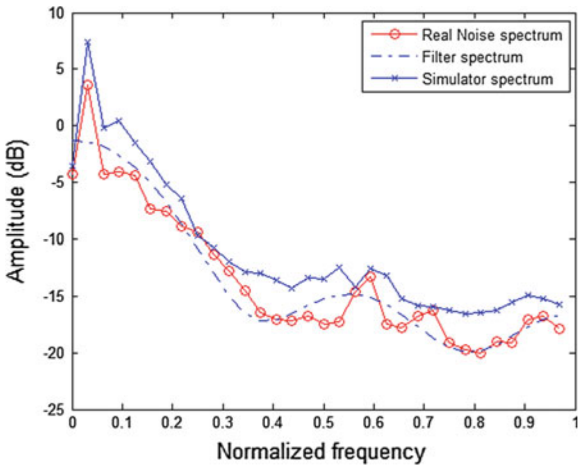


**Fig. 17** Real, simulation and filter spectrum

correctness when compared with real scenarios. The developed simulator (SimTwo) has already been used on some educational settings where the students tested their control algorithms on a model before porting them to real robots. Simtwo was also used on PhD and Msc thesis reaching a mature state. With the purpose of increasing the results quality of the simulation the developed model of a laser scanner was implemented in simulation. Specifications such as target angle, illumination, and noise frequency were approached. Results, when comparing real to simulated data, allow to validate the model. Moreover, with this laser model, it is possible to model industrial tasks such as pick and place of objects with unknown position. As future work, the dependency of surface color and target illumination are ways to increase the realism of the model. Furthermore, mobile industrial robot localization applications based on a laser scanner could be simulated in SimTwo.

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## References

1. Michel O (2004) WebotsTM: professional mobile robot simulation. Int J Adv Rob Syst 1(1):40–43
2. Chen D-Y, Tian X-P, Shen Y-T, Ouhyoung M (2003) On visual similarity based 3D model retrieval. Comput Graph Forum 22(3):223–232
3. Okubo Y, Ye C, Borenstein J (2009) Characterization of the Hokuyo URG-04LX laser rangefinder for mobile robot obstacle negotiation. In unmanned systems technology XI, Orlando, FL (SPIE 7332)

4. Kneip L, Tache F, Caprari G, Siegwart R (2009) Characterization of the compact Hokuyo URG-04LX 2D laser range scanner. In: IEEE international conference on robotics and automation (ICRA)
5. Costa P, Gonçalves J, Lima J, Malheiros P (2011) SimTwo realistic simulator: a tool for the development and validation of robot software. Theory Appl Math Comput Sci 1(1):17–33
6. Costa P (2012) Simtwo webpage. Available at http://www.fe.up.pt/~paco/wiki/
7. ODE, Open Dynamics Engine. Available at http://www.ode.org/
8. Glscene. Available at www.glscene.org/

# On the Application of Discrete-Event Simulation in Production

**Farhad Norouzilame and Mats Jackson**

**Abstract** The current fierce competition within the manufacturing industry throughout the world is a result of globalization and dynamic changes in the market. This new era within the production world requires shorter lead times, integrated logistics, capabilities regarding handling changes in product volumes and variety, as well as conformity to environmental rules and regulations legislated by governments and organizations. Apparently, the multitude of variables needed to solve problems complicates the decision-making process. In order to provide solutions for complex problem solving within production development which include many variables and a certain amount of uncertainty there is a need for robust decision making tools. Discrete-event simulation (DES) is one of the virtual tools that can be used as a support for decision-making for production related problems. The current paper addresses challenges which cause low utilization of DES in industry along with a framework for handling those challenges and performing DES projects in an effective and efficient way.

## 1 Introduction

A constant challenge within production development in the manufacturing industry is the need for a continuously analysis of processes, whether the production process itself or the working methods. To be able to improve the production processes, the development engineers and managers must have two types of perspectives in their mind. First of all, they must be clearly aware of the current

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situation of their processes. Secondly, they have to have a good estimation of the future state of their processes. While the first perspective lets them manage their process, resources, and how they should interact in the current time, the second one would enable them to initiate developments in the right direction and reacting to the changes accordingly. Having a suitable estimation of the future state of the process would let production managers to predict, plan, and eventually decide better in future.

Simulation is a valuable tool that provides the possibility of modeling a process in a virtual environment which enables investigation of different possible scenarios based on possible future events. If used in the proper context, simulation can provide useful information about both current and forthcoming state of the desired system. Still, simulation within production development is not used commonly tool in industry due to several challenges connected to the application and use of the tool in everyday work in companies. The objective of this paper is to provide a generative framework to cope with the challenges of utilizing DES for production improvement purposes.

The paper is structured as following. First, it has been tried to provide some definitions of simulation followed by a background about discrete event simulation. After that the application of DES in production has been introduced plus reasons for low level of its integration. Then methodology and some information regarding the case study have been provided. The paper continues by analyzing challenges regarding the use of DES in industry. Then the suggested framework for practical implementation of DES in production along with its three main parts will be introduced. Finally, conclusion and future research areas have been discussed.

## 2 Literature Background

### *2.1 Simulation*

There are several definitions of simulation available from different perspectives. A simulation is the imitation of the operation of a real-world process or system over time [1]. Through the imitation of reality, one would be able to investigate the simulated process far in advance. This is mainly because of one of the evident but significant advantages of simulation, i.e., time compression which has become possible thanks to the technological improvements of modern computer hardware.

Other resources has defined simulation as the use of mathematical or logical model as an experimental vehicle to answer questions about a reference system [2] or the act of reproducing the behavior of a system using a model that describes the process of the system [3]. Each of these sources defines simulation from a different perspective. However, simulation considering its contemporary applications could be defined as the creation a virtual version of a real-world process with a certain level of abstraction (depending on the purpose of the simulation), in order to study a process for either gaining insight or providing a solution regarding a problem aroused in the system. This definition, although long, reflects a wider spectrum of the term 'simulation' with an inclination toward its application within technology.

### 2.2 Discrete Event Simulation

There are different categories of simulation depending on which criteria are considered. Three main categories of simulation are [4]:

- Static versus dynamic
- Deterministic versus stochastic
- Discrete versus continuous

The first two classifications are not in favor of this paper but the last classification which divides simulation models into discrete or continuous would be elaborated. A *discrete system* is one in which the state variables(s) change only at a discrete set of points in time whereas a *continuous system* is one in which the state variable(s) change continuously over time [1]. Figure 1 simply shows how a discrete system is differed from a continuous system considering the change of state over time.

A *system* is defined as a group of objects that are joined together in some regular interaction or independence toward the accomplishment of some purpose. The *state* of the system is defined to be that collection of variables necessary to describe the system at any time, relative to the objectives of the study [1]. Although systems are categorized as discrete or continuous, "few systems in practice are wholly discrete or continuous, but since one type of change predominates for most systems, it will usually be possible to classify as system as being either discrete or continuous" [4].

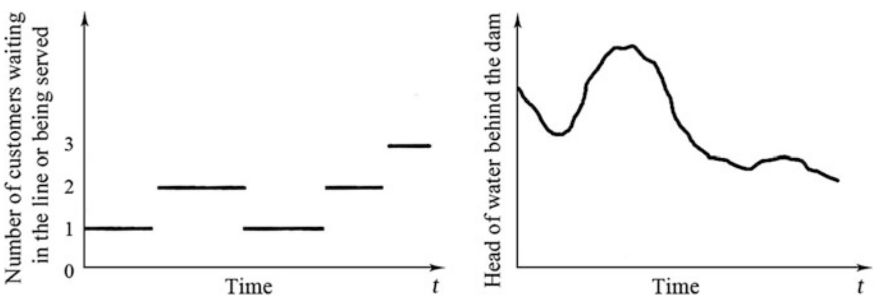


**Fig. 1** Discrete versus continuous system state variable

A flashback to the history of the simulation languages shows that there have been five different periods of chronological development of simulation programming languages [5].

1. The Period of Search (1955–1960)
2. The Advent (1961–1965)
3. The Formative Period (1966–1970)
4. The Expansion Period (1971–1978)
5. Consolidation and Regeneration (1979–1986)

### *2.3 Discrete Event Simulation and Production Improvements*

One of the areas where DES technology is most frequently used is manufacturing [6]. Simulating production systems allows system experts to:

- Analyze the system capacity and output
- Analyzing assembly operation
- Optimizing the utilization and cycle time
- Investigate the dynamics of the supply chain
- Evaluate the flow of materials

Furthermore, DES could be used for scenario-making or scenario-planning for production companies where it can be a useful tool for both short-term and long-term decision making. Scenario, a "tool" in the "strategist's arsenal" is predicted on the assumption that if you cannot predict the future, then by speculating upon a variety of them, you might open up your mind and even, perhaps, hit upon the right one [7]. Discrete event simulation enables managers to run their models based on different conditions and assumptions that results in different hypothetical scenarios which can be analyzed later to provide clues for taking best decision.

### *2.4 Diffusion of Discrete Event Simulation into the Manufacturing Industry*

Simulation integration has been defined as the integration of simulation from functional, structural, hierarchical, and procedural aspects into the manufacturing system development process, where development refers to the entire life-cycle of the system, i.e., the planning, design, redesign, development, reconfiguration, etc. of manufacturing system [8].

As mentioned earlier, discrete event simulation languages have been developed and consolidated for many years ago and there are numerous tools for performing discrete event simulation projects. Also, the knowledge of simulation techniques and concepts has developed up to a sophisticated level. However, despite the

**Table 1** Studies conducted on the use of DES in industry, adapted from [9]

| Usage measured (%) | Replies | Response rate (%) | Main country studied | Conducted year | Reference |
|---|---|---|---|---|---|
| 9 | 431 | NA | UK | 1991 | SSG referred to in [10] |
| 4 | 95 | 42 | Sweden | 1992–93 | [11] |
| 7 | 140 | 20 | Sweden | 1999 | [10] |

mentioned facts, DES has not been fully integrated and routinely used in production-related decision making processes albeit being a powerful tool for system analysis. Table 1 reflects the studies conducted on the use of DES in industry.

The low level of DES integration into industries is caused by different challenges, among them:

- Cost of simulation projects: simulation projects are considered to be rather expensive.
- Time: simulation projects sometimes take so long due to several factors
- Complexity of the model for the end user: the model created by DES tools may become too difficult for the end user to understand and use.
- Lack of a DES team in organization structure: companies normally do not realize the potential of DES as a support tool and therefore tend to use it as a partial temporary "thing."

Looking from a general perspective, two types of knowledge needed for a DES project are system expertise and simulation expertise. System expertise includes the knowledge about the desired system which is supposed to be modeled and simulation expertise is the knowledge needed to perform a productive simulation project which in its turn encompasses the modeling techniques plus how to manage a simulation project as shown in Fig. 2. While all factors play an important role in accomplishing a constructive DES project, management of DES projects is of crucial importance and can affect the whole project.

The problems with integration are not so much related to the lack of technology, as they are to the lack of knowledge of and capability to use that technology and related standards, methods, models, and tools in a structured way and with a

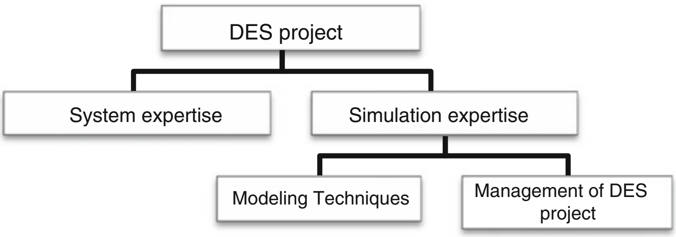


**Fig. 2** The required competence for conducting a DES project

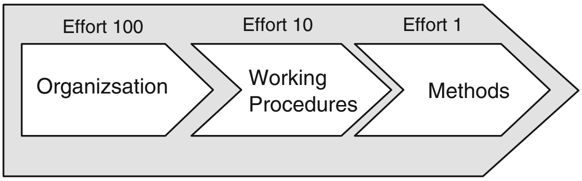


**Fig. 3** Effort to implement DES at different levels of a company [14]

holistic view on the systems and processes concerned [8]. Same concept applies to the integration of DES to industries as the problem is aroused from managerial perspective rather than the simulation technique itself. In another words, companies suffer more from not having a clear process of utilizing DES in their decision makings rather than not having access to the knowledge or tools. Therefore, before companies start to use simulation as a tool for decision-making, it is of great importance for them to have a platform which includes clear methodologies and working methods which ensures the reliability and quality of DES projects.

Having a systematical procedure for performing DES projects would be extremely beneficial and helpful for industrial companies. It allows them not only to make the best use of discrete-event simulation but also helps them to realize how they are supposed to act before, during and after DES projects execution.

For improving the application of DES in production environments, The integration of DES into a company's decision-making process demands its adaptation in different levels as shown in Fig. 3. Several authors have written about the methodologies used for a DES project [1, 4, 12]. However, the other two parts, i.e., organization structure and working procedure are ill-structured and weakly organized in companies today in the DES field [13].

# 3 Methodology

## *3.1 General*

The paper presents a case study that is based on the combination of a literature survey around the application of DES tools in production environment and a practical case. In parallel to the literature study a simulation project has been conducted for a real-world industrial problem to investigate the practical challenges of using DES as a decision-making support in industries.

A case study is a preferred research method when a specific phenomenon is to be closely studied within its natural context [15]. Case studies can be characterized by the fact that they often study a phenomenon when and where it happens and that the exact context or delimitations are not fully known [15].

The mentioned DES project has been conducted in an industrial company in Sweden with the objective to provide decision-making support for the production development. The real-life project has reinforced the practicality of the research which has allowed to see and to experience challenges which arise during the use of DES for overcoming a problem in production environment. Performing a DES project in parallel to the theoretical studies allows applying and analyzing the available methodologies and investigating their efficiency in industrial cases.

Furthermore, it was a useful practice for learning and understanding when and how to regard DES as a tool for achieving solution. The performance of a DES project is a valuable experience which let the team which performs it going through a transition from considering DES a vague IT tool to a useful decision making support tool. Moreover, this experience causes the team to find the best structure, working procedure, and techniques which saves considerable amount of time and cost in further projects.

## 3.2 The Case Study

As mentioned before, the conducted case study was based on a combination of a theoretical study as well as a world-life case of DES project in the manufacturing industry. Both aspects of the project have been considered in an attempt to provide a framework considering the practical aspects of a DES project. The case study is about the simulation of an Automatic Storage and Retrieval System which is couples into a heat treatment process. The ASRS, simply an automatic storage between the machining process and heat treatment:

- Stores the incoming soft parts
- Feeds the furnace with raw articles according to priorities
- Receives the hardened parts from the furnace and stores them
- Delivers ready parts as output to next process (further machining or assembly).

Figure 4 shows the current layout of the equipments including the ASRS and hardening process.

Today, the hardening department works smoothly in accordance with other production units and can fulfill the current demand of the assembly unit. However, due to the increasing high demand, the company has started to think of another automated heat treatment furnace for working in parallel to the old one. In that case two furnaces that are supposed to work in parallel would use the ASRS in common that should be analyzed precisely to avoid further problems. So, a DES project was considered to study the system behavior under prospective conditions.

Along having a model of the ASRS system which allowed the investigation of possible layouts and output rate, the case-study was an opportunity to perform a DES project in an industrial environment and understand the practical challenges and obstacles in front of using DES for production development purposes.

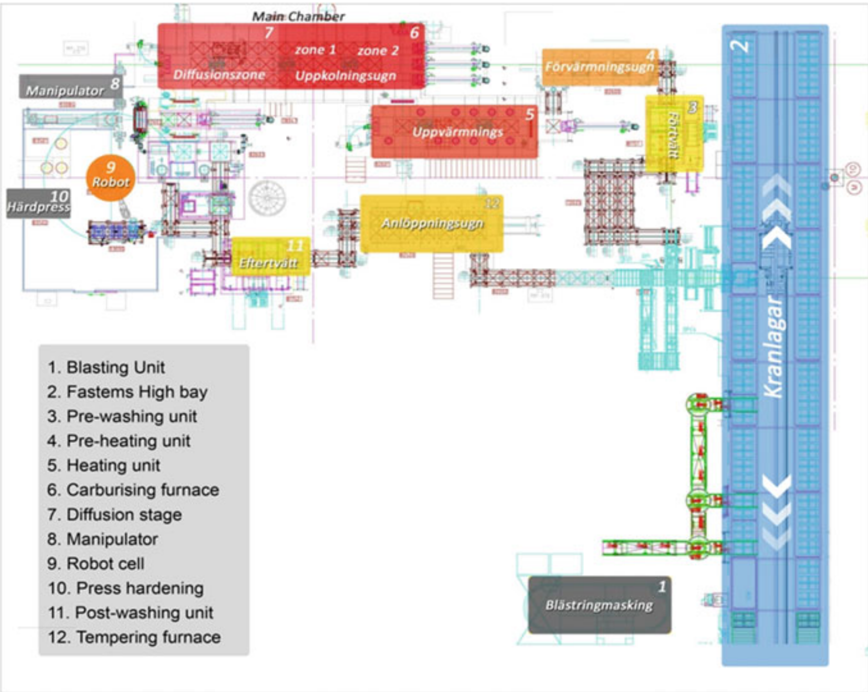


**Fig. 4** Layout of the equipments in hardening department

# 4 The Proposed Framework for Application of DES

## *4.1 Background*

Simulation projects within industries usually tend to become more complicated than what it seems before kickoff due to some practical problems which are not considered in theory. Therefore a gap is felt when using classical methodologies such as the one shown at Fig. 5 when performing DES projects for production improvement sake. When it comes to industrial context, DES projects require a well structured organization or team which uses clear cut practical algorithms. Industrial projects are capital intensive and cannot be performed on a trial and error basis.

There is often a dilemma when it comes to using DES for problem-solving in industries. In one hand, DES could be seen as a powerful tool for providing solutions for solving complex problems. On the other hand, managers know about the challenges of DES projects which create skepticism. In a higher level it is often the organization which lacks a suitable perception of how to utilize DES as an efficient tool in production. Therefore, an integrated framework which helps organizations to perform DES projects by going through a certain process which

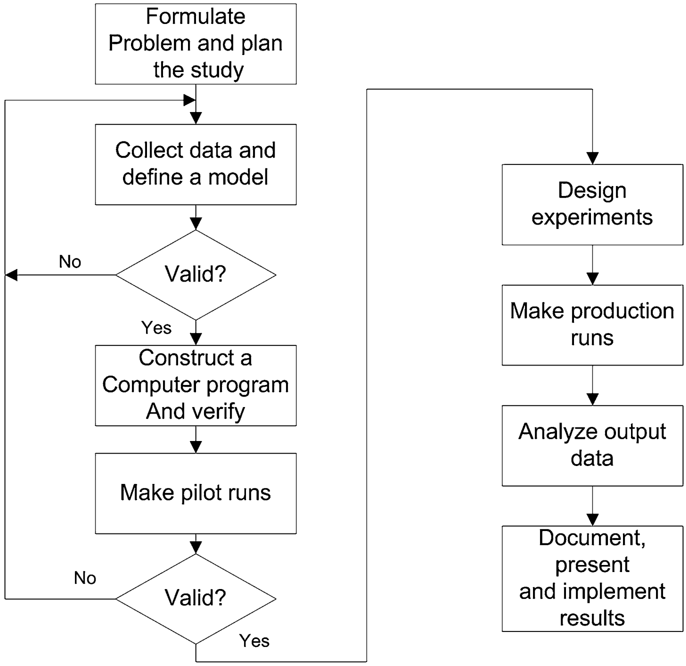


**Fig. 5** Steps in a simulation study [4]

defines the required structure plus the action plans along with the defined resources would be extremely useful (Fig. 6).

## *4.2 Formation of DES Team*

For performing DES projects in industrial context, a DES team with sufficient expertise in three main areas, i.e., production, simulation, and management should be created in the organization.

A DES team must have three areas of competence shown in Fig. 7. It should be reminded that the DES team does not necessarily require the presence of people on each of those areas, rather the expertise and competence is the necessity. Also, the DES team members can conduct DES projects in parallel to their routine job which

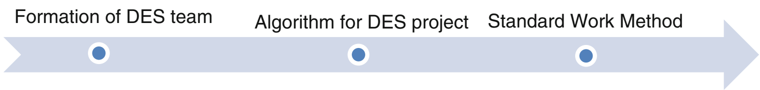


**Fig. 6** Main parts of the suggested framework

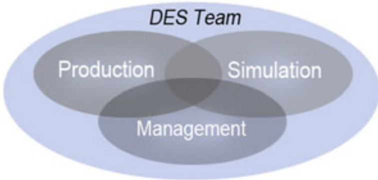


**Fig. 7** Formation of a DES team in an industrial organization

provide more flexibility. Any lack of competence in DES team would lead to the inefficiency of the project results in a way.

## 4.3 Algorithm for Performing DES Project

Once the DES team is formed, it is of great importance to have a standard procedure for confronting different problems which need DES as a decision making tool. The algorithm provided in this research could be the base of the DES projects in organizations to provide a common standardized way. A clear cut procedure makes further steps much simpler and lets the whole project proceed smoothly. Having the right criteria for deciding to consider or not consider DES as a decision-making tool is very crucial in the first place and relieves a lot of ambiguity for the project executives. The first phase of the suggested algorithm focuses on the preparations of DES project while the second phase is more about how to precede the project.

First part of the algorithm focuses on the preparations before the project kick-off and ensures the availability of needed resources of the project (Fig. 8). The latter phase (Fig. 9) which is similar to the classic ones provided by [1, 4] clarifies the steps that must be taken when decision about the use of DES is made. It includes the design of Graphical User Interface (GUI) which is a significant step to make the model both understandable and usable

## 4.4 Standard Work Method for Performing DES

Irrespective of the size of DES team and the type of DES project, there must be a standard work method for performing DES projects which guaranties the quality of the project and prevent redundancy by using stable methods. The suggested standard work method for DES project provides a clear procedure and ensure that all tasks of the project is performed by the right person at the right time giving deliverables of each step (Fig. 10).

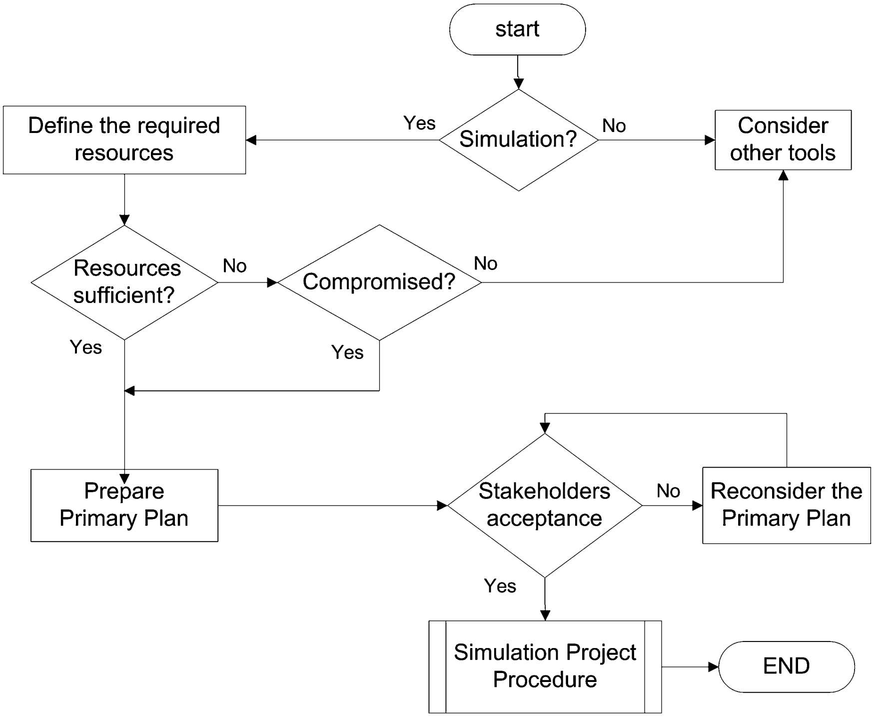


**Fig. 8** Suggested algorithm for performing DES projects in industries, phase 1

## 5 Summary and Future Work

Application of discrete event simulation tools within production, despite of it power to solve complex problems containing uncertainty and probability, demands a standard methodology which takes into consideration all the practical issues within and around DES projects which is often underestimated in classic, theoretical methodologies. Such methodology must be able to provide solutions for all the principal questions of industrial managers such as the consideration of using discrete-event simulation or how to use it for achieving the desired results.

Regarding the application of DES in production systems, some potential areas for further study could be:

- Applying suggested methods, get more feedbacks, improve and adapt them to industrial context.
- Studying different organizational structure which provides the most efficient DES projects.
- Exploring innovative methods of using DES within different areas of production for instance using simulation as an enabler tool to achieve flexibility in production.

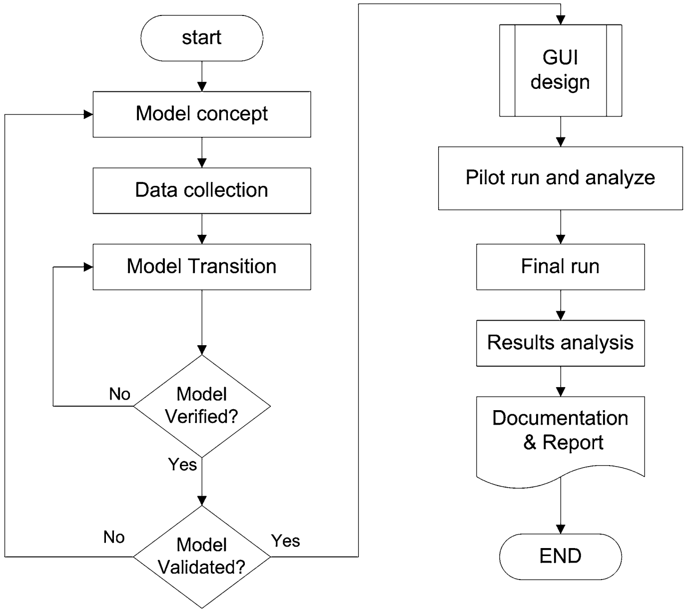


**Fig. 9** Suggested algorithm for performing DES projects in industries, phase 2

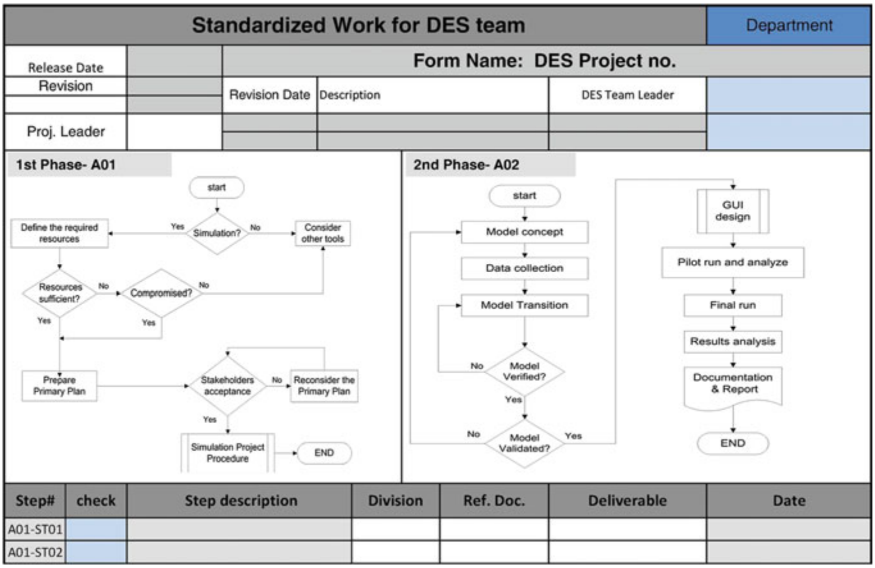


**Fig. 10** Standard work method for performing DES projects

DES has great capacity to be used for production improvement purposes. However, the main challenge is 'how-to' perform DES projects in a way that it pays off reasonably. Would DES be integrated to industrial companies' decision making process? Would it be reasonable to conduct DES projects in industries at all?

For achieving the most efficient use of discrete event simulation and finding the most suitable areas of application of DES, more strategic steps must be taken by companies rather than partial and sporadic use of DES. Companies above all must be able to know their processes and have a good understanding of the results of implementing simulation tools. They require a systematic approach for using DES as a support tool for decision making which best fits to their organization. This included methodologies, working methods, and even changes in the organization structure for achieving best results out of utilizing DES.

Holst [8] in his study around DES and its integration to the manufacturing system development mentions about the future of modeling and simulation originally from the Next-Generation Manufacturing (NGM):

"… modeling and simulation (M&S) will reflect a new way of doing business rather than supporting technology. It will make virtual production a reality. All production decisions will be made on the basis of modeling and simulation methods, rather than on build-and-test methods. M&S tools will move from being the domain of the technologist, to being a tool for all involved in the product realization, production and business process."

## References

1. Banks J, Carson JS, Nelson BL (1995) Discrete-event system simulation. Prentice Hall, US
2. Page EH (1994) Simulation modeling methodology: principles and etiology of decision support, Ph.D. Dissertation, Department of Computer Science, Virginia Tech, Blacksburg, VA
3. Krajewski LJ, Ritzman LP, Malhotra MK (2007) Operations management, 8th edn. Pearson, New Jersey
4. Law AM, Kelton WD (2000) Simulation modeling and analysis, 3rd edn. McGraw-Hill, US
5. Nance RE (1993) A history of discrete event simulation programming languages, Department of Computer Science, Virginia Polytechnic Institute and State University, Blacksburg, Virginia
6. Cornford T, Doukidis GI (1991) An investigation of the use of computers within operational research. Eur J Inf Syst 1(2):131–140
7. Mintzberg H, Ahlstrand B, Lampel J (1998) Strategy safari—A guided tour through the wilds of strategic management. The Free Press, New York
8. Holst L (2004) Discrete-event simulation, operation analysis, and manufacturing system development; towards structure and integration, Doctoral dissertation, Department of Mechanical Engineering, Lund University, Lund, Sweden
9. Johansson B (2006) On virtual development of manufacturing systems: proposal for a modular discrete event simulation methodology, Doctoral dissertation, Chalmers University of Technology, Gothenburg, Sweden

10. Ericsson U (2005) Diffusion of discrete event simulation in Swedish industry, one way to an increased understanding, Doctoral thesis, Department of Materials and Manufacturing Technology, ISBN 91-7291-577-3, Chalmers University of Technology, Gothenburg, Sweden
11. Saven B (1994) Beslutstöd och simulering i verkstadsföretag- en sammanfattning av två enkätstudier (In Swedish), Technical Report LiTH-IDA-R-94-17, Department Of computer and Information Science, Linköping University, Sweden
12. Johansson B, Grünberg T (2001) An enhanced methodology for reducing time consumption in discrete event simulation projects, 13th European Simulation Symposium, SCS Europe BVBA, pp 61–64
13. Johansson B, Johnsson J, Kinnander A (2003) Information structure to support discrete event simulation projects. In: Proceedings of the 2003 winter simulation conference, Chick S, Sanchez PJ, Ferrin D, Morrice DJ (eds), New Orleans, Louisiana, Dec 7–10, (invited paper)
14. Östman J (1998) Virtual reality and virtual prototyping—Tillämpningar i Amerikansk Fordonsindustri, (In Swedish). Utlandsrapport USA 9806, Swedish Office of Science and Technology, Sweden
15. Yin KR (1994) Case study research—Design and methods, 2nd edn. Sage, Thousand Oaks

# A Simulation Study on Assemble-to-Order Production for a Taiwan Machine Tools Manufacturer

**Yi-Chi Wang, Toly Chen and Fu-Chun Chuang**

**Abstract** Machine Tools Assembly has being one of the most important industries in Taiwan for past few decades. Assembling a single modern CNC machine tool may take a few weeks or even months depending on factors such as the complexity of the machine structure, the supply of key components such as spindle, bed, coolant systems, and tool magazine, management of human resources, and the availability for required equipment or tools. The most costly resource for machine tools assembly is the space for assembly. At least an area of 15–20 $m^2$ is necessary for a single machine and essentially the space will be occupied as long as the machine is completed. Besides this spatial problem, Taiwan's machine tools manufacturers today also face serious unstable supply of the key components offered by outside suppliers. This study focuses on two important decisions faced by every Taiwan machine tools manufacturer: selecting the customers' orders for assembly launch and determining the priority of the on-going assembly projects for allocating the limited resources like equipment and tools, and human forces. A discrete-event simulation model for a complicated machine tools assembly system considering the spatial problem and the quality issue of key components is developed to evaluate several rule combinations for making these two decisions. Simulation experiments are then properly designed and conducted under various system conditions for detailed investigation.

## 1 Introduction

Many people might hear about the great performances of Taiwan's enterprises in global semiconductor industry, but few may be aware that machine tools industry in Taiwan has become an important contributor to Taiwan's economy. After

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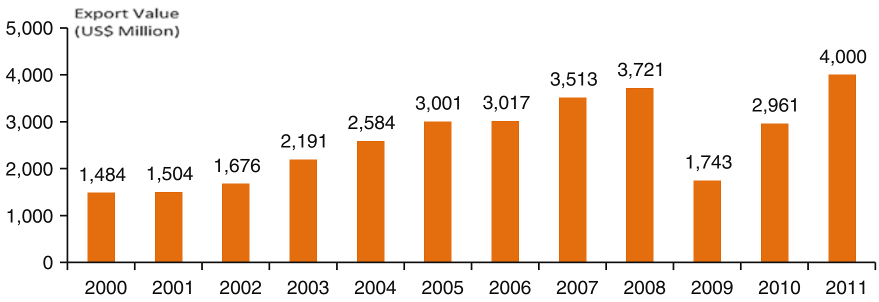


**Fig. 1** Export values of Taiwan's machine tools industry since 2000

weathering in the global recession of 2009, Taiwan's machine tools industry evidently demonstrated its rapid recovery compared with their counterpart of the other countries. The total export value of Taiwan machine tools was close to 3 billion US dollars in 2010 and reached 4 billion US dollars in 2011. Figure 1 shows the export values of Taiwan's machine tools industry since 2000. This achievement made the country the fourth in the world behind Japan, Germany, and Italy. Taiwan's machine tool products are favored by global users because of their flexible customization, reliable quality, and reasonable price. The major regions of sales include China, United States, Turkey, Thailand, Germany, India, Brazil, Netherlands, and so on. According to Taiwan's Ministry of Economic Affairs, currently there are around 600 machine tool and the accessory manufacturers in this island and 72 % of these companies are clustered in the central area of Taiwan. Business Weekly, one of the most popular magazines in Taiwan, touted the cluster in central Taiwan with the 3 billion US dollars worth of business in machine tools and its related industries generated in 2010 and concluded "Without this cluster, half of the world's 100 million iPhones could not be made."

Most of the companies in this machine-tool cluster of central Taiwan are small- or medium- sized firms (less than 500 employees). It is not uncommon that such the small/medium-sized companies only offer a certain types of machines. Their strategy is to stay long-term focused at these machine types trying to develop more reliable products with competitive pricing and timely delivery. More importantly, these companies investigated and predicted the needs of end-user of their products. They then improved their offerings to meet their customer's demands.

A machine tool is composed of complex mechanisms. The main function of the mechanisms is smoothly and precisely to move either the tool or the workpiece, or both simultaneously. The mechanisms also determine the degrees of freedom for the machine tool (called number of axes). The main body of the machine tool structure constitutes the machine frames made of welded steels, casting irons, or polymer concrete [1]. It can be built in one block (called bed) or assembling several individual sub-frames. The configurations could be C frame with fixed/transverse column, or gantry frame. The other basic element is the guide system, together with the drive motors, controlling the precision and smoothness of the machine axis movements. Ball screws have been widely employed because they are a reliable mechanical solution to convert rotational movement to linear movement required for tools or working tables. Nowadays, they are viewed as one of the symbols for a modern machine tool. In addition to the frames and guide system, spindle plays a key role in machining operation because it not only offers the required cutting speed but also provides sufficient power to get the material removal processes done. It is the heart of a machine tool. The characteristics of the spindle in terms of its power, speed, stiffness, drive method, bearings, and thermal properties highly impact the machining performance and the quality of the end product. It is evident that the recent trend of machine tool technologies is focused on developing multi-tasking machine tools capable of running high speed or high performance machining on harder materials with environmental friendly coolant systems. Other than that, the most critical requirement for machine tool manufacturers is high modularity and customization of their offerings. This is the key for a machine tool builder to hold competitive edge in the market. The standard accessories like the spindle, tool holder, automatic tool changer (ATC), tool magazine, oil/coolant separator, etc. are for certain specifications of a machine tool. Many optional accessories like the workpiece measuring system, coolant system for spindle, auto door, etc. should be offered for the customers to choose for their machine. Therefore, Taiwan's machine tools manufacturers must be able to provide a large variety of configurations and flexible options of machine tools in order to meet the needs of various customers in different industries.

According to statistics released in 2007 by the directorate General of Budget, Accounting and Statistics (DGBAS) of Taiwan, the population density of this island is the second highest in the world among countries with a population of at least 10 million. That indicates space is one of the most costly resources for any business in Taiwan. This issue is even more severely especially in machine tools industry. At least an area of 15–20 $m^2$ is required for assembling a single machine and essentially the space will be occupied as long as the machine is completed and shipped to the customer. The other nightmare which Taiwan's machine tool manufacturers also suffer from is the problems of unstable supply of the key components offered by outside suppliers. This issue may cause the shop floor production several weeks behind scheduled. Besides the spatial problem and availability of key components, limited resources such as skilled labors and special tools and equipment are also critical to complete the machine tool assembly before the due date committed to the customer.

The purpose of this paper is to provide a detailed simulation analysis on two important decisions of assembly planning and control in a machine tools shop floor. The paper is structured in the following way. Section 2 reviews the literature regarding to make-to-order machine tools assembly. Section 3 outlines the machine-tools assembly system and presents the simulation model employed in this study. Section 4 describes the experimental design settings for this study. Section 5 provides the simulation results and discusses the results. Finally, in Sect. 6 we draw our conclusions and provide some directions for future research.

## 2 Literature Review

Kolisch [2] described four different types of make-to-order assembly problems, namely ship assembly, airplane assembly, assembly of synthetic fiber production lines, and machine tool assembly. In machine tools assembly, several make-to-order machines in the shop floor are assembled simultaneously through multi-stage processes under various resource constraints. Obviously, for such highly customized products, traditional mass production systems are not suited for this small batched and make-to-order assembly problem. A shop scheduling system, called PRISMA-Leitstand, has been developed by the machine tool laboratory at Aachen Institute of Technology [3] in cooperation with several machine tool manufacturers, software companies, and research institutes. The system consisted of several features: a hierarchical working scheme for long-term aggregate planning and medium-term detailed scheduling, the visual representation of data and schedules and an interface to MRP system, different model-based finite scheduling procedures, modules for schedule evaluation, as well as a graphical layout component that treats the shop floor area as a scarce resource.

Assembling a single machine tool is like to complete a project. Kolisch [2] showed that this assembly problem can be modeled as a resource-constraint multi-project scheduling problem (RCMPSP). A classical resource-constrained project scheduling problem is well known a NP-hard problem. It is one of the most widely studied project scheduling problems in literature. The problem is to schedule all for activities required for completing a single project. The activities are interrelated by two types of constraints: the precedence constraints forcing an activity not to be started before all its immediate predecessors have been finished and the performing the activities requiring resources with limited capabilities. The objective of the problem is to minimize the makespan of the project. A comprehensive review of solving the classical resource-constrained project scheduling problem was provided by Hartmann and Kolisch [4]. They evaluated the performance of several heuristics and pointed out the most promising procedures. They also analyzed the behavior of the heuristics with respect to their components such as priority rules and meta-heuristic strategy. In 2006, the same author provided an update of their previous survey [5]. Their studies have contributed to significant improvements of some heuristic results.

Kolisch [6] extended the classical RCMPSP by adding spatial resource and part availability constraints. The problem that he dealt with was a practical case for a German company producing customized palletizing systems for chemical or food industry. He formulated a MIP model for the problem that is a generalization of three allocation problems. The objective is to minimize the sum of the weighted tardiness. He proposed an approach and evaluated it on a set of instances. Based on this approach, Kolisch and Hess [7] compared three other heuristic methods and found the one with critical neighborhood optimization method offered better solutions than the other two methods. Kolisch [8] addressed the problem of integrating of assembly scheduling and fabrication lot sizing for make-to-order


**Fig. 2** Five stages for machine tool assembly

production. He presented a MIP model and discussed its properties. A top-down backward method for making several heuristics was proposed to solve the problems.

# 3 Simulation Model

## *3.1 System Description*

In most of the past studies for the RCMPSP, the processing time for each activity is treated as a constant. In real-world machine tools assembly, however, the assembly time for each procedure is highly variable definitely. Detailed scheduling for each assembly procedure is then not suited for such a case. Hence, assembly scheduling in an aggregated manner is very common in the shop floor for Taiwan's machine tool builders. Normally, assembling a machine tool requires five stages shown in Fig. 2. The assembly work in each stage takes a few days depending on the complexity of machine and customer's requests. That's the best case with all the required resources available. If some key-component suppliers are short of stock or if their offerings somehow don't fit the assembling machine, it takes even a few weeks waiting for the new ones to be delivered.

In this study, we try to simulate a assembly planning and control system for a Taiwan machine tools company located in central Taiwan. The company offering a series of vertical/horizontal machining center, CNC turning center, multi-tasking turning center, etc. has totally around 150 employees, 100 of them working in shop floor for assembly. This company does not do any in-house fabrication for the parts and components of their final products. Instead, all the parts and components are procured from outside suppliers. The average revenue of the company in 2011 is close to 50 million US dollars. The products the company offers can be divided into two types of machine tools: small/medium-sized machine (SM) series and large-sized machine (LM) series. Assembling SM series requires fewer resources in terms of the space, number of assemblers, and number of tools. Contrary to the SM series, assembling LM series requires larger space, more assemblers, and tools. The complexity of LM also leads to take more assembly time for each stage. Tables 1 and 2 present an example of assembly information for a SM and a LM, respectively.

We then develop a discrete-event simulation model for this assembly system. Figure 3 shows a schematic illustration for the machine tools assembly system in

**Table 1** An example of assembly data for a small/medium-sized machine

| | Stage | No. of assemblers | No. of tools | Assembly time (days) | | Standard components | | Customized components | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean | Stdv. | Service level (%) | Waiting (days) | Service level (%) | Waiting (days) |
| SM | 1 | 2 | 1 | 3 | 1 | 95 | 3 | 70 | 6 |
| | 2 | 3 | 2 | 4 | 1 | 95 | 3 | 90 | 7 |
| | 3 | 3 | 1 | 1 | 0 | 95 | 3 | 70 | 7 |
| | 4 | 4 | 1 | 1 | 0 | 95 | 3 | 70 | 9 |
| | 5 | 2 | 0 | 3 | 1 | 95 | 3 | 80 | 8 |

**Table 2** An example of assembly data for a large-sized machine

| | Stage | No. of assemblers | No. of tools | Assembly time (days) | | Standard components | | Customized components | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean | Stdv. | Service level (%) | Waiting (days) | Service level (%) | Waiting (days) |
| LM | 1 | 2 | 2 | 5 | 1 | 95 | 3 | 90 | 8 |
| | 2 | 3 | 1 | 5 | 1 | 95 | 3 | 60 | 6 |
| | 3 | 3 | 2 | 6 | 1 | 95 | 3 | 70 | 9 |
| | 4 | 4 | 2 | 4 | 1 | 95 | 3 | 70 | 7 |
| | 5 | 3 | 2 | 7 | 1 | 95 | 3 | 70 | 11 |

this study. The simulation model consists of three modules: order arrival module, shop floor module, and inventory control module. The order arrival module deals with the customers' demand arrivals. The time between individual customer demand arrivals follows an exponential distribution with a mean value of 3 days. The demand size is uniformly distributed from one to eleven machines. Machines within the same demand may be the same type or different possibly, and may be committed with various due dates after communicating with the customers. Each machine will later be treated as an individual order in shop floor. Before being launched for assembly, the orders will first be classified as one of the two groups (the SM and the LM). In the shop floor, two types of areas are separately laid out for the SM and the LM. A single SM requires a space of 15–20 $m^2$, and a single LM needs a larger space. The company offers 5 different types of SM and 4 types of LM. All the orders waiting for assembly launch must be checked whether all the following requirements are satisfied before proceeding forward:

1. There must be a space available for a SM or a LM.
2. The number of assemblers and the number of the tools must be enough to process the operations of the first stage of the order.
3. The inventory module must provide the information regarding the availability of the standard components, as well as the customized components. All the components required must be ready.

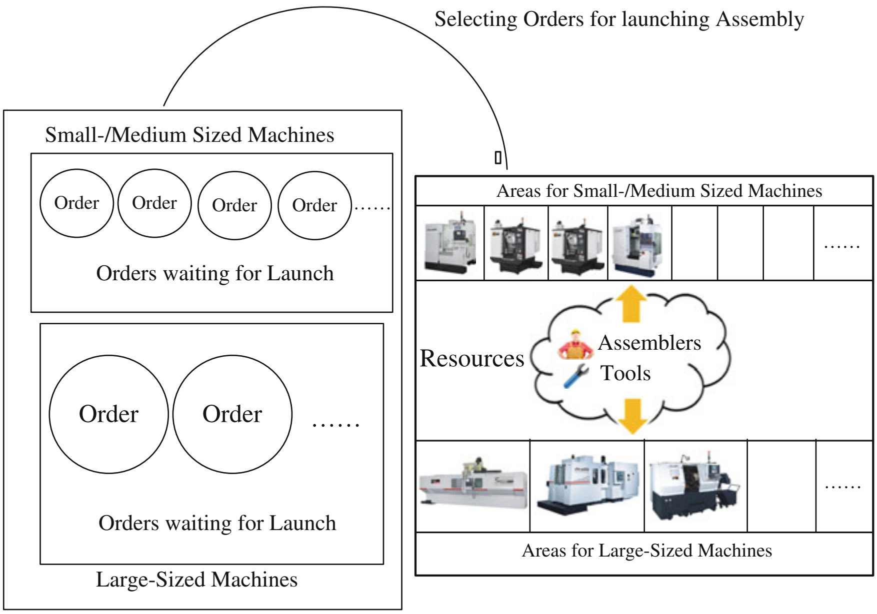


**Fig. 3** A schematic illustration for the machine tool assembly system

It should be noted that outsourcing of components plays a very important role in Taiwan's machine tools industry. Here we use the service levels of the components (standard and customized) that the suppliers can offer to determine the availability of the components and how long the machine tool company may need to wait for delivery of the components.

## *3.2 Order Releasing Rules*

Once the orders are ready for assembly launch, the shop floor manager adopts the order releasing rule to select one among these orders. The following are the four order releasing rules tested in this research:

- First Come First Served (FCFS): The order that has been placed first by the customer is selected for assembly launch.
- Shortest Total Assembly Time (STAT): The order with the shortest total assembly time is selected. It should be noted the assembly times given for all the five stages here are all estimated by the shop floor operators.
- Earliest Due Date (EDD): The order with the earliest due date is selected.
- Random (RAND): Randomly select an order to launch for assembly.

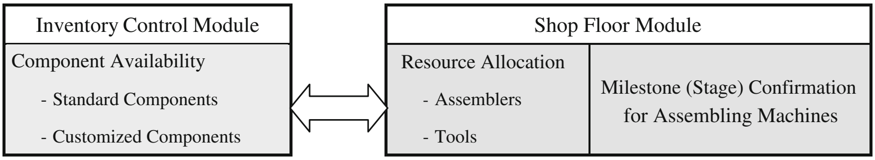


**Fig. 4** The work of shop floor module and inventory module

## *3.3 Resource Allocation Rules*

Once the order has been launched for assembly, the shop floor module is responsible for checking progress of each assembling machine and resource allocation. Figure 4 demonstrates the relations between shop floor module and inventory module. Whenever all the procedures for a certain assembly stage of a machine tool are completed, the shop floor module will contact with the inventory module to check the inventory status of components. If all the required components are available then the shop floor module then starts handling the resources (assemblers and tools) allocation problem. Only the machines with components ready for next-stage assembly send resources requests to the shop floor module. The shop floor module then selects one among the requests with one of the following rules to assign highest priority for having the requested resources first when they are available.

- First Come First Served (FCFS): The machine fist sending the resource request is selected.
- Least Remaining Stages (LRS): The machine with the fewest number of remaining stages is selected.
- Shortest Assembly Time (SAT): The machine with the shortest assembly time for its next stage is selected.
- Shortest Remaining Assembly Time (SRAT): The machine with the shortest assembly time for all its remaining stage(s) is selected.
- Minimum Operators Required (MOR): The machine requiring the fewest operators for its next stage is selected.
- Minimum Equipment Required (MER): The machine needing the minimum amount of equipment for its next stage is selected.
- Earliest Due Date (EDD): The machine with the earliest due date is selected.
- Random (RAND): Randomly select one of the machines sending resource requests.

If tied with all the above rules except the last one, RAND is used to break the tie. The machine is ready for its next-stage assembly after being given enough assemblers and tools.

This discrete-event simulation model is developed in Visual C++ with an Intel Core i3 CPU. All the mentioned elements for this machine tool company are programmed as modules. With such a modular architecture, the size of this simulation model can be easily extended to assemble as many types of machine tools as user wants. This simulation model and its results have been verified and validated by the techniques recommended by Law [9]. This discrete-event simulation model logically mimics practical production planning and control of a real-life machine tool manufacturer of Taiwan and can be used to see how the output measures of performance are affected by exercising numerically the model for the inputs.

## 4 Experimental Design

The warm-up period is set 2 years to have this system to reach a steady state. After system warm-up, the performance measures are computed for the next 5 years. We evaluated four order releasing rules integrated with eight resource allocation rules described above under four different system conditions. These four system conditions were set by varying the mean demand size and service level that the key component suppliers can offer. The minimum demand size is one machine and the maximum demand size is set eleven for the condition of stable demand, while the condition of the unstable demand is designed to follow the real demand pattern of 2007–2011 including the most recession year, 2009. Table 3 shows the maximum machine quantities per customer demand for the company. The system conditions also rely on the component procurement. Maximum demand size of 11 machines indicates that the company, on average, will receive orders of around 780–800 machines per year. The service level here determines the proportion of all the components demanded by the company is delivered without delay. Two different levels (40–70 % and 60–90 %) for the suppliers' service level are designed for the experiments. The parameter settings for the four system conditions are summarized in Table 4. The due date of the order is determined based on the following equation:

$$\begin{aligned}\text{Due Date} = {} & \text{Arrival Time} + \text{Allowance factor (K)} \\ & \times \text{Estimated Total Assembly Time}\end{aligned}$$

The allowance factor (K) was drawn from the uniform distribution between 2 and 3 for orders with tight due dates and between 6 and 8 for orders with loose due dates. 30 % of all the orders are set with the tight due dates. The system is conducted with 30 replications under each system parameter setting.

**Table 3** Maximum machine quantity per customer demand (each demand size)

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| Stable demand | 11 | 11 | 11 | 11 | 11 |
| Unstable demand | 12 | 13 | 6 | 10 | 14 |

**Table 4** Experiments are conducted under the following conditions

| System condition | Demand | Procurement (service level %) |
|---|---|---|
| C.1 | Stable | 40–70 |
| C.2 | Stable | 60–90 |
| C.3 | Unstable | 40–70 |
| C.4 | Unstable | 60–90 |

Three performance measures as follows are used for system evaluation.

- Total number of orders completed: The total number of machines shipped to the customers within the simulation period (5 years).
- Mean Tardiness for the orders completed: This measure is the average of the positive differences between the completion times of the orders and their committed due dates.
- Service Rate: The ratio of the number of no-tardy orders to the total number of orders completed.

## 5 Results and Analysis

Figures 5, 6, and 7 each shows the performances of various rule combinations on total number of finished machines, mean tardiness, and service rate, respectively. It is obvious that STAT dominates the other three rules on all of the three measures. With STAT, the company can be more productive by making 150–200 more machine tools in this five-year simulation compared with EDD, which is currently employed by the company. That means STAT can help the company earn about

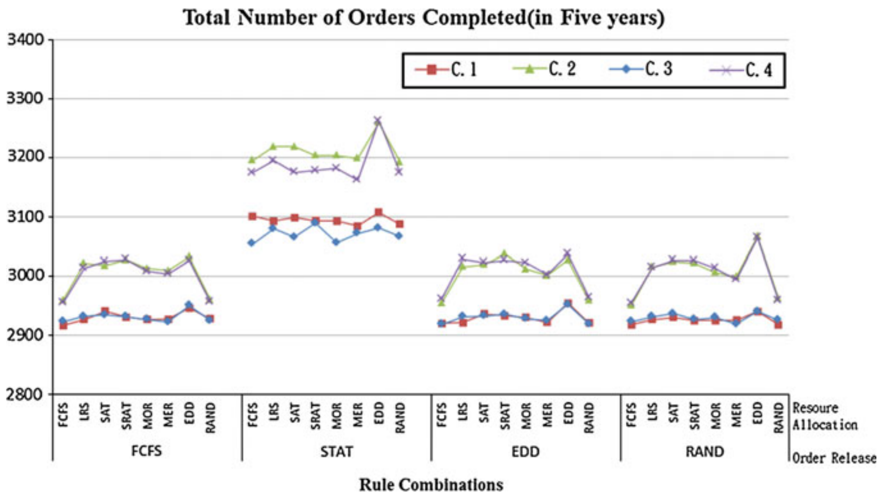


**Fig. 5** Total number of orders completed for various rule combinations

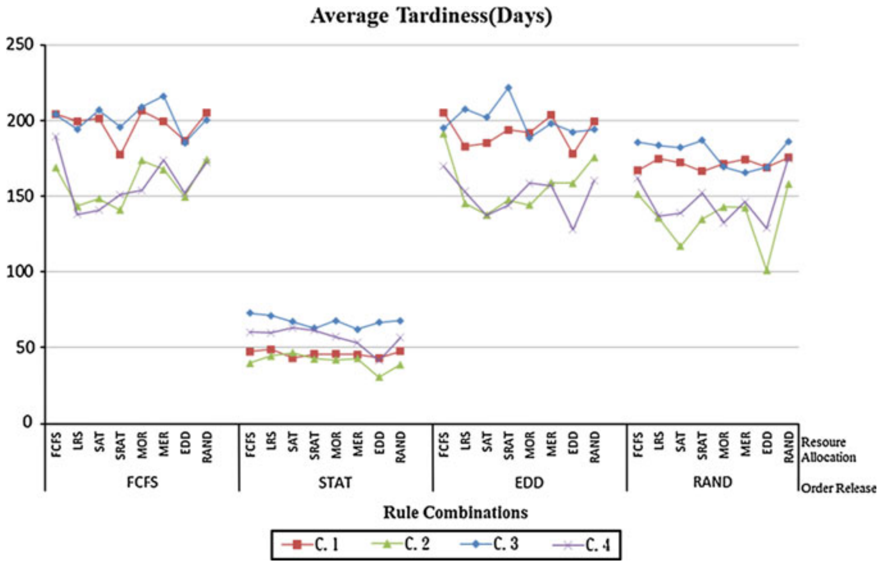


**Fig. 6** Mean tardiness for various rule combinations


**Fig. 7** Service level for various rule combinations

6 million US dollars more per year, reduce the mean tardiness around 100 days, and raise the service rate from around 10 to 60 %.

Among the resource allocation rules, EDD currently employed in the shop floor of the company outperforms the other seven rules on total number of completed orders. It should be noted that EDD especially combined with STAT as the order releasing rule showing better performance on mean tardiness and mean service rate. According to the figures, the service level that the suppliers can offer impacts the performance on total number of completed orders and mean tardiness. However, this influence can be reduced if the shop floor manager adopts STAT as their order releasing rule.

## 6 Conclusions

In this study, the analysis of order releasing and resource allocation decisions in shop floor of a Taiwan machine tools builder has been carried out using a discrete-event simulation model. Four order releasing rules integrated with eight resource allocation rules are evaluated for various performance measures under different conditions of demand patterns and key component procurements. The simulation outputs revealed that for order release STAT dominates the other rules on all the three performance measures, while for resource allocation EDD seems the best among the tested rules. The quantitative analysis of the present study also indicates that using this best performing rule combination STAT-EDD can result in making 30–40 more machines per year, reducing 110–130 days on mean tardiness, and improving service rate from around 10 to 60 % compared with the EDD–EDD combination which is currently employed by the machine tools company.

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## References

1. de Lacalle LNL, Lamikiz A (2009) Machine tools for high performance machining. Springer, New York
2. Kolisch R (2001) Make-to-order assembly management. Springer, New York
3. Drexl A, Kolisch R (1996) Assembly management in machine tool manufacturing and the PRISMA-Leitstand. Prod Inventory Manage 37(4):55–57
4. Hartmann S, Kolisch R (2000) Experimental evaluation of state-of-the-art heuristics for the resource-constrained project scheduling problem. Eur J Oper Res 127(2):394–407
5. Kolisch R, Hartmann S (2006) Experimental investigation of heuristics for resource-constrained project scheduling: an update. Eur J Oper Res 174(1):23–37
6. Kolisch R (2000) Integrated scheduling, assembly area- and part-assignment for large-scale, make-to-order assemblies. Int J Prod Econ 64(1):127–141
7. Kolisch R, Hess K (2000) Efficient methods for scheduling make-to-order assemblies under resource, assembly area and part availability constraints. Int J Prod Res 38(1):207–228
8. Kolisch R (2000) Integration of assembly and fabrication for make-to-order production. Int J Prod Econ 68(3):287–306
9. Law AM (2006) Simulation modeling and analysis. McGraw Hill, New York

# The Use of Computer Simulation in Warehouse Automation

Joanna Oleśków-Szłapka and Agnieszka Stachowiak

**Abstract** The aim of this paper is to present results of the project conducted in the manufacturing company in the furniture industry. The main objective was to automate the warehouse operation as much as possible and to minimize the number of staff in the store. The process was modeled using software FlexSim Simulation Software. The proposed solution reduces the number of used forklift trucks and warehouse workers through automatic insertion and retrieval pallet racking with stacker cranes. In addition, the range of the production hall to the storage area are transported by feeder roller (like the storage to the point of completion). All facilities have a chance for long-term use of their stock in the draft. They also allow for maximum cost savings by manufacturing company while maintaining full and accurate customer service and their satisfaction with the delivery of the warehouse. In the future authors want to develop a simulation model with respect to safety stock optimization and optimization of product location.

## 1 Introduction

The furniture industry in spite of the difficult market situation in 2011 reached a record level of production and sales. It is estimated that a total of micro firms approached it to 30 billion, of which exports accounted for about 27 billion zlotys (about 90 % of production sold). Despite the record-breaking results as business situation is very different.

The furniture industry in Poland is highly competitive. The market operates several thousand active players—about 6,000 companies. Entities, which declared

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the production of furniture as the main activity is more than 23.5 thousand, including 21 thousand a micro business. However, the share of companies defined as large and medium in the structure of sales is still for a long time close to 80 %. It is these companies largely determine the potential of Polish furniture [9].

The objective of hereby project was to automate the warehouse operation as much as possible and to minimize the number of staff in the store. Assumptions limit were as follows: 24 h per day, production volume, finished goods size, warehouse dimensions, distribution racks in stock, the volume of orders, and safety stock.

After analyzing the collected data was selected a ventilation system—heating, electrical installation to the storage of finished products, and the right equipment store: a row pallet racks PHR, stacker cranes, pallet roller conveyor.

Manufacturing company in the furniture industry has been producing covers and sofas. The goal of the company is to continuously improve efficiency and gain a competitiveness of products produced by the factory. The company regularly develops its machinery, investing in cutting-edge storage solutions, and conducts systematic training program for their employees.

## 2 Comparison of FlexSim Software with Simulation Tools

Nowadays there is a wide range of various simulation tools available on the market for potential users. Among them there can be mentioned such software as Arena, Promodel, Witness, Automod, and FlexSim.

The first four are often seen on the market simulation software. But they have developed a simulation technique from 80 to 90 in the late 1990s, so they have to fall behind. Arena, Witness, Promodel not ternary virtual technology. Virtual Technology Automod ternary and only wire-frame model (wireframe) representatives, non-real simulation technology. Some software can only be representative and not actually reflect the real situation. FlexSim it is a complete 3-D modeling software, in essence, to reflect the actual situation. FlexSim virtual technology less than other software. Whether in a simulated drive (engine), statistics analysis, and graphics can reflect on behalf of the situation.

In a simulation analysis, we can obtain real and digital image analysis. In the 3-D virtual FlexSim, users can use the mouse to zoom and change the visual angle. In other software, is not one [11].

There are five basic steps to building a model in FlexSim. (1) Develop a layout, (2) Connect objects, (3) Detail the objects, (4) Run the model, and (5) Review the output.

FlexSim simulation environment is an object-oriented software system used to model, simulate, visualize, and monitor dynamic-flow process activities. The FlexSim simulation environment consists of the FlexSim compiler, the FlexSim developer, and FlexSim applications.

This concept makes model building and analysis easier and more powerful. The FlexSim concept also increases the value and lifecycle of models because Objects are reusable and the models can be used on an operational basis for either defining or for monitoring real systems. Users can use C++ or flexscript and the internal language for development or model building. This eliminates the need for users to learn a specialized simulation language that is not used in other applications. Organizations who (1) Develop simulation products, (2) build models, (3) simulate models, (4) visualize the relationships of the model's components, and (5) monitor real-time processes will generate greater insight and knowledge about their complex and uncertain systems—and success will come to organizations that have the best information and wield it most effectively [4].

One of the most venerable and still one of the most frequent, uses of simulation in practice is the simulation of manufacturing systems [1].

Simulation, once the magic wand of a simulation professional, has the opportunity to become a common tool for analyzing and solving real-world problems in today's fast paced, dynamic environment, Seeing the marketplace changing, simulation software providers began to utilize computer technology to simplify the use of their programs. As a result, the technology that used to be the realm of experts is starting to be recognized as a tool that's available to a much wider audience for analyzing and solving real-world problems. From manufacturing to container terminals, from airport security to emergency response, from mining to health care, simulation technology is making a difference. Leaders in all sectors of our economy are beginning to realize the value of simulation—not so much as a technology but as a means to solve problems [2].

Simulation is often used when the real environment cannot be used or replicated. The real world version might be too expensive, too dangerous or just impractical to use [10].

The role of simulation has been known for a long time. However, it's only been since 1980 that simulation applications have reached a point where they are truly accessible to a wide range of users. Simulation starts with modeling and models. A simulation is then puts models in motion. An operating scale model of a piece of equipment is actually a physical simulation. Modern simulation applications are based on mathematical models but can look physical as well through three dimensional graphics.

According to Sturrock [3] when you first think about conducting a simulation study, one of the earliest things to consider is the project objectives. Why does someone want to simulate this system and what do they expect to get out of it? To be more specific, you must determine who your stakeholders are and how they define success. Each simulation must relies on functional specification, i.e., what is the model scope and how it shall be detailed.

Topics should include [3]:

- Objectives—summarize from initial high-level objectives what are the problems to solve.

- Level of detail—a model is always just an approximation of reality and can always be improved. It is important to define the limits of this model, for example the level of detail for a particular model might be suitable for comparing the relative productivity of alternate designs, but might have insufficient detail to provide a reliable prediction of absolute system productivity.
- Data requirements—identify what data will be necessary to support the agreed level of detail. Where will this data come from? Who will be responsible for providing it? When will it be provided?
- Assumptions and Control Logic—summarize how to understand the logic at various points in the system. List of any assumptions that must be made so that the all stakeholders have a common understanding of how much detail will be modeled for each part of the system.
- Analysis and Reports—determination who will be involved in the analysis phase of the project. A mock-up of a final report is an important part of a functional specification. On review of the mockup, the stakeholders will almost certainly identify things that are missing and things that are unnecessary. It is much better to identify such items at this point than at the final project presentation.
- Animations—a certain level of animation is generally necessary for model development and validation. In many cases stakeholders initially may indicate that animation has little importance to them.
- Due Date and Agility—simulation is often a process of discovery. There can be found the new alternatives to explore and possibly areas of the model requiring more detail. Adequately exploring those areas can potentially make the project much more valuable. But the best results possible have no value if they are delivered after the decision has been made. When are results expected? When is the absolute "drop-dead" date after which the results will have no value?

Design and operation of warehouses have been subject to numerous research activities and case studies as the comprehensive surveys by Gu et al. [5], Rouwenhorst et al. [6], and Vis and Roodbergen [7], Spieckermann et al. [8] are showing.

## 3 Process Analysis and Simulation Using FlexSim Software

The process in question was modeled using software FlexSim Simulation Software. Simulation was prepared for the 24 h working day warehouse. At the beginning of the process packed pallets were going down from the production line, and the final result is the end of loading vehicles.

The main objective of the simulation is to verify the operation of storage of all proposed solutions.

All production lines for covers work on 3 shifts, 3 lines producing sofas as well, and one production line for sofas work on 1 shift.

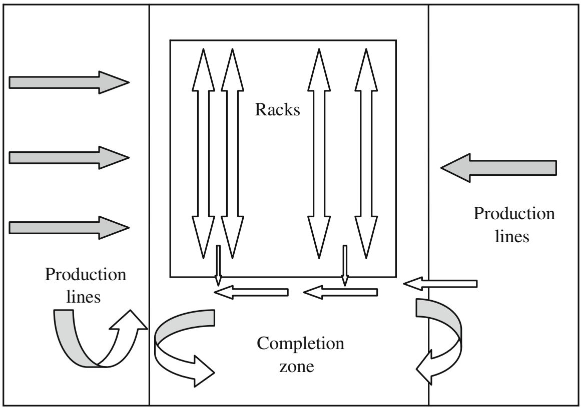



**Fig. 1** The initial model/object flow diagram

The main objective of the simulation is to verify the operation of storage for all developed solutions.

There is stock maintained in a warehouse to cover 2 week demand. An important requirement was to design a storage system-based warehouse management system (WMS) and according to the FIFO (first in first out) method. It was based on data related to the number of covers and sofas manufactured on production lines (volume: 32,945 units within 2 weeks including covers 20,286 units, 12,659 units sofas, a total of 5,462 units of trucks)

Key performance metrics were analyzed: time picker, number of forklifts needed, flow time of finished products. Considered decision variables: number of employees, number of forklifts, and number of racks and shelves, the number used at the time loading ramp.

Figure 1 illustrates a scheme by which the flow is finished by the production lines for loading ramp.

The beginning of the process is packed pallets from the production line, and the end of the loading end cars. The simulation was carried out for the four production lines, manufacturing sofas AA, AC, AD, and covers C. The period of time considered in the simulation is one day. The aim is to verify the operation of all the storage solutions that have been developed. Thanks to that the amount of forklifts, needed was identified, as well as custom-picking time, the amount of trucks, and time for loading.

Data was received from the company (Table 1)

Products in bold were used in simulation. For simplification they are called:

- product A.A- sofa type 1
- product A.C- sofa type 2
- product A.D- sofa type 3
- product C- cover type 1

The aim of this work was to automate the warehouse as much as possible. Automation is also associated with the reduction of the number of staff needed for

**Table 1** Data from the company

| | | | | | |
|---|---|---|---|---|---|
| Time of one shift for covers (min) | | 420 | The difference is the result of quality issues and complexity of process (sofas are more complex than covers) | | |
| Time of one shift for sofas (min) | | 400 | | | |
| Product | Products per pallet (szt.) | Product type | Weight (kg) | Dimensions (mm) | Weight of packed pallette (kg) |
| A | 60 | Cover | 3.5 | 1,200 × 800 × 1,100 | 235.00 |
| B | 95 | Cover | 2 | 1,200 × 800 × 800 | 215.00 |
| **C** | **20** | **Cover** | **5** | **1,200 × 800 × 1,100** | **125.00** |
| D | 45 | Cover | 4 | 1,200 × 800 × 1,200 | 205.00 |
| E | 150 | Cover | 1.5 | 1,200 × 800 × 1,500 | 250.00 |
| **A.A.** | **2** | **Sofa** | **35** | **1,200 × 800 × 2,200** | **95.00** |
| A.B. | 4 | Sofa | 17.8 | 1,200 × 800 × 900 | 96.20 |
| **A.C.** | **1** | **Sofa** | **69** | **1,200 × 800 × 2,300** | **94.00** |
| A.D. | **3** | **Sofa** | 43,7 | 1200 × 800 × 1600 | 156,10 |

the stock, which has been achieved. By selecting the appropriate option simulation, we were able to adjust the time of completion of the contract and determine the best number of forklift trucks.

The decision concerning resources included:

- 310 cases of 1.5 m cell height and total height 11 m
- 269 cases 2 m cell height and total height 10.5 m
- 501 cases 2.5 m cell height and total height 10.5 m

Designing the warehouse authors considered several solutions. It was possible to use conventional pallet racking, which staff delivers the goods with forklifts. In this case, however, had a negligible degree of automation in the warehouse. Another option under consideration was the use of the automatic shelf. This possibility must be ruled out because the auto racks are designed to hold smaller packaging than the euro pallets.

In the end, the decision was made to purchase an automatic stacker crane, which moves between putting goods on the shelves designated for this place based on barcodes. Pallets of production facilities will be provided to the stacker cranes with roller trays and transported the same way to the point of completion. With this solution the number of forklift trucks used and employees has been significantly reduced because their job is only to provide pallets from the production site to the tray and the tray to the loading ramp.

FlexSim system simulation was carried out for the four production lines, manufacturing sofas AA, AC, AD, and covers C. The period of time considered in the simulation is one day. The aim was to verify the operation of all the storage solutions we have proposed. Conceptual model made in the model shown in Figs. 2 and 3

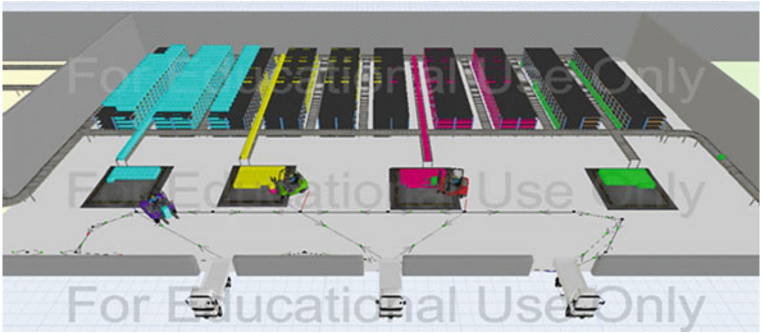
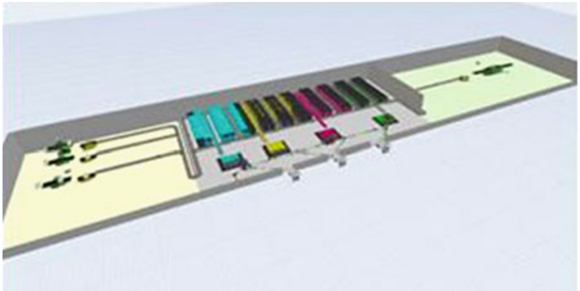


**Fig. 2** The idea/flows diagram

**Fig. 3** Warehouse model in FlexSim



The solution developed gives the company a number of benefits. First of all, it is possible to reduce the number of staff (3–5 people). Forklift operators will carry the loaded pallets to the production hall of the place of production to the end of the roll feeder zone and assembling the means of transport (for dock leveler). Internal transportation of pallets is automated and goes through electric conveyors from production lines to racks and then to completion zones.

If a different number of solutions which run on stock were used trucks would have to be higher because of the need to put their pallets on racks and their subsequent retrieval. This approach also increases the safety of the work in the warehouse, which helps to minimize transport traveling in the area.

During the project work appeared necessary to take into account constraints such as the stock kept in reserve (at stock to cover 2-week demand) and setting spans. The assumed volume of production for 2 weeks was 32,945 pieces including: 20,286 covers, 12,659 sofas, i.e., 5,462 pallets units. Dimensions of warehouse: 40 × 70 × 11.5 m.

In order to develop simulation model there have been made following operational stipulations: warehouse contains 1,100 racks, 5,411 pallets places, one shift for covers takes 420 min and for sofas 400 min, distance between racks is 1.5 m, trucks do not break down.

Racks had to be placed so as to obtain the largest possible surface storage. It was also necessary to take into account the number of pallets and their height and to choose the correct size and number of shelves.

Improvement of warehouse logistics has been a very important part of investment process connected with the extension of buildings and modernization of storage areas. SSI Schaefer proposed an idea based on self-automatic conveyor system integrated with multi-sector system of mobile racks, served by transporters of reach-truck type.

93 thousands locations of pallets for semi-products and final goods have been divided in three sections of hall. The crucial role in movement of materials plays electric conveyor for pallets. Decrease of manual transportation either increase an efficiency or decrease substantially the costs. Customized interface system enables a safe connection with WMS system.

## 4 Summary

The aim of the project was to design a warehouse automated as much as possible. The proposed solution reduces the number of used forklift trucks and warehouse workers through automatic insertion and retrieval pallet racking with stacker cranes. In addition, the range of the production hall to the storage area are transported by feeder roller (like the storage to the point of completion). The simulation made it possible to determine whether the treatment adopted will preserve the timeliness and effectiveness subjected to the analysis process.

All facilities have a chance for long-term use of their stock in the draft. They also allow for maximum cost savings by Manufacturing company while maintaining full and accurate customer service and their satisfaction with the delivery of the warehouse.

Warehouse in analyzed company has been also improved and there introduced SSI Schaefer idea of self-automatic conveyor system integrated with multi-sector system of mobile racks, served by transporters of reach-truck type.

In the future authors want to develop a simulation model with respect to staff availability, safety stock optimization.

## References

1. Miller S, Pegden D (2000) Introduction to manufacturing simulation. In: Joines JA, Barton RR, Kang K, Fishwick PA (eds) Proceedings of the 2000, winter simulation conference. Institute of Electrical and Electronics Engineers, Inc, Piscataway, New Jersey, pp 63–66
2. Greenwood A, Beaverstock M (2011) Mississippi State Simulation education—seven reasons to change. In: Jain S, Creasey RR, Himmelspach J, White KP, Fu M (eds) Proceedings of the 2011 winter simulation conference

3. Sturrock DT (2011) Tips for successful practice of simulation. In: Jain S, Creasey RR, Himmelspach J, White KP, Fu M (eds) Proceedings of the 2011 winter simulation conference
4. Nordgren WB (2002) FlexSim simulation environment. In: Yücesan E, Chen C-H, Snowdon JL, Charnes JM (eds) Proceedings of the 2002 winter simulation conference
5. Gu J, Goetschalckx M, McGinnis LF (2010) Research on warehouse design and performance evaluation: a comprehensive review. Eur J Oper Res 203:539–549
6. Rouwenhorst B, Reuter B, Stockrahm V, van Houtum GJ, Mantel RJ, Zijm WHM (2000) Warehouse design and control: framework and literature review. Eur J Oper Res 122:515–533
7. Vis IFA, Roodbergen KJ (2009) Scheduling of container storage and retrieval. Oper Res 57:456–467
8. Spieckermann S, Stauber S, Bleifub R (2012) A case study on simulation and emulation of a new case picking system for a us based wholesaler
9. OIGPM (2011) http://www.biznes.meble.pl/aktualnosci,oigpm-podsumowanie-roku-2011-i-perspektywy-na-rok-2012,12486
10. TMN Simulation (2012) http://tmnsimulation.com.au/what-is-simulation-part-2/. Accessed Dec 2012
11. Several logistics software comparison (2013) (http://www.anyang-window.com.cn/several-logistics-simulation-software-comparison/). Accessed March 2013

# Optimal Safety Stock Policy for a Hybrid Manufacturing System: A Simulation Study

**Horng-Chyi Horng**

**Abstract** A real-world factory simultaneously adopting make-to-order (MTO), make-to-stock (MTS), and assembly-to-order (ATO) production strategies for its foreign and local customers is understudied. Foreign orders are more unpredictable and with long lead time where MTO is implemented. On the other hand, local orders are fulfilled by agencies that constantly place orders demanding short lead time. Therefore, for local orders, the factory implements both MTS and ATO strategies depending on the manufacturing lead time of the product. In an attempt not only to minimize inventory cost and work-in-process (WIP) levels, but also to fulfill customer demands by maximizing customer service level, an optimal safety stock policy must be implemented. In this study, a safety stock policy contain safety stock level and reorder point of subassemblies, manufacturing batch size, order review and release (ORR) mechanisms, as well as dispatching rules. This study conducts a two-stage simulation experiment to first evaluating performances of dispatching rules and ORR rules, and then using results from the first stage to further design several safety stock policies that will be evaluated in the second stage for the hybrid manufacturing system.

## 1 Introduction

In Taiwan, domestic market is the main target for small and young companies. As business grew gradually, many of these companies turn their focuses on the much larger foreign markets. Inventory is one of the most important factors in the success of these companies doing both domestic and foreign business simultaneously. Domestic market often requires short manufacturing lead time and fast

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delivery speed. Pre-manufacturing what domestic market would purchase and keeping in the warehouse before customer orders arrived can shorten time-to-customer, and thus improve market share. However, inventory indeed is a waste for a company and should be kept in minimum size to avoid capital sluggish. Therefore, a common approach adopted by these companies is to implement both make-to-stock (MTS) and assembly-to-order (ATO) production strategies. That is, implement a policy that prepares subassemblies inventory via MTS approach and then performs final assembly via ATO when customer orders arrive. Foreign market, on the other hand, allows more lead time to deliver. The most common way to deal with foreign orders is to implement make-to-order (MTO) strategy so as to minimize manufacturing costs and increase customer service level.

The production scheduling for domestic business and foreign orders are quite different. For domestic business, the production schedule mainly relies on accurate sales prediction. With safety stock, there is no immediate threat of losing business if production is behind schedule. Thus the major concern is how to maintain in-stock inventory sufficient for the fulfillment of domestic market demand. However, for foreign orders, production schedule focuses on satisfying due dates of on-hand orders. Earliness of orders increases inventory management cost while tardiness reduces customer service level and with a potential threat of losing business. Therefore, in an attempt not only to minimize inventory cost and work-in-process (WIP), but also to fulfill customer demands by maximizing customer service level, an optimal safety stock policy must be implemented for a hybrid manufacturing company that adopting MTO, MTS, and ATO production strategies simultaneously. However, these objectives are also affected by how orders are released to the manufacturing system and what kinds of production control are implemented, for example the manufacturing batch size and dispatching rules. Thus in this study, a safety stock policy is expanded to contain safety stock level and reorder point of subassemblies, manufacturing batch size, order review and release (ORR) mechanisms, as well as dispatching rules. The objective of this study is to conduct a simulation experiment to evaluate several safety stock policies on the performance of a hybrid manufacturing system.

## 2 Literature Review

Soman et al. [1] simulated and compared several dynamic scheduling policies for hybrid MTO and MTS production systems with stochastic demand. They evaluated various run-out time scheduling and sequencing heuristics, and found that methods that perform well for pure MTS situations do not necessarily perform well for hybrid MTO-MTS situations. Meredith and Akinc [2] called this hybrid MTO-MTS production strategy as make-to-forecast (MTF) strategy if the manufacturer launches major product models to a demand forecast and then modify the partially completed products as the actual orders arrive. The MTS-ATO compound strategy in this study for domestic demand can be viewed as MTF strategy as well.

Moreover, Persona et al. [3] evaluated optimal safety stock levels of subassemblies and manufacturing components. Thy proposed cost-based analytical models for setting optimal safety stock level for ATO and MTO systems, respectively.

However, optimal safety stock level is affected by order release/acceptance and scheduling [4]. Betrand and van Ooijen [5] tried to optimal work order release for MTO job shops with order lead time costs, tardiness costs, and work-in-process (WIP) costs. They derived expressions for the optimal value for the maximum number of orders that is allowed to be in process. Sharda and Akiya [6], on the other hand, provided a guideline for a company to choose best production strategy among MTO, MTS, and postponement.

This study tries to minimize inventory cost and work-in-process (WIP) levels, but also to fulfill customer demands by maximizing customer service level, an optimal safety stock policy must be implemented for a hybrid manufacturing company that adopting MTO, MTS, and ATO production strategies simultaneously. Other related literatures are outlined below.

## 2.1 Manufacturing Inventory Policy

To effectively respond to domestic demand, an appropriate manufacturing inventory policy must be implemented. Silver et al. [7] mentioned that there are two main categories of inventory strategy, i.e., continuous review and periodic review. Typical continuous review inventory policies are (R, Q) and (R, S). Meanwhile (T, S) and (T, R, S) belong to periodic review inventory policies. In this study, (R, Q) policy is adopted with several modifications. That is, safety stock is viewed as reorder point (R) for the MTS manufacturing order, while ordering quantity (Q) is now the manufacturing order quantity. In addition, each manufacturing order can be divided into several batches according to production scheduling.

## 2.2 Order Review and Release

Ragatz and Mabert [8] and Philipoom et al. [9] found there are interactions among ORR, dispatching rules, and due date settings. Five ORR rules they applied are listed and defined in Table 1.

## 2.3 Dispatching Rules

Dispatching rule is the most simplified and easy-to-implement scheduling tool for a production system. Over the past few decades, many dispatching rules have been

**Table 1** Common order review and release methods

| Rule | Description | Definitions |
|---|---|---|
| IMM | Immediate release | Release jobs according to first-in-first-out (FIFO) rule |
| BIL | Backward infinite loading | The release date of job $i$ ($RD_i$) is its due date ($DD_i$) minus number of operations ($n_i$) times $k$, i.e., $RD_i = DD_i - kn_i$, where $k$ is a multiplier |
| MIL | Modified infinite loading | The release date of job $i$ ($RD_i$) is its due date ($DD_i$) minus number of operations ($n_i$) times $k_1$ and number of jobs in queue ($Q_i$) times $k_2$, i.e., $RD_i = DD_i - k_1n_i - k_2Q_i$, where $k_1$ and $k_2$ are multipliers |
| MNJ | Maximum number of jobs | Release $m$ jobs according to dispatching rule |
| BFL | Backward finite loading | Release jobs according to their due dates, i.e., $DD_i$ |
| DBR | Drum-Buffer-Rope | Follow theory of constraint (TOC) which releases jobs according to the situation of the bottleneck stations |

developed and proven to be effective for flow shops and job shops. Ramasesh [10] reviewed simulation-based research on dynamic job shop scheduling from the year 1965 to 1986 and found that SPT (shortest processing time) is the best rule for minimizing $\overline{F}$ but has higher variance of flowtime ($\sigma_F^2$) than others. For job shops with low, medium, and high utilization rate, Waikar et al. [11] evaluated 10 dispatching rules. They showed that SPT and LWKR (least work remaining) minimize $\overline{F}$ and the percentage of tardiness of jobs, while DDT (due date time) and SLK/RO (least ratio of slack time remaining to number of operations remaining) perform well under $\overline{T}$ criterion. Holthaus [12] evaluated compounded rules in job shops and showed that PT + WINQ, AT-RPT (arrival time minus remaining processing time), SPT, RR (rule created by Raghu and Rajendran [13]), and PT + WINQ + SL (processing time plus work in next queue plus slack) perform well in $\overline{F}$, $F_{\max}$, $\sigma_F^2$, $\%T$, $\overline{T}$, maximum tardiness ($T_{\max}$), and tardiness variance criteria ($\sigma_T^2$), respectively. Another rule created by Holthaus and Rajendran [14], PT + WINQ + AT + SL (processing time plus work in next queue plus arrival time plus slack), also performs well on $F_{\max}$, $\sigma_F^2$, $T_{\max}$, and $\sigma_T^2$ criteria. They further compared flow shops and job shops, and showed that different production type and job routings have significant impact on the selection of the best dispatching rule over different performance criteria [15]. In an attempt to improve job shop performance, they further developed new rules and found that 2PT + WINQ + NPT (double processing time plus work in next queue plus processing time at next operation) is better than PT + WINQ in minimizing $\overline{F}$ while PT + WINQ + NPT + WSL (processing time plus work in next queue plus processing time at next operation plus "WINQ" slack) outperforms PT + WINQ + SL in minimizing $T_{\max}$ and $\sigma_T^2$ [16]. Considering mean time to failure and repair time of machines in the job shop, Liu [17] found that FIFO should be adopted for minimizing $\overline{T}$ and $\%T$ of jobs. Table 2 lists the best dispatching rules for job shops summarized from literature under different performance criteria.

**Table 2** Common used dispatching rules

| Performance criteria | Best rule(s) | References |
|---|---|---|
| $\bar{F}$ | SPT, LWKR, PT + WINQ, RR, SPT, PT + WINQ, 2PT + WINQ + NPT | [11, 12, 14, 15] [16] |
| $F_{max.}$ | AT-RPT, PT + WINQ + AT, PT + WINQ + AT + SL, AT-RPT, PT + WINQ + AT | [12, 14, 15] |
| $\%T$ | MOD, SPT, LWKR, FIFO, RR, 2pt + WINQ + NPT | [11, 19] [12, 14, 15, 17] |
| $\bar{T}$ | MOD, DDT, SLK/RO, RR, FIFO | [11, 19] [12, 14, 15, 17] |
| $T_{max.}$ | RR, PT + WINQ + SL, PT + WINQ + NPT + WSL | [12, 15] [14, 16] |

## 3 Methodology

This study focuses on the simulation study of optimal safety stock policy in a hybrid manufacturing system. The hybrid manufacturing system, a real-world company, adopts MTO, MTS, and ATO production strategies so that both domestic and foreign demand can be fulfilled. To ensure on-time delivery and increase customer service levels, an optimal safety stock policy must be implemented. The optimal safety stock policy consists of setting safety stock levels and manufacturing order quantity, as well as manufacturing batch size. However, this optimization is influenced by ORR rule and dispatching rule chosen by the factory. It's inappropriate to design a simulation experiment simultaneous considering all of these factors. Therefore, the methodology is sequential as depicted in Fig. 1. After adequate and sufficient literature review, a simulation model is built to represent this real-world manufacturing system, followed by a validation process. Simulation experiment is then divided into two stages. First stage focuses on the effects of ORR and dispatching rules, and their interactions on the system performance. The purpose of this stage is to perform a complete simulation analysis on most popular ORR and dispatching rules, not only to validate simulation modeling of these rules, but also to screen out inefficient rules so that total simulation runs in the second stage can be reduced significantly. The second stage of the simulation experiment then introduces safety stock levels, manufacturing batch size, manufacturing order quantity, and production strategies. ORR rules and dispatching rules that performed better in stage one are picked and take into considered in this stage. With appropriate analysis, research findings are outlined followed by a list of recommendations for future research.

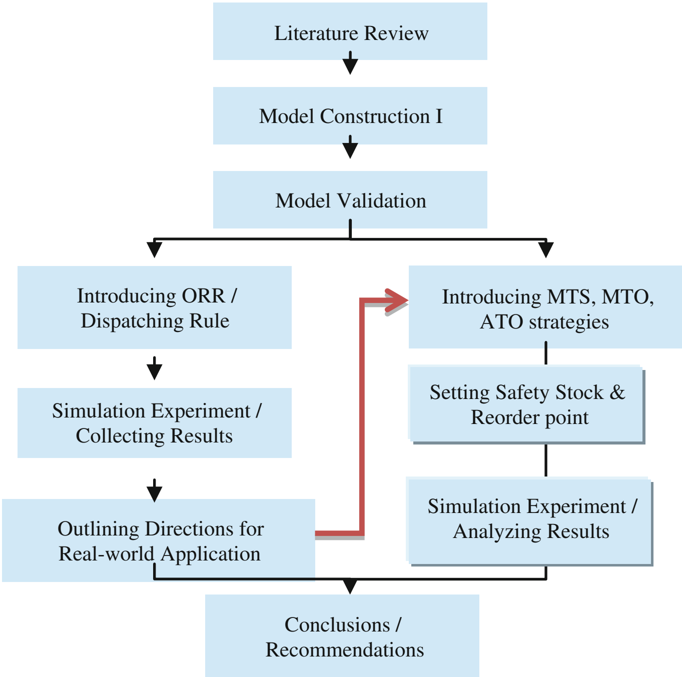


**Fig. 1** The methodology

# 4 Results and Analysis of Stage One

## *4.1 Model Description*

As discussed in the previous section, the simulation experiment is divided into two parts. The first part focuses on the effectiveness of ORR rules and dispatching rules, and their interactions. A base model for this experiment is a job shop with 4 cells adopted from [17]. Each cell has one machine, except in cell 3 where two machines are available with different processing speed. The routing and processing times of the three different parts are listed in Table 3. The inter-arrival time of parts is exponentially distributed with mean of 13 min.

The proportions of sale for these three parts are 26, 48, and 26 %, respectively. The routing complexity as depicted in Table 6 is relatively high for part 2, medium for part 1, and low for part 3. In addition, three types of job shops are considered, each has 4, 8, and 12 cells, expending from the base model.

The settings for the due date follow the TWK method [19], as in equation below.

**Table 3** Routing and processing times of parts for the base model

| | Part 1 | Part 2 | Part 3 |
|---|---|---|---|
| Cell/time | **1**/TRIA(6 ,8, 10)<br>**2**/TRIA(5, 8, 10)<br>**3**/TRIA(15, 20, 25)<br>**4**/TRIA(8, 12, 16) | **1**/TRIA(11, 13, 15)<br>**2**/TRIA(4, 6, 8)<br>**4**/TRIA(15, 18, 21)<br>**2**/TRIA(6, 9, 12)<br>**3**/TRIA(27, 33, 39) | **2**/TRIA(7, 9, 11)<br>**1**/TRIA(7, 10, 13)<br>**3**/TRIA(18, 23, 28) |

**Table 4** Allowance factor and parameter settings for ORR rule

| Utilization (%) | c | k | k1 | k2 |
|---|---|---|---|---|
| 75 | 3 (I), 9 (III) | 13 | 10 | −0.9 |
| 84 | 3 (II) | 11 | 12 | −0.3 |
| 93 | 3 (I), 5 (III) | 9 | 12 | −0.4 |

$$d_i = r_i + c\sum_{j=1}^{m_i} p_{ij} \quad (1)$$

where $d_i$ is the due date for job $i$, $r_i$ is the arrival time of job $i$, $c$ is the allowance factor, and $p_{ij}$ is the processing time of job $i$ on machine $j$.

According to different utilization levels of the job shop, the settings for the allowance factors and factors for ORR rules are different as listed in Table 4.

## *4.2 Experimental Design and Simulation Settings*

The first one is to explore which combinations of ORR rule and dispatching rule performs best with respected to different system configurations and performance index. Table 5 is the list of factors and their levels at the first stage of the experiment.

Each scenario is replicated 30 times with run length of 50,000 min and warm-up period of 10,000 min. Performance index collected for comparison are mean flow time, mean tardiness, maximum flow time, maximum tardiness, and percentage of tardiness. For each combinations of ORR and dispatching rule, number of machines and utilizations of the job shop serve as experimental factors to perform a $2^2 + (n_c = 4)$ design (as in Table 6) so that the main effect, interaction,

**Table 5** Factors and their levels at stage one

| Factor | Levels |
|---|---|
| ORR | BIL, MIL, IMM, DBR |
| Dispatching rule | CR, EDD, FIFO, MDD, MST, PT + WINQ, PT + WINQ + AT, PT + WINQ + SL, PT + WINQ + AT + SL, RR, SPT, S/RMOP, WINQ |

**Table 6** The $2^2 + (n_c = 4)$ design with different system configurations

| RUN # | # of machines | Utilization (%) |
|---|---|---|
| 1 | 4 | 75 |
| 2 | 12 | 75 |
| 3 | 4 | 93 |
| 4 | 12 | 93 |
| 5 | 8 | 84 |
| 6 | 8 | 84 |
| 7 | 8 | 84 |
| 8 | 8 | 84 |

as well as quadratic effect can be gathered. Therefore, there are a total of $8 \times 30 \times 4 \times 13 = 12{,}480$ simulation runs.

## *4.3 Simulation Results*

For demonstration purpose, Table 7 is the simulation results for the shop with eight cells and 84 % average utilization. As depicted in the table, DBR paired with SPT can optimize the flow time of part 1, paired with CR can optimize the flow time of part 3, while MIL paired with PT + WINQ + AT performs best for part 2 flow time. That is, the best pair of ORR and dispatching rule changes as the routing complexity of the part differs. List below are the findings summarized through all combination of system configurations as in Table 6:

(a) (MIL, PT + WING + AT) is the best for average flow time of part 2.
(b) (BIL, SPT) is the best for maximum flow time of part 1.
(c) (MIL, PT + WINQ + AT) is the best for average WIP of part 2.

**Table 7** Simulation results for job shop with eight cells and 84 % average utilization

| Performance measurement | Best (ORR, Dispatching rule) | Value |
|---|---|---|
| Part 1 average flow time | (DBR, SPT) | 181.20 |
| Part 2 average flow time | (MIL, PT + WINQ + AT) | 329.88 |
| Part 3 average flow time | (DBR, CR) | 181.01 |
| Part 1 maximum flow time | (BIL, SPT) | 299.13 |
| Part 2 maximum flow time | (DBR, PT + WINQ + AT + SL) | 1,137.13 |
| Part 3 maximum flow time | (DBR, PT + WINQ + AT + SL) | 1,016.51 |
| Tardiness | (DBR, PT + WINQ + AT + SL) | 0.1820 |
| Max tardiness | (DBR, PT + WINQ + AT + SL) | 12.15 |
| Percentage of tardiness | (DBR, PT + WINQ + AT + SL) | 0.0012 |
| Part 1 WIP | (DBR, SPT) | 3.39 |
| Part 2 WIP | (MIL, PT + WINQ + AT) | 11.31 |
| Part 3 WIP | (DBR, CR) | 3.39 |

(d) (DBR, PT + WINQ + AT + SL) is the best if concerning average tardiness, maximum tardiness, and percentage tardy.
(e) DBR works better in general since it takes into account the bottleneck workload.
(f) There exist interaction between the effect of ORR and dispatching rules on the systems performance.
(g) Utilization, number of machines, and routing complexity all are key parameters in selecting the best ORR as well as dispatching rule for a system.

# 5 Model Description and Experimental Design of Stage Two

Figure 2 is the simulation model for the hybrid manufacturing system. This factory simultaneously adopts MTO, MTS, and ATO production strategies for its foreign and local customers. Foreign orders are more unpredictable and with long lead time where MTO is implemented. On the other hand, local orders are fulfilled by agencies that constantly place orders demanding short lead time to deliver. Therefore, for local orders, the factory implements both MTS and ATO strategies depending on the manufacturing lead time of the product. In an attempt not only to minimize inventory cost and WIP levels, but also to fulfill customer demands by maximizing customer service level, an optimal safety stock policy must be implemented.

Foreign orders account for 75 % of total orders. Basically there is no inventory required for foreign orders except small amount of rush orders. On the other hand, for domestic orders, a MTS strategy that produces adequate inventory followed by an ATO strategy that flexibly assemble final products according to each order is the production strategy adopted by the factory. There are primary four manufacturing steps: injection molding, lathing, assembly and testing, and packaging. Injection molding and lathing take long processing time and require batch processing to lower manufacturing cost. Therefore, stock keeping units are those subassemblies that finished molding and lathing processes.

The experimental design in the second stage introduces safety stock levels, manufacturing order quantity, manufacturing batch size, and production strategies. Two ORR rules and five dispatching rules picked from stage one are also considered as shown in Table 8.

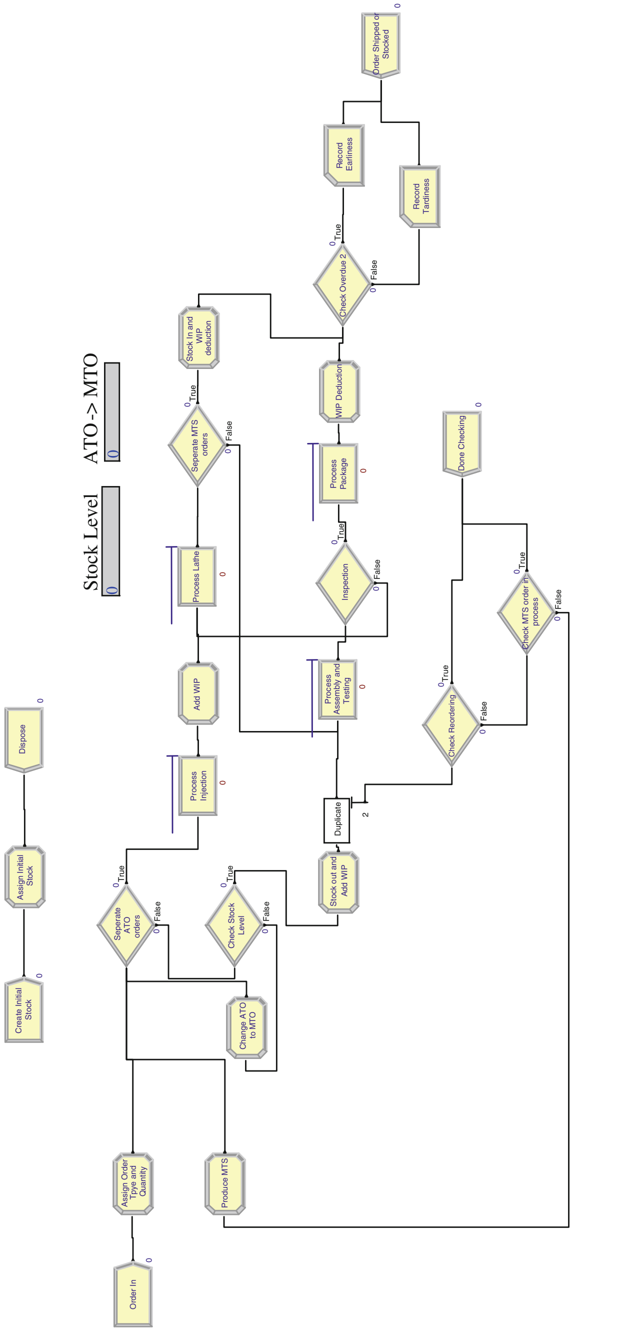


**Fig. 2** ARENA simulation model for the hybrid manufacturing system

**Table 8** Factors and their levels at stage two

| Factor | Levels |
|---|---|
| Safety stock | Low, medium, high |
| Manufacturing order quantity | Low, medium, high |
| Manufacturing batch size | Small, medium, large |
| ORR | BIL, MIL, DBR |
| Dispatching rule | SPT, EDD, CR, PT + WINQ + AT, PT + WINQ + AT + SL |

# 6 Conclusions and Recommendations

Inventory cost has been the most important factor in the success of a company doing both domestic and foreign business. Domestic market requires short manufacturing lead time and fast delivery where both MTS and ATO production strategies are implemented. Foreign market, on the other hand, allows more lead time to deliver that is suitable for adopting MTO strategy. In an attempt not only to minimize inventory cost and WIP levels, but also to fulfill customer demands by maximizing customer service level, an optimal safety stock policy must be implemented for a hybrid manufacturing company that adopting MTO, MTS, and ATO production strategies simultaneously. In this study, a safety stock policy is expanded to contain safety stock level and manufacturing reorder point of subassemblies, manufacturing batch size, ORR mechanisms, as well as dispatching rules. The objective of this study is to conduct a simulation experiment to evaluate several safety stock policies on the performance of the hybrid manufacturing system.

The research findings from stage one indicated: (1) there exist interaction between the effect of ORR and dispatching rules on the systems performance; (2) Utilization, number of machines, and routing complexity all are key parameters in selecting the best ORR as well as dispatching rule for a system; (3) Three ORR rules and five dispatching rules that perform well for different system configurations are selected for stage two experiment. It is expected that future research focuses on analytical models for optimal safety stock policy for hybrid manufacturing systems.

# References

1. Soman CA, van Donk DP, Gaalman G (2006) Comparison of dynamic scheduling policies for hybrid make-to-order and make-to-stock production systems with stochastic demand. Int J Prod Econ 104:441–453
2. Meredith J, Akinc U (2007) Characterizing and structuring a new make-to-forecast production strategy. J Oper Manage 25:623–642
3. Persona A, Battini D, Manzini R, Pareschi A (2007) Optimal safety stock levels of subassemblies and manufacturing components. Int J Prod Econ 110:147–159

4. Slotnick SA (2011) Order acceptance and scheduling: a taxonomy and review. Eur J Oper Res 212:1–11
5. Betrand JWM, van Ooijen HPG (2008) Optimal work order release for make-to-order job shops with customer order lead-time costs, tardiness costs and work-in-process costs. Int J Prod Econ 116:233–241
6. Sharda B, Akiya N (2012) Selecting make-to-order and postponement policies for different products in a chemical plant: a case study using discrete event simulation. Int J Prod Econ 136:161–171
7. Silver EA, Pyke DF, Peterson R (1998) Inventory management and production planning and scheduling. Wiley, New York
8. Ragatz GL, Mabert V (1988) An evaluation of order release in a job shop environment. Decis Sci 19(1):167–189
9. Philipoom PR, Malhotra MK, Jensen JB (1993) An evaluation of capacity sensitive order review and release procedures in job shops. Decis Sci 24(6):1109–1132
10. Ramasesh R (1990) Dynamic job shop scheduling: a survey of simulation research. Omega 18(1):43–57
11. Waikar AM, Sarker BR, Lal AM (1995) A comparative study of some priority dispatching rules under different job shop loads. Prod Plann Control 6(4):301–310
12. Holthaus O (1997) Design of efficient job shop scheduling rules. Comput Ind Eng 33(1/2):249–252
13. Raghu TS, Rajendran C (1993) An efficient dynamic dispatching rule for scheduling in a job shop. Int J Prod Econ 32:301–313
14. Holthaus O, Rajendran C (1997) Efficient dispatching rules for scheduling in a job shop. Int J Prod Econ 48:87–105
15. Rajendran C, Holthaus O (1999) A comparative study of dispatching rules in dynamic flow shops and job shops. Eur J Oper Res 116:156–170
16. Holthaus O, Rajendran C (2000) Efficient job shop dispatching rules: further developments. Prod Plann Control 11(2):171–178
17. Liu KC (1998) Dispatching rules for stochastic finite capacity scheduling. Comput Ind Eng 35(1):113–116
18. Kelton WD, Sadowski RP, Swets NB (2010) Simulation with Arena. McGraw Hill, New York
19. Baker KR, Kanet JJ (1984) Job shop scheduling with modified due dates. J Oper Manage 4(1):11–22

# Modeling and Simulation of the EMG30 Geared Motor with Encoder Resorting to SimTwo: The Official Robot@Factory Simulator

José Gonçalves, José Lima, Paulo J. Costa and A. Paulo Moreira

**Abstract** This paper describes the EMG30 mechanical and electrical modeling and its simulation resorting to SimTwo (Robot@Factory mobile robot competition official simulator). It is described the developed setup applied to obtain the experimental data that was used to estimate the actuator parameters. It was obtained an electro-mechanical dynamical model that describes the motor, its gear box, and the encoder. The motivation to model and simulate the EMG30 is the fact that it is an actuator worldwide popular in the mobile robotics domain, being a low cost 12v motor equipped with encoders and a 30:1 reduction gearbox. The Goal of this work is to provide more realism and new features to the Robot@Factory official simulator, allowing participating teams to produce and validate different robot prototypes and its software, reducing considerably the development time.

## 1 Introduction

Robotic competitions are an excellent way to foster research and to attract students to technological areas [1]. The robotic competitions present standard problems that can be used as a benchmark, in order to evaluate and to compare the performances of different approaches. Although there are many robotic competitions [2–5], there is the need to create new ones, in order to solve new challenges. The factory environment is a prime candidate to use robots in a variety of tasks. A competition where mobile robots are tackling transportation problems in the shop floor is a

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challenge that can foster new advances in service robots and manufacturing [6, 7]. The Robot@Factory competition presents problems that occur when using mobile robots to perform transportation tasks. The robots must be able to navigate, cooperate, and to self-localize in an emulated factory plant, to transport and handle materials in an efficient way [8].

This paper describes the EMG30 mechanical and electrical modeling and its simulation resorting to SimTwo. SimTwo is a realistic simulation software that can support several types of robots. Its main purpose is the simulation of mobile robots that can have wheels or legs, although industrial robots, conveyor belts, and lighter-than-air vehicles can also be defined. Basically any type of terrestrial robot definable with rotative joints and/or wheels can be simulated in this software [9].

The motivation to model and simulate the EMG30 is the fact that it is an actuator worldwide popular in the mobile robotics domain, being a low cost 12v motor equipped with encoders and a 30:1 reduction gearbox, and also to provide more realism and new features to SimTwo (the Robot@Factory official simulator), allowing participating teams to produce and validate different robot prototypes and its software, reducing considerably the development time. The paper is organized as follows: After a brief introduction it is described the developed setup applied to obtain the experimental data and the actuator parameters estimation. Then its simulation resorting to SimTwo is presented. Finally some conclusions and future work are presented.

## 2 Modeling of the EMG30 Actuator

The EMG30 is an actuator worldwide popular in the mobile robotics domain, being a low cost 12v motor equipped with encoders and a 30:1 reduction gearbox. The fact that it is equipped with encoders is an important feature because it provides important data to obtain the closed loop velocity control and to obtain relative measurements based on the odometry calculation [10]. An EMG30 is shown in Fig. 1.

The EMG30 model can be defined by the following equation, where $U_a$ is the converter output, $R_a$ is the equivalent resistor, $L_a$ is the equivalent inductance, $e$ is the back emf (electromotive force) voltage, $I_a$ is the motor current as expressed by Eq. (1).

$$U_a = e + R_a i_a + L_a \frac{di_a}{dt} \tag{1}$$

The motor can provide a torque $T_L$ that will be applied to the load, being the developed torque $T_d$ subtracted by the friction torque, which is the sum of the static friction $T_c$ and viscous friction, as shown in Eq. (2).

$$T_L = T_d - T_c - B\omega \tag{2}$$

**Fig. 1** EMG30 geared motor

Current $i_a$ can be correlated with the developed torque $T_d$ through Eq. (3), the back emf voltage can be correlated with angular velocity through Eq. (4) and the load torque $T_L$ can be correlated with the moment of inertia and the angular acceleration through Eq. (5) [11].

$$T_d = K_s i_a \tag{3}$$

$$e = K_s \omega \tag{4}$$

$$T_L = J \dot{\omega} \tag{5}$$

In order to obtain experimental data, a setup, shown in Fig. 2, was implemented. The experimental setup is based on the Arduino micro-controller, the L6207 Drive, a DC Power source, an EMG30 actuator, and the motor Load. The obtained data is the load angular velocity, the input voltage, and the motor current. Two tests were performed, the first was to obtain the step response for a 12 V input (transitory response data) and the second test was the steady state response for

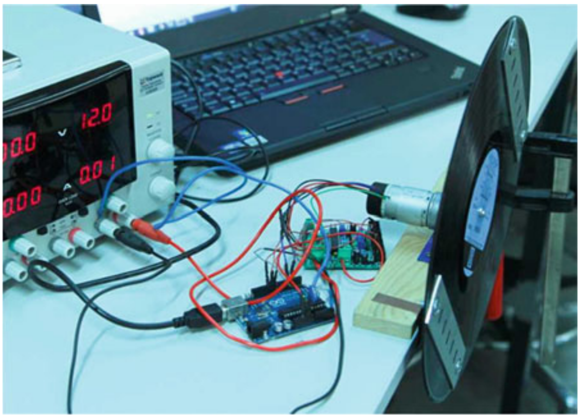


**Fig. 2** Experimental setup

several input voltages (steady state data). Resorting to Eqs. (2), (3), and (5), Eq. (6) was obtained.

$$\dot{\omega} = \frac{K_s i_a - T_c - B\omega}{J} \tag{6}$$

After discretizing Eq. (6), Eq. (7) was obtained, where ΔT is the sampling time (50 ms).

$$\omega[k] = \omega[k-1] + \Delta T \frac{K_S i_a[k-1] - T_c - B\omega[k-1]}{J} \tag{7}$$

By minimizing the sum of the absolute error between the estimated (7) and the real transitory response data (assuming initial know values for $R_a$ and $K_s$, parameters B and J were estimated. Then using Eqs. (1), (2), (3), (4), and (5) and assuming that voltage drop due to $L_a$ is negligible, Eq. (8) is obtained.

$$J\dot{\omega} = \frac{K_s}{R_a}(U_a - K_s\omega) - B\omega - T_c \tag{8}$$

Solving the first order differential equation, Eq. (9) is obtained:

$$\omega(t) = \frac{a}{b}\left(1 - e^{-bt}\right) \tag{9}$$

$$a = \frac{K_s U_a - R_a T_c}{R_a J} \tag{10}$$

where:

$$b = \frac{k_s^2 + R_a B}{R_a J} \tag{11}$$

In steady state $\omega = a/b$, resulting in Eq. (12).

$$\omega = \frac{K_s}{K_s^2 + R_a B} U_a - \frac{R_a T_c}{K_s^2 + R_a B} \tag{12}$$

By minimizing the absolute error between estimated and the steady state data, assuming an initial value for $R_a$, parameters $K_s$ and $T_c$ are estimated. Finally resorting to Eq. (9), by minimizing the absolute error between the estimated data and the transitory response data, $R_a$ is estimated. The described optimization process must be repeated until the estimated parameters converge to their true values. Parameters such as $T_c$, $R_a$ and $k_s$ that are initially assumed as known are replaced by the estimated ones, every time the estimate process is repeated. The estimated and the real transitory and steady state responses are shown in Fig. 3.

The load has a known moment of inertia, given by the sum of three moments of inertia. A moment of inertia of a vinyl record $J_d = 0.5 m_d r_d^2$ (where $m_d$ is the record mass and $r_d$ is its radius) summed with the moments of inertia of two planar rectangles, each one given by the equation $Jr = m(a^2 + b^2)/12$ (where a and b are

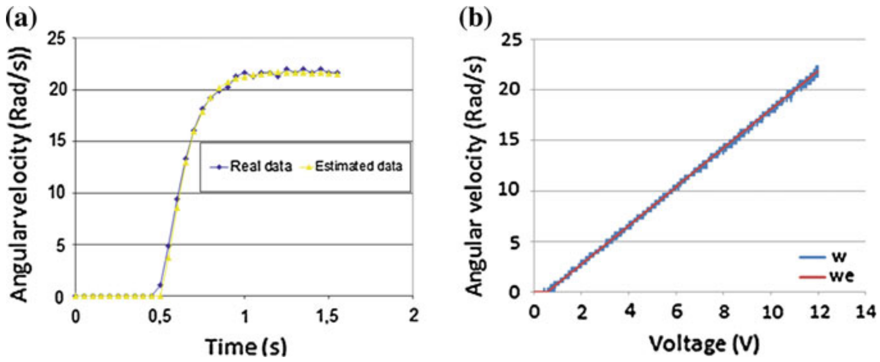


**Fig. 3** **a** Motor transitory response. **b** Motor steady state response data

**Table 1** EMG30 estimated parameters

| Parameters | Value |
|---|---|
| $k_s$ | 0.509 |
| $L_a$ | 3.4E-3 |
| $R_a$ | 7.101 |
| B | 0.000931 |
| $T_c$ | 0.0400 |
| J | 0.00567 |
| $J_M$ | 0.00377 |
| $J_L$ | 0.0019 |

the planar rectangles sides dimensions and m is the planar rectangles mass). Having in mind that the **Parallel axis theorem** has to be used in order to calculate the moment of inertia of the planar rectangles, $mr_p^2$ has to be summed to the previous calculated moment of inertia (where m is the rectangular plane mass and $r_p$ is the perpendicular distance between the axis of rotation and the axis that would pass through the Center of mass of each rectangular plane) [12]. In order to estimate the motor moment of inertia it is subtracted to the estimated value J the calculated moment of inertia, being $J_L$ the load moment of inertia and $J_M$ the moment of inertia. The estimated parameters are shown in Table 1, where the presented equivalent inductance was directly measured.

## 3 Simulation of the EMG30 Resorting to SimTwo

SimTwo is the official simulator of the Robot@Factory competition. The competition arena, shown in Fig. 4, emulates a factory shop floor where there are warehouses and machinery. A real robot prototyped with the EMG30 actuator moving in the competition arena is shown in Fig. 5.

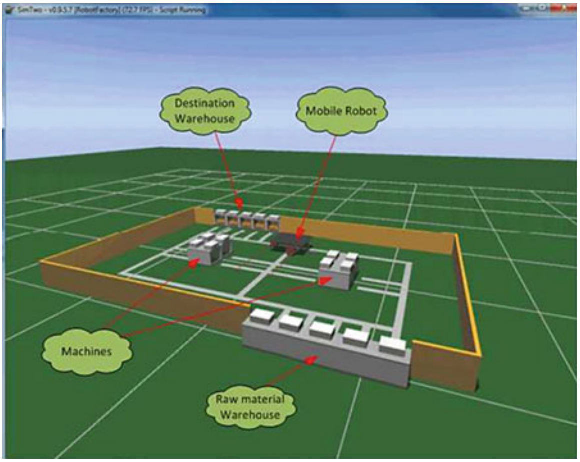


**Fig. 4** Competition arena modeled in the SimTwo

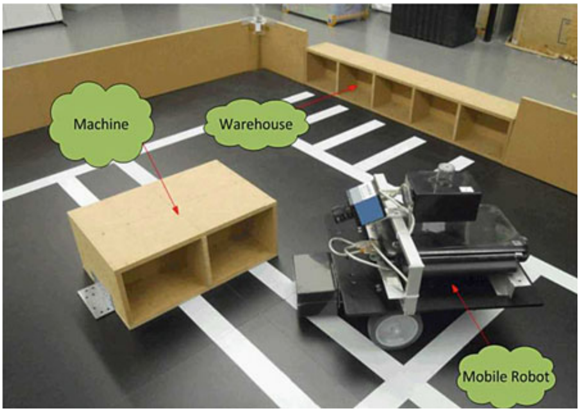


**Fig. 5** Robot in the competition arena

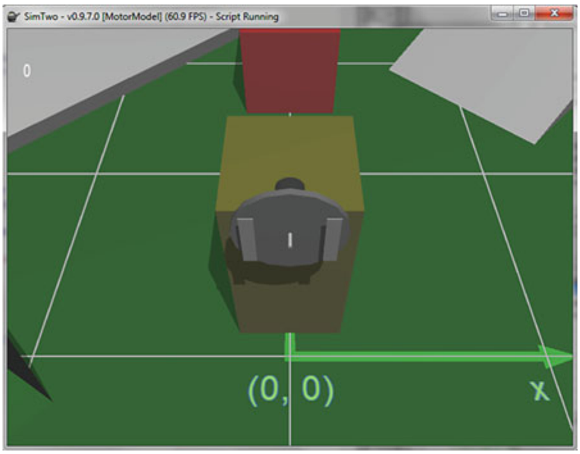


**Fig. 6** EMG30 simulated in SimTwo

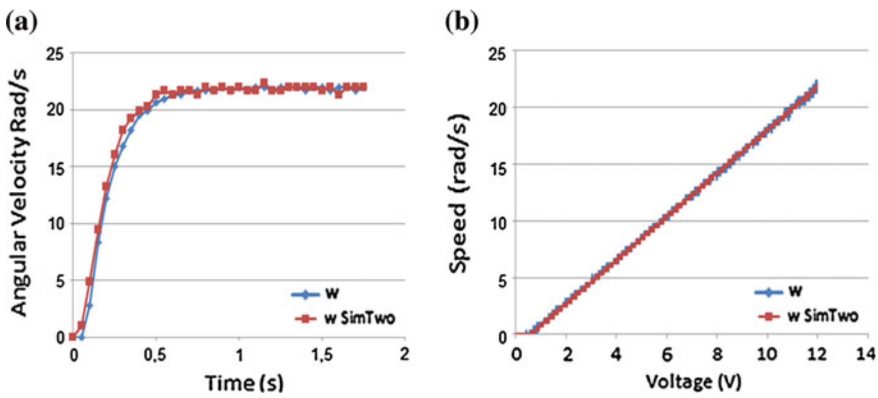


**Fig. 7** **a** Actuator transitory response. **b** Actuator steady state response

In this section it is presented an example of a simulation of the EMG30 motor, being a very popular actuator among teams participating in the Robot@Factory competition. The experimental setup presented in Sect. 2 was simulated resorting to SimTwo, a snapshot of its simulation is shown in Fig. 6. The presented previously experiments were simulated, the real results and the simulated are shown in Fig. 7.

## 4 Conclusions

In this paper it is presented the EMG30 mechanical and electrical modeling and its simulation resorting to SimTwo (Robot@Factory mobile robot competition official simulator). It is described the developed setup applied to obtain the experimental data, that was used to estimate the actuator parameters. It was obtained an electromechanical dynamical model that describes the motor, its gear box, and the encoder. The motivation to model and simulate the EMG30 was the fact that it is an actuator worldwide popular in the mobile robotics domain, and in particular in the Robot@Factory participating teams, being a low cost 12v motor equipped with encoders and a 30:1 reduction gearbox. The referred robot competition can play an important role in education due to the inherent multi-disciplinary concepts that are involved, motivating students to technological areas. It also plays an important role in research and development, because it is expected that the outcomes that will emerge here, will later be transferred to other application areas, such as service robots and manufacturing. As future work the authors intend to produce robot code resorting to SimTwo with a robot prototyped with EMG30 actuators and apply it to the real robot.

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## References

1. Almeida L, Azevedo J, Cardeira C, Costa P, Fonseca P, Lima P, Ribeiro F, Santos V (2000) Fostering advances in research, development and education in robotics. In: Proceedings of the 4th Portuguese conference in automatic control
2. Browning B, Bruce J, Bowling M, Veloso M (2005) Ustp: Skills, tactics and plays for multi-robot control in adversarial environments. IEEE J Control Syst Eng
3. Lund H, Pagliarinis L (2000) Robocup jr. with lego mindstorms. International conference on robotics and automation, San Francisco, CA, IEEE
4. Nakanishi R, Bruce J, Murakami K, Naruse T, Veloso M (2006) Cooperative 3-robot passing and shooting in the RoboCup small size league. In: Proceedings of the RoboCup symposium, Bremen, Germany
5. Ribeiro F, Moutinho I, Silva P, Fraga C, Pereira N (2004) Controlling omni-directional wheels of a RoboCup msl autonomous mobile robot. In Scientific Meeting of the Portuguese Robotics Open
6. Yuta S, Asama H, Thrun S, Prassler E, Tsubouchi T (2003) Field and service robotics, recent advances in research and applications. Volume 24 of Springer tracts in advanced robotics, Lake Yamanaka, Japan, 14–16 July 2003
7. Nambiar AN (2010) Challenges in sustainable manufacturing. In: Proceedings of the 2010 international conference on industrial engineering and operations management, Dhaka, Bangladesh, January 9–10 2010
8. Gonçalves J, Costa P, Lima J, Moreira A (2012) Manufacturing education and training resorting to a new mobile robot competition. Flexible Automation Intelligent Manufacturing (FAIM), Ferry Cruise Conference Helsinki-Stockholm-Helsinki, 10–13 June 2012
9. Costa P, Gonçalves J, Lima J, Malheiros P (2011) SimTwo realistic simulator: a tool for the development and validation of robot software. Int J Theory Appl Math Comput Sci
10. Borenstein J, Everett H, Feng J (1996) 'Where am I?' Sensors and methods for mobile robot positioning. Technical Report, The University of Michigan
11. Bishop R (2002) The mechatronics handbook. CRC Press, New York
12. Ramsey A (2009) "Dynamics", Cambridge Library Collection—Mathematics

# New Concepts for a Flexible and Industrialized Production Process for FRP-Based Transport Infrastructure Components

**Andreas Kluth and Jens Michael Jäger**

**Abstract** Using Fiber Reinforced Polymers (FRP) have become a fast growing matter in new construction structural components. First transport infrastructures, e.g., road and pedestrian bridges are built out of such components, today already made manually in manufactory workshops. The cooperative EC funded project, TRANS-IND—New Industrialized Construction Process for transport infrastructures based on polymer composite components, shifts from existing manual approaches to industrialization concepts. It targets a cost-effective integrated construction process that will enable the maximum capability of components for transport infrastructures using polymer based materials (carbon fiber, glass fiber, etc.) as well as to industrialize the whole construction process of the FRP components. This paper presents the different planning activities for the conceptual design of the off-site industrialization process and a detailed description of each planning phase and their related planning activities. First the paper surveys important theoretical basic approaches to define the fitting conceptual design of the off-site industrialization process. Further the infrastructure components to be manufactured and the required manufacturing processes are introduced. Subsequently for each infrastructure component, generic production structures are assigned and evaluated. The results are specific models of planned production areas, logistics as well as rough and final layouts for the factory.

## 1 Introduction

Polymer composites, also known as Fiber Reinforced Polymers (FRPs), are commonly used for strengthening existing structures in concrete and steel in civil and building construction. Fiber composites were almost 10–15 years exclusively

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“high-end” applications in aerospace industry or exemplary applied in Formula 1, but today they have become well established in other segments. While they have been used only in niche applications and the overall market is still modest, many experts see high growth in coming years for FRP materials, mainly due to the significant potential regarding lightweight construction [1]. Fiber Reinforced Polymers are used more and more in new construction structural components [2]. Today already first transport infrastructures, e.g., road and pedestrian bridges are built out of such components, mainly manufactured manually and not automated. These materials have not yet been exploited regarding potential capacities because of complex manufacturing processes for composites components in construction that currently are based either on inefficient manual processes or on processes unable of taking advantage of the full capacity of these new materials [2].

The presented work is a part of the European research project “New Industrialised Construction Process for transport infrastructures based on polymer composite components” (TRANS-IND—EU FP7-NMP) on innovative concepts and technologies to enable the maximum capability of industrialization of components for transport infrastructures (road and pedestrian bridges, underpass, containing walls, acoustic and safety barriers) using polymer based materials.

As it can be seen in Fig. 1, the target is to achieve a 10 % reduction of the overall construction cost of bridge and other transport infrastructure elements compared to current concrete components, by providing a competitive and cost-effective alternative to concrete materials based on FRP. Moreover, this cost reduction level will represent roughly around 33 and 17 % with respect to the current manual and semi-automated manufacturing processes, respectively, in use for FRP construction elements [3]. These reductions will be obtained mainly through savings in

- time reduction in the whole industrialization process,
- labor off-site and on-site costs by the use of ICT tools as well as automation and robotization of the manufacturing, logistics, and assembly processes,
- avoiding rework and “bad-quality” costs,
- reducing wasted material costs by improved overall manufacturing efficiency,
- reducing energy costs by optimized consumption and needs of the new industrialization process,
- reducing transport cost due to the lighter weight of FRP components compared to concrete ones.

In order to develop such a cost-effective production construction process that will enable the maximum capability of automation of components for transport infrastructures based on polymer materials like carbon fiber or glass fiber, there is a need to industrialize the whole construction process for the FRP components. Therefore, the main objective is to conceive and develop an automated off-site production process for manufacturing modular FRP based transport infrastructure components. This overall concept should cover the whole production process from the procurement of raw materials up to the transport of the produced components,

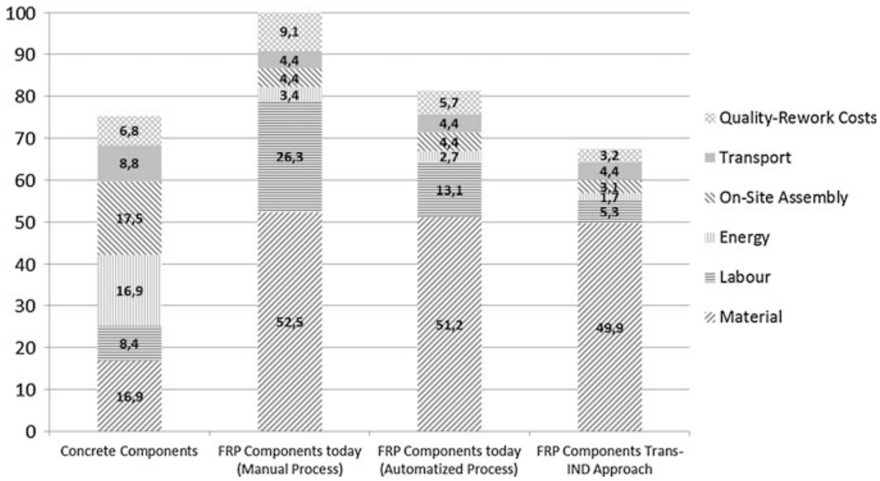



**Fig. 1** Comparison of the normalized total building costs of bridge elements, of the current existing technologies and the future ones

as well as the facility layout and the management of involved human resources. The overall concept represents the systematization and structuring of all planning activities and their related planning objects. Different involved planning activities for the conceptual design of the off-site industrialization process are presented and a detailed description of each planning phase and their associated planning activities is given. Based on that, production areas, logistics, and a rough layout for the factory will be analyzed and finally different variants for the possible final factory layout are presented.

## 2 Digital Factory Planning Tools

In this section certain digital planning tools are presented and described. These planning tools support factory planners during their different planning activities and they were used within this work to perform the single planning steps presented in Sect. 4. For each tool a general description is given and the main functionalities are listed.

### *2.1 Process Designer*

The rough and detailed planning is carried out with the Computer Aided Planning (CAP) system "Process Designer" from Siemens Industry Software. The selected CAP system is a factory engineering system, which enables the planning, optimization, and organization of products, processes and resources of the factory to be planned as well as the visualization, planning, and optimization of plant layout. It is used for planning, analysis, and management of manufacturing processes. It is therefore able to support numerous planning phases like

- process, equipment, and workplace planning (e.g., manufacturing and assembly process planning, production and capacity planning, resource planning, work scheduling, human resources/personnel planning, system construction);
- rough and detailed layout planning e.g., dimensioning and positioning of resources and machines, planning of transportation paths.

"Process Designer" enables the development of processes, 3D visualization of the factory layout and the product model as well as the modeling of manufacturing processes including the allocation and calculation of process durations. Furthermore, the line balancing of production systems can be performed, as well. The huge variety of manufacturing processes and process sequences, which are caused by a huge variety of product variants, are managed by variant filters. Furthermore, this tool has the functionality of execution (run) of numerical simulations for the purposes of optimization of process parameters. Thus, these simulations can be performed in parallel to other process planning activities, by improving so the process times [4].

## 2.2 Process Simulate

"Process Simulate" is used in the phase "Process Simulation and Workplace Planning." It is a digital manufacturing solution for the simulation of manufacturing processes. It also enables their optimization and verification using a 3D environment and visualization. The functionalities of "Process Simulate" are the 3D kinematic process simulation, static and dynamic collision detection, and a sequencing of operations. It can also be employed to plan assembly paths and to model resources (3D and kinematics). Finally its functionalities include line and workstation design as well as workplace planning [5].

## 2.3 FactoryCAD/FactoryFLOW

"FactoryCAD/FLOW" is a software application that generates material flow and aisle congestion diagrams/reports. With such flow information, represented directly in a layout drawing of a factory, it is possible to identify and perform following issues:

- Identify critical paths,
- Planning or improving the layout of a single work cell, a production line, a department or a plant,

- Identify potential flow bottlenecks,
- Working to improve the material flow efficiency of a product, a part or groups of parts or products,
- Production flow, material handling, and storage space requirements,
- Changing product mix, adding new production or working to improve plat efficiency, presenting layout alternatives.

"FactoryCAD/FLOW" enables engineers to rapidly evaluate alternative factory layouts based on material flow distances, frequency, and costs. With "Factory-CAD/FLOW" you can combine a layout drawing with part routing information, material handling equipment specifications, part packing (containerization) information, and material storage needs and then perform calculations and generate reports and diagrams in order to numerically and graphically compare alternatives [6]. The main functionalities of "FactoryCAD/FLOW" include the evaluation of material handling requirements, the elimination of non-value-adding material handling, and the reduction of total product travel and therefore the improvement of the product throughput. Additionally, it is able to be used to reduce work-in-progress inventories, to redesign material flows for different technologies, and to identify storage space requirements. Finally, it supports the analysis of the feasibility of operator walk paths in a factory layout [7].

## 3 Manufacturing of FRP-Based Transport Infrastructrue Components

The next sections focus on the product components and the required manufacturing processes for this purpose. To establish the relationship between the product components and the manufacturing processes the product is presented first. Once the components are described, they can be assigned to the appropriate manufacturing processes according to the desired shape and characteristics and further planning activities. Figure 2 presents the schematic concept of the standard bridge and the basic components. In the side view of the bridge on the right, the light-gray beams rest on the two pillars. In front view on the left it is one of the pillars with three beams on top. On top of the beams two FRP decks with concrete surface are placed as well as little joints to connect the deck to the beams.

### *3.1 Beams*

A beam is a structural element that enables the absorption of load and resists bending. The beams are designed to carry horizontal loads like earthquakes or wind as well as vertical loads. Beams are characterized through their profile, their length, and their material. Different profiles of the beams can be realized: open-

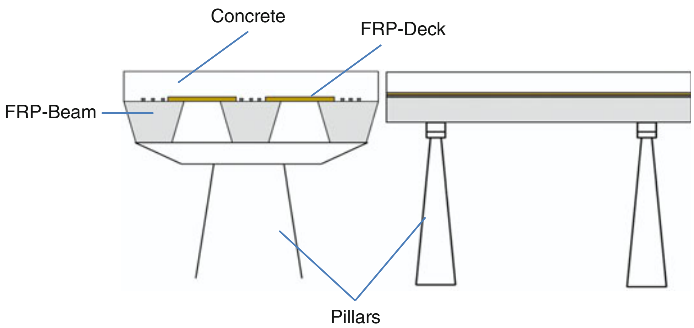



**Fig. 2** Schematical representation of a standard bridge

**Fig. 3** Open-shaped beam

shaped, closed-shaped, and u-shaped [8]. The expected beams are 10–40 m long and consist of the following components: Sheath and diaphragm modules. The assembled beam is mounted on two concrete pillars. It is expected that a manufactured beam which has to stand on two pillars therefore consists of a sheath and diaphragms, while the number of diaphragms depends on the beam‘s design (length and type of the beam). Figure 3 shows a schematical representation of the aforementioned components in an early planning phase.

The material for the FRP beams can be made with the production of so called UniDirectional (UD) resin material, which can be separated between thermoplastic resins and thermoset resins. The process for thermoplastic resins is using an extruder for the supply of the molten resin to the fibers. The fibers are pulled from a creel and guided in such manner that they are evenly distributed over the length of the rollers. The resin film is held at the appropriate temperature and impregnates the fibers as they pass through the nip of the rollers. After the impregnation, the UD material is cooled and by means of the pull rollers transported to the winder.

A related process is used for UD thermoset resins [9]. The UniDirectional resins are used for the production of FRP closed shaped beams.

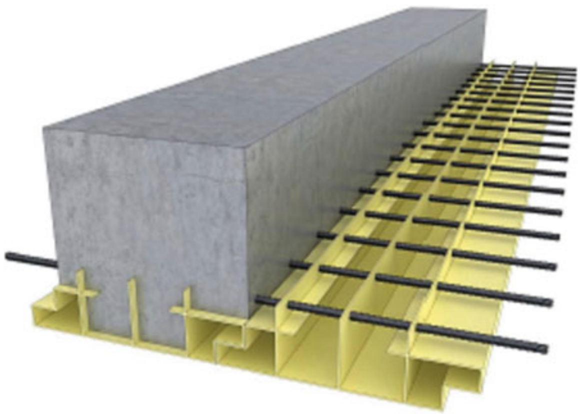
The manufacturing of such beams can be achieved by using Filament Winding—In this process fibers are combined, which are wound after wetting with resin on a mandrel/spindle [10]. Therefore, only the spindle rotates and the material is applied on the spindle by using a slide. Through the horizontal reciprocating movement of the slide it is able to vary the angle of application and therefore the verification of the structure, e.g., thus, at the same rotational speed, the angle is flatter the faster the movement of the slide. During the winding process the necessary pressure originates caused by the rotation to combine the fibers and cure the resin, so there is no more pressure needed. Through the rotation of the mandrel only straight products can be produced with a high degree of automation.

## *3.2 Decks*

A deck is a flat surface capable of taking weight and is designed for applications in vehicular and pedestrian bridges (see Fig. 4). The used materials to manufacture this deck are glass, epoxy resin, and concrete. The deck components can be applied on different types of beams mentioned in the former section [8]. The FRP decks can be manufactured in different types, either made of thermoset material or made of thermoplastic material. These bridge components have to pass other manufacturing processes (off-site) like pultrusion processes or cutting processes until they can be shipped to their final destination site.

The pultrusion is an automated and continuous production process that allows the manufacturing of parts with a constant cross-sectional area. The solid product can be an open cross-section, such as a sheet, a closed cross-section like a tube or complex cross-section as a panel with reinforcing ribs. For the processing, the fibers are guided to the reinforcing material through the resin tank, where they connect

**Fig. 4** FRP deck with concrete



with each other and where they are already brought in the first form. Then the material is drawn through a die casting mold which is heated and thus to cure the resin. Depending on the shape of the product it is necessary to make sure that the resin cures correct and proper to prevent the cause of cracks in the product. The last process step is that the solid product is cut to size. In summary, this process has a high degree of automation, low investment cost, and fast production speed [11].

The material for the FRP decks is prepared with so called Resin Transfer Molding (RTM) process, which is like a resin injection process and is a kind of wet-press method [12]. In this production process a dry fibrous material preform is laid into a casting form and sealed. Through an opening the resin is introduced and filled the entire mold with resin [12]. Once all the air has escaped from the mold the curing process can begin. This process step can be accelerated by a heated mold. The Resin Transfer Molding enables the production of complex parts with a medium level of automation and medium-speed [11, 12]. For the RTM process standard machines are not defined yet and could not be found by investigation, such as the machines used for the conventional injection molding process. The investigated machines are customized work stations. For this reason the assumption is to continue conceptual planning with the assumption of customized machines [13].

### 3.3 Acoustic and Safety Barriers

For bridges made out of FRP structural components, two different types of barriers can be defined, acoustic barriers and safety barriers. An acoustic barrier is an element to protect sensitive land uses from noise pollution. They are the most effective method of mitigating roadway, railway, and industrial noise. Within this work three topologies of acoustic barriers are considered to assure the most suitable solution for noise reduction: Simple acoustic barriers, acoustic barriers with vegetation, and curved acoustic barriers. All these acoustic barriers systems consist of panels made of Glass Reinforced Polymers (GFRP), supported by glass fiber H-shaped soldier piles [8].

A safety barrier is a component which prevents unwilled access to a locked or potentially deadly area. In traffic it is a guard, such as a fence, to keep the vehicle away from falling down, e.g., a bridge or cliff. Hard barriers are fixed or removable guards which prevent entry. Soft barriers are devices such as light curtains which detect the presence of a foreign body and are tied into the control circuit to stop the machine. Within this work safety barriers can be divided in two typologies: Simple safety barriers or safety barriers with foam. All these safety barriers consist of two closed cap FRP profiles supported by steel posts. For each type of safety barrier, geometrical dimensions and figures related to the impact analysis are provided. Simple safety barriers and safety barriers with foam have the same geometrical dimensions and consist of the same elements. The only difference is the foam within the closed cap profiles [8].

The material for the safety barriers is made out of Crossply Material and can be basically separated between laminates with the UD (UniDirectional) layers oriented at 0 and 45° and UD layers oriented at 0 and 90°. The UD material is unwound and fed by means of the supply belt to the cutting unit. The length of the cut piece corresponds with the width of the ultimate product. The cut piece is placed by a positioning belt on top of the UD layer which is unwound from a second unwinder. The angle of the UD layer is determined by the angle at which the turn section is placed. Both layers are laminated together by means of the laminator unit and wound on the winder. Multi-axial laminates are made by multiple passes through the machine, for example to include a 90° layer on the laminate [14]. These crossply laminates are used for production of closed cap profiles for the safety barriers components.

The profiles for the safety barriers are manufactured by Continuous Compression Molding, which is a semi-continuous process in which several pressing tools are included in one press. These tools are arranged in a row and the material is transported through them. The main objective of this process is to separate the heating and the cooling zone of the tool in order to realize high heating and cooling rates. This means that the impregnation and the solidification take place in different parts of the tool. In the heated section at the beginning the material is impregnated and consolidated and then it is still consolidated and also solidified in the cooling section. The Continuous Compression Molding can be split into four steps: first the mold will be closed, a constant pressure will be applied, the mold will be lifted and at the end the laminate will be transported to the output unit. Although various materials are suitable mostly carbon or glass fiber reinforced polymers are used for Continuous Compression Molding [15]. Within this production step various profiles can be produced, which are used to manufacture closed shape profiles for the FRP safety barriers.

## 4 Conceptual Production Line for FRP Infrastructure Components

The bridge components which are planned to be produced are as presented: beams, decks, and secondary elements (safety barriers). These components are produced in the factories (off-site) to be planned, transported to the construction site, and assembled there (on-site). In this chapter the main planning activities and steps for the development of a conceptual production line for FRP infrastructure components have been identified as follows:

- Product planning for manufacturing;
- Process and resource planning for manufacturing;
- Rough and detailed layout planning.

Several approaches to support the engineering in the various planning phases of the factory planning are taken into account [16–21].

## 4.1 Product Planning for Manufacturing

While designing an off-site production process, it is necessary to handle the lack of required planning data within the Trans-IND project. In order to get first estimations for continuation of planning activities many data values are created by methodical assumptions and experts' experience with the aim to plan an ideal production plant. The lack of planning data regards the annual number of units to be produced, the specification of variants, the number of units per variant as well as the dimensions of variants. The number of components for a bridge is determined by own contribution. Therefore, it is stated to perform the overall planning with the mentioned expert assumptions of an ideal standard bridge production. It is defined that the standard bridge has two lanes with a width of 2.75 meter per line, which leads to two decks and three beams. The standard beam length is maximum 14 meter per beam as well as one sheath and 15 diaphragms in each beam. The dimensions of the bridge components are given by Trans-IND project description of work as well as by Trans-IND project partners involved, but most dimensions for product planning for manufacturing have to be completed by methodical assumptions and experts' experience as well.

## 4.2 Process and Resource Planning for Manufacturing

The process sequence is planned in reference to the presented manufacturing processes and the restriction through the Trans-IND project. In reference to the structure of the products and their components the process sequence is divided into four main sections: Safety barriers, deck, and beam (sheath manufacturing + diaphragm manufacturing) (see Fig. 5). Important for process planning is the consideration of process time, set-up time, and downtime. Therefore, no specific figures are available yet. The further planning is based on assumptions and the process times have to be estimated. Nevertheless, the process times are estimated, care is taken to get realistic values for the specific figures. For each product component the project documents define the manufacturing process. Therefore, the approximate processing time of each manufacturing process can be investigated.

After the determination of the process sequence the required manufacturing resources can be defined with reference to process duration times and production area dimensions. Due to the fact that the filament winding process requires a high process time per unit and that the winding machine is quite expensive, the filament winding process is determined as the reference schedule (bottleneck) for all preparatory and subsequent manufacturing processes. Therefore, it has been

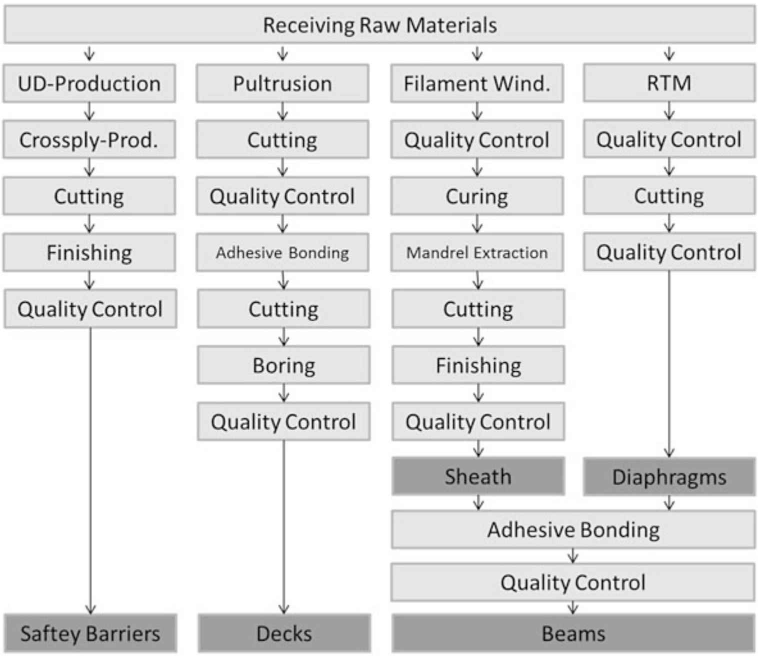



**Fig. 5** Overall process sequences

appointed that the winding machine should be fully utilized and all other processes have to be designed in respect to this condition. The overall process duration time for reference filament winding process has been calculated with 5 h to manufacture one unit. Table 1 summarizes a cross section of all manufacturing processes for the beam production, their needed process duration time per unit, the calculated number of required resources, related specifications as well as the required area dimensions for the machines. These mentioned requirements and factors are the basis for the structured functional production segments. Functional orientation, process orientation as well as hybrid principle component orientation is considered for the planning of different scenarios.

### *4.3 Rough and Detailed Layout Planning*

Within the rough layout planning three principles are presented (see Fig. 6), which represents possible configurations of the production lines and the factory, taking into account restrictions and input from previous planning steps as well as needs of the given content from project partners. The design of the first variant is based on a material flow oriented positioning of the resources. The production will be in a clear and simple process flow. Another variant could be to arrange a compact

**Table 1** Cross section of summarized processes, resources, specifications, and area dimensions

| Process | Process time (h/u) | Required resources (#) | Specification | Area dimensions ($m^2$) |
|---|---|---|---|---|
| Filament winding (FW) | 5 h/1u | 1 | Bottleneck | 34.6 |
| Cutting sheath | ≤5 h/1u | 1 | Sub sequent FW | 22.3 |
| Finishing sheath | ≤5 h/1u | 1 | Sub sequent FW | 43.8 |
| QC sheath | ≤5 h/1u | 1 | Sub sequent FW | 42.6 |
| RTM diaphragms | 8.7 h/15u | 2 | 8.7 h > 5 h | 62.2 |
| Cutting diaphragms | 8.1 h/15u | 2 | 8.1 h > 5 h | 73.5 |

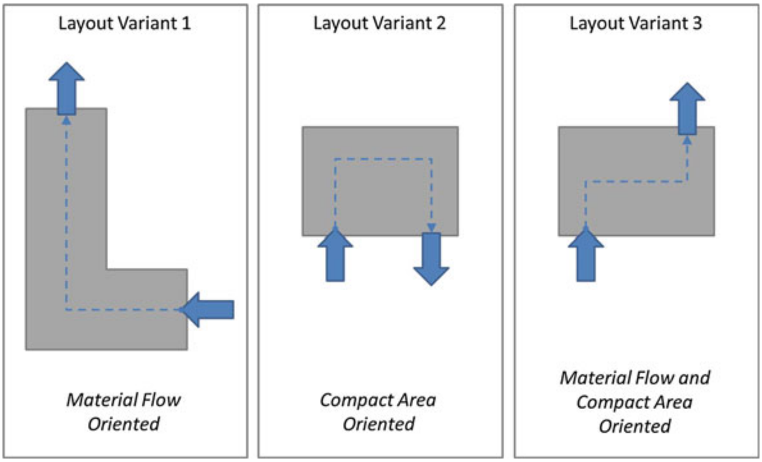



**Fig. 6** Schematic rough layout variants

layout in order to optimally exploit the smallest possible area. The third variant takes into account principles of methodical arrangements in order to create a combined production area of compact and flow oriented segments. Depending on the focus of planning preferences and weighting of specific criteria (e.g., stability of the production process, productive use of area, expansion options, etc.), the variants differ with respect to their suitability. For the evaluation, alternative scenarios were planned and evaluated by means of a cost-benefit analysis. As an outcome variant 1 has the lowest utility value, with large space requirements, which leads to high transportation efforts in many other areas. Variant 2 has a clearer and more efficient factory structure which leads to a higher utility value. Due to the combined layout and material flow structure, improving accessibility of stations, as well as the productive flow of material, variant 3 receives the highest value and therefore the highest rating.

During the detailed layout planning the mentioned CAP system is used to create a 3D environment and graphical representation. The required resources have to be modeled in a compatible 3D format, so that they can be placed in the detailed factory layout. First the exact arrangement of the machines has to be determined

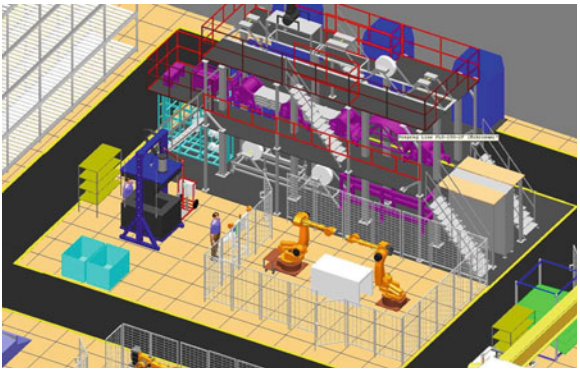


**Fig. 7** Detailed layout planning and graphical representation

with consideration of the arrangement and position of the other devices. Accessibility to transportation routes and other factors like the space available are crucial and have to be considered in an early phase. Furthermore for occupational safety minimum distances as well as safety fences must be met urgently. The planning for the handling devices and storage elements will be specified clearly, e.g., the exact dimensions and the identification of the transport routes and storage areas can be determined. Figure 7 presents an extract of the planned layout and the graphical representation within 3D environment.

## 5 Conclusion and Future Work

Within this paper an approach for the design of new concepts for a flexible and automated off-site production process for FRP based infrastructure components is presented. Each planning phase is described as well as their associated planning activities. To define a conceptual design of the off-site production process, the components that should be produced and the needed manufacturing processes are shortly presented. As a result of this for each component of the bridge as well as for the overall concept, a generic production structure can be assigned and evaluated. Different production areas, logistics as well as rough layout variants for the factory have been analyzed and finally a detailed factory layout was developed. At this stage of this work the main data within this production concept like process times, machine dimensions, sales data, and product data have been assumed and estimated. Detailed planning using real process, product, and resource data has to be evaluated, included, and integrated within future work.

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## References


1. Lässig R, Eisenhut M, Mathias A, Schulte R, Peters F, Kühmann T, Waldmann T, Begemann W (2012) Serienproduktion von hochfesten Faserverbundbauteilen.- Perspektiven für den deutschen Maschinen- und Anlagenbau; Study—Roland Berger Strategy Consultants; 09/2012
2. Poneta P (2011) A new industrialized construction process for transport infrastructures -In No 64 April 2011/jec composites magazine
3. Poneta P (2012) New innovative processes for structural elements in composite materials for transport infrastructures. In: 1st international conference on civil engineering infrastructure based on polymer composites CECOM 2012, Krakow, Poland
4. Siemens industry software: process designer—powerful 3D environment for manufacturing process planning; available at: http://www.plm.automation.siemens.com/en_gb/Images/7456_tcm642-4941.pdf (13.12.2012)
5. Siemens industry software: process simulate—manufacturing process verification in powerful 3D environment; available at: http://www.plm.automation.siemens.com/en_gb/Images/7457_tcm642-80351.pdf (13.12.2012)
6. Schmidt K (2002) Methodik zur integrierten Grobplanung von Abläufen und Strukturen; Dissertation, Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen
7. Kohler U (2007) Methodik zur kontinuierlichen und kostenorientierten Planung produktionstechnischer Systeme. Dissertation, Lehrstuhl für Werkzeugmaschinen und Fertigungstechnik der Technischen Universität München
8. Trans-IND catalogue: components descriptions and specifications; available at: http://www.trans-ind.eu/media/files/Trans-IND+Catalogue_v14_HD.pdf (13.12.2012)
9. Van Wees UD and Crossply Technology: UD impregnation/coating; available at: http://www.vanwees.nl/en/products++services/ud+impregnationcoating.html (13.12.2012)
10. Samoil S, Sokoloski Z, Bogdanoski D, Capeska S, Maneski G (2012) Fiber reinforced plastic beam manufacturing process. In: 1st International conference on civil engineering infrastructure based on polymer composites CECOM 2012, Krakow, Poland
11. Sheikh-Ahmad JY (2009) Machining of polymer composites. Springer, New York
12. Flemming M, Ziegmann G, Roth S (1996) Faserverbundbauweisen—Halbzeuge und Bauweisen. Springer, Berlin
13. Stephan W, Matzner B, Schachinger A (2010) Schlüsseltechnologie—Eigene RTM Fertigung bei FACC. In: take off—Ausgabe 25; January 2010 Ausgabe 25., Ried, Austria: FACC p 14f
14. Van Wees UD and Crossply Technology: Crossply technology; available at: http://www.vanwees.nl/en/products++services/crossply.html (13.12.2012)
15. Holschuh R, Christmann M, Mitschang P (2012) Continuous compression molding process for production of transport infrastructures. In: 1st international conference on civil engineering infrastructure based on polymer composites CECOM 2012, Krakow, Poland
16. Association of German Engineers VDI 5200: VDI 5200 Fabrikplanung; (2009) Düsseldorf
17. Zürn M (2010) Referenzmodell für die Fabrikplanung auf Basis von Quality Gates; Jost Vetter Verlag Heimsheim 2010; IPA- IAO Forschung und Praxis, Universität Stuttgart, Dissertation
18. Aggteleky B(1987) Fabrikplanung Werksentwicklung und Betriebsrationalisierung. 2. Auflage. Hanser, München, Wien
19. Grundig CG (2006) Fabrikplanung. Planungssystematik—Methoden—Anwendungen. 2. aktualisierte Auflage. Hanser, München, Wien
20. Kettner H, Schmit J, Greim H-R (1984) Leitfaden der systematischen Fabrikplanung. Hanser, München
21. Wiendahl HP, Reichardt J, Nyhuis P (2009) Handbuch Fabrikplanung—Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten; Hansa, München, 2009.VDI 5200: VDI 5200 Fabrikplanung, Düsseldorf

# Increasing Flexibility and Productivity in Small Assembly Operations: A Case Study

**P. M. S. Nunes and F. J. G. Silva**

**Abstract** Despite the high production rates required in the automotive industry, some small components are being produced manually in peripheral countries where the labor costs are lower than in the middle of the Europe. When the production must be highly flexible, new challenges are placed and, in these cases, some companies adopt intensive labor processes. This work is based on an industrial demand in order to become an intensive labor process in intensive technology process, minimizing human intervention (without removing it), increasing productivity ensuring the quality, and maintaining the high flexibility already achieved in the assembly process of drive systems for automotive windscreen wiper. The equipment developed uses intensive technology through automation systems, needing an operator who is responsible by the initial feeding process. After that, all the process is automatic. The production cycle time is reduced from 11 to 7 s and the quality is ensured. The equipment is very flexible, allowing to assembly 20 different kinds of sets for the same purpose, changing just the gig where the main component is assembled.

## 1 Introduction

In the past, vehicles' producers offered a very limited number of models those had a small variety of attributes and long life cycles, as Ford T and Volkswagen Beetle. Nowadays, automotive industry must provide a high product variety to keep on competitive and follow the customers' wishes, remaining focused to all the technological innovations [1]. The desire of these organizations is to cover the different requirements, matching its offer with the different costumers'

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requirements [2–4]. This effect has been felt more sharply because in the last decade, the automotive industry has been carrying out the expansion of traditional vehicle segments with the so-called 'cross-over' and niche vehicles [5, 6]. However, this strategy brings new challenges for companies due to the increase of the manufacturing complexity. Nevertheless, the main strategic question with regards to product variety concerns is selecting the 'optimum' or 'adequate' level of variety: offering variety increases cost but, providing product differentiation in the market, companies can expand their market share and sales volume [7]. The automotive industry requires, usually, high production rates with a high level of accuracy, in order to ensure final products with high quality and reduced costs. As product variety increases, a company can also feel a performance reduction in many of its supply chain activities due to the reduced economies of scale, with potential negative impact on component costs, lead time, and component inventory levels. This trend is also generating a continued transformation of the production environment, which evolved in a few couple of years from mass production to mass or extreme customization [8–10]. Furthermore, the number of components in stock increases, implying higher costs of inventory [11–13]. Usually, flexible company refers the ability of this plant manufacturing a range of products (mostly pre-programmed) with versatile equipment [14].

Some small manufacturing or assembly operations are being made manually in countries where the labor costs is lower. In this case, the production is based on intensive human labor in detriment of intensive technology. The job related to these tasks is deeply stressful, mainly when ergonomic concerns are not taken into account. Workers usually generate tendonitis and other occupational diseases which decrease their ability to carry out these tasks. Because people are one of a manufacturing organizations' most valuable resources, manufacturing designers must develop a safe and healthy work environment [15]. Many studies have been done in order to understand the worker performance and comfort in repetitive assembly tasks [16–20]. Analyzing the effect of workstation design, assembly design, jig design, and working postures on assembly line, it was possible to understand that jig design have the most significant effect on the worker comfort [21]. The efficiency of a workstation will be better if the anthropometry data matches with the workstation design [22].

Automation and robotics must play an important role in this matter, overcoming ergonomic problems and increasing substantially both productivity and flexibility. However, there are usually some conflicts between productivity and flexibility because the systems thought for high production rates tend to be dedicated and not flexible. Despite this, the automobile assembly industry is able to gathering different vehicle models based on a similar platform in the same production line through intelligent feeding systems. This manufacturing philosophy can be transposed to assembly lines of small automotive components, such as drive systems for automotive windscreen wipers. Automation allows to reduce the setup time, increases the productivity, ensures the assembly accuracy, and reduces the human factor associate to assembly operations. Thus, the errors associated to fatigue and occupational diseases tend to be eliminated.

Nowadays, automation plays an essential role in manufacturing, petrochemical, pharmaceutical, paper, automotive, and metal industry, in conversion and distribution of energy, and in many services. The weighty challenges are becoming ever more intricate, and learning how to address them with the help of automation is a great task [23]. A correct combination of conveyors, sensors, and actuators, connected and commanded by computing systems, allows carry out automatically almost whole manufacturing and assembly operations, avoiding routine tasks by human resources. Humans have always pursued to increase the capability of their tools and their extensions, i.e., machines. A natural extension of this dream was making tools capable of self-operation in order to (a) Detect when performance was not achieving the initial expected result, (b) Initiate a correction in operation to return the process to its expected result in case of deviation from expected performance, (c) Adjust ongoing operations to increase the machine's productivity in terms of volume, dimensional accuracy, overall product quality or ability to respond to a new previously unknown disruption, and (d) Carry out the previously described functions without human intervention [24].

The main goals of this work were defined together with the people of the company where this system will be applied. Data was collected from head of manufacturing, quality manager, human resources, and operators of the current task, getting a full overview of how is the usual process flow, which are the most common problems, when they occur, and when they are detected. Two different approaches were thought: (a) full integrated system of assembly, without human intervention, using automation and robotics, ensuring lower assembly cycle time and very good reproducibility but creating social problems with many people who lose their jobs, or (b) partial automation, ensuring the same features of the full integrated system but where a person will be needed in order to feed the process, putting the main component in the gig, with all the remaining process being made automatically. For many organizations the process of transformation has been gradual, starting with the introduction of programmable logic controllers and personal computers to machines and processes. Nevertheless, for others the change has been quick and is still accelerating [25]. Attending the social responsibilities of the company considered, it was selected the second way, keeping the need of an operator aggregate to each assembly machine. After a few sketches, the usual 'in circle' assembly architecture was selected, keeping the final equipment more compact and allowing a better perception by the operator over all the automatic tasks performed in each different stage.

## 2 Case Study

This chapter is divided into two main sections: the identification of the problem and the ways considered in order to overcome it. As referred previously, initial situation was based on intensive human labor. Figure 1a shows a scheme how the

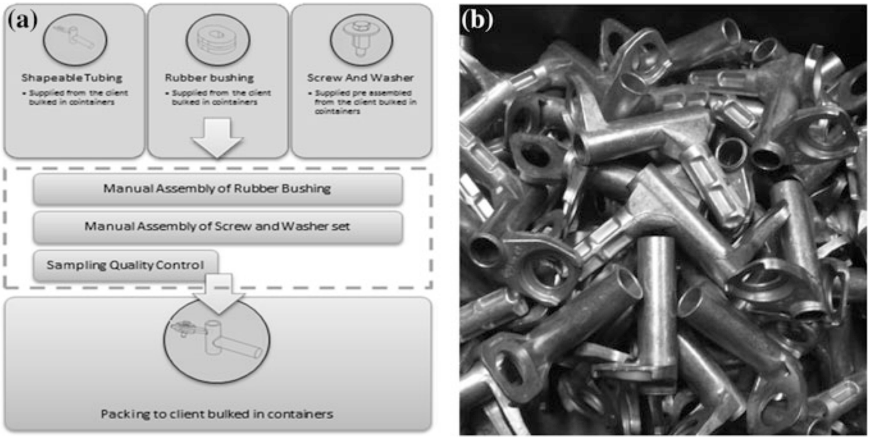


**Fig. 1** **a** Initial process flow chart and **b** Morphology of the main component of the set 19

assembly is performed by the operator, without special gigs, and based on human dexterity. Figure 1b depicts the geometry of the

It will be referred that the cycle time of assembly for these sets is about 11 s, with all the tasks being made manually. The company intends to invest some money in this assembly process increasing productivity and ensuring better results in terms of reproducibility and traceability, minimizing the ratio between non-acceptable and assembled parts. Furthermore, the use of an automated assembly process increases confidence in your customers, which is one of the main goals of this project.

This work does not intend to optimize logistic aspects into the plant because they are already optimized for the hand-made assembly process. Thus, the premises for the development of this project are based essentially on the process of assembling the various components, bearing in mind that all the components will be supplied to the machine.

## *2.1 The Problem*

The main problem of this project was the variability of the sets in current assembly. Effectively, there are 20 different types of drive systems for automotive widescreen wipers assembled in this plant because each automotive model obliges a different system, with different requirements due to different weight of the wipers and fastening systems. The complete list of parts that the company intends to cover with this project can be seen in Fig. 2. Secondary problems are related to geometric complexity. As can be seen in Fig. 2, there are pronounced geometric differences among these parts, which implies different support plans, allowing that assembling plan corresponding to the rubber bushing is always in the horizontal

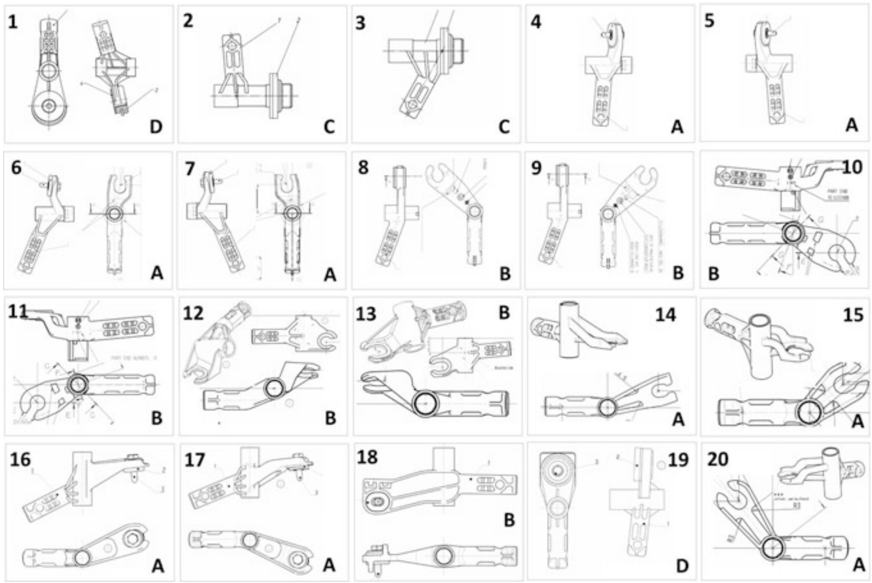

**Fig. 2** Complete range of sets that equipment needs to assembly

plan because the assembling movement will be do on it. Furthermore, the cavity made in each gig must have easy output of the part, ensuring simultaneously that the main component is assembled in a unique position and no vibration or further movement is allowed during the remaining assembly tasks.

## 2.2 The Solution

After a first study about the geometry of the different sets, they were cataloged in families, allowing a systemic approaching. In Fig. 2 it can be seen the sets labeled with A, B, C, and D, i.e., the different families as they were cataloged. Subsequently, different approaches have been studied for the assembly cycle. A balance between the levels of automation needed versus the price to pay for it is seriously taken into account. In Fig. 3 it is possible to observe that the number of parts to be assembled per minute determine the level of automation to be adopted [26]. Taking into account the number of sets to be assembled per minute (about 9), the optimal system becomes in-between a partial automation and a revolving transfer machine. As usual in assembly processes related with automotive industry, the revolving transfer system was selected because the cycle time is generally lower and the space occupied by the equipment is smaller. In order to allow an accurate assembly process, the number of stages selected was four, accommodating all the set types. For each kind of set it was drawn a gig, which allows the assembly of the

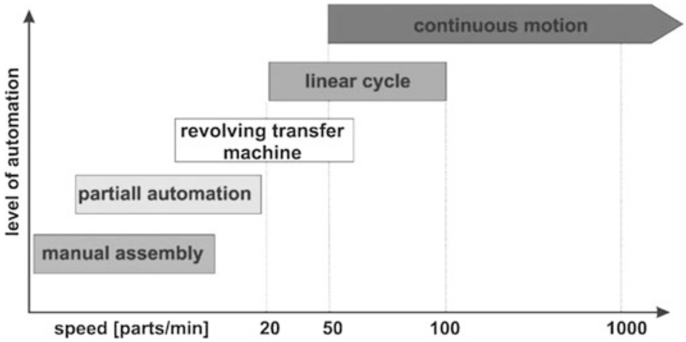


**Fig. 3** Tendency of the process-speed in automated assembly [26]

main component just in one position, ensuring the correct positioning of the remaining components. The equipment is doted of a core stage where the main component is assembled in the gig by the worker and fixed with maximum accuracy at the index system responsible for the movement between stages. After that, the main component within the gig goes toward the next stage where the rubber bushing is assembled. In order to make easy its access, the rubber is slightly mechanically compressed, making it oval and helping its assembling. The rubber bushings have a small groove around them, which should be in the same plane and direction of the fork's hole of the main component. After that, the gig will be drive to the next stage by the conveyor system, in order to put in the screw.

#### 2.2.1 Feeding Systems Required and Selection

The final product of this system will be assembled from three different parts. These parts need to be fed to the system in different stages and tasks. All the three parts have one common requirement: system should be capable of identifying which component is being fitted on each stage and prevent the assembly of wrong references.

In a first stage, as referred previously, the main part (shapeable tubing) needs to be fed, which is the startup part for all other components. The shapeable tubing has a very complex shape, in a wide range of references; thus, flexibility and precision were the main goals. In order to simplify the next tasks, it was also required that the main assembly point was kept in the same position for all the references. To solve this challenge a gig, like a mold, was created. The concept is to change the gig set from reference to reference, not only to increase flexibility and improve the setup time of the system, but also preventing errors and keeping the assembly point in the same position for all references. The concept of the gig was created by Selective Laser Sintering (SLS) technology, and future molds will be casted in Al–Si alloy. For the first approach to this project an operator will be responsible for fitting the main parts into the gig, Fig. 4a, pre-setup in the machine. After

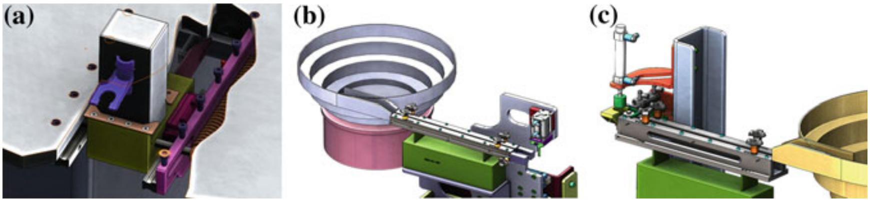


**Fig. 4** **a** Gig with shapeable tubing. **b** Bushing feeding system. **c** Screw and washer feeding system

validation of the complete system this operation can be automated thought a robotized pick and place system working in the same position of the operator. Each reference of main part has his own unique gig, and each gig has different measures so it is impossible to assembly a different reference from the one that the machine is working with, avoiding any operator/feeding mistakes.

For rubber bushings and screw, their shape and weight suggested the use of a vibratory bowl feeder already often used and reliability proven on these tasks. For this system it was choose a well-known producer of these systems, with wide range of products and experience in this kind of industry, RNA Vibrant S.A. For the bowl feeder it was selected the SRCN-400 Series and for linear guides SLL400. Thus, the challenge was to prevent errors and to guide the rubber bushings and screw to their assembly positions. As both components have cylindrical shape, similar systems were used, where the vibratory bowl feeder drops the parts into an adjustable guide, which should be setup for the working reference. Along the guide, three optical sensors measure the dimensions of the parts, identifying and validating them. On this same guide, there is the option to use a small lubricating system, which can apply a small quantity of soap and water to increase quality and speed in the assembly process of the rubber bushings.

### 2.2.2 Indexing Systems Required and Selection

Boxes with the main part of the set, Fig. 1b will be provided through an inlet motorized rollers conveyor which stands near the operator working position, with easy access and optimal picking level. The conveyor has a second level with gravity free rolls to send empty boxes back. Boxes with final product will be taken out from outlet rollers conveyor similar to the one used for inlet.

The movement of the gig with main part is provided by an indexing rotary table with capacity for eight gigs, each one connected to the table through an advanced locking system with high precision linear position sensing that can identify which gig is attached, sending this information to the main Programmable Logic Controller (PLC). Additionally, each gig has integrated an RFID tag that helps to catalog them. The indexing rotary table is totally designed in aluminum with optimized shaped parts to keep the moment of inertia as lower as possible. It is driven by a zero backlash gearbox from SEW, model FAZ37R17 i:1/365, with

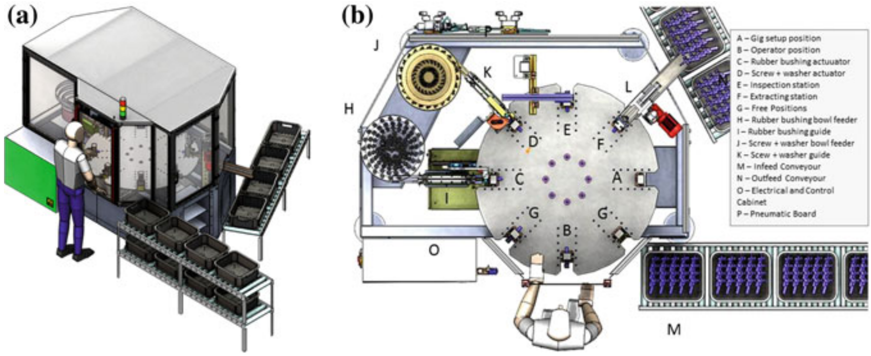


**Fig. 5** **a** Global aspect of the equipment. **b** *Top* view/layout of the working place and equipment

synchronous servo motor attached, also from SEW, model CM80L, with 0.8 N·m torque and incorporated encoder. The table rotates 45° each step, which is the angular distance between each stage.

### 2.2.3 Actuators Required and Selection

As the locking system of the gigs is tightened by a spring system, a release actuator is needed to allow gig change. When machine is in setup mode, a Festo DNCB-32 with 100 mm stroke and 483 N force at 6 bar pneumatic cylinder open the gig locking system in the setup position of the machine Fig. 5b (A).

For rubber bushing assembly task, two pneumatic cylinders were used, one Festo ADVUL 32 with 30 mm of stroke, acting vertically with a smooth aluminum finger attached that come in the middle hub of the bush, and other Festo DSNU-25 with 125 mm of stroke and 300 N of force at 6 bar, acting horizontal, sliding the bush, and inserting it into the hole on the main part, through his groove. These two movements are guided through strong guiding systems from INA and Festo and assembled with high accuracy on milled aluminum plate Fig. 5b (C). Both movements are controlled through proportional valves, allowing high precision control on applied force, and also allow pressure change if needed from reference to reference.

For screw and washer set, a pneumatic gate driven by a Festo ADNGF12 with 25 mm stroke cylinder makes a mechanical stop of screw feeding during screw and washer fitting task, preventing other screws being fed, and at the same time guiding the current set to the correct assembly position. Another vertical pneumatic cylinder, Festo DSNU-25, with 50 mm stroke and 180 N force at 6 bar and, with a concave head attached to the piston rod, push the screw and washer set into is final position Fig. 5b (D).

In the last stage, for part removal from the gig, a Festo HGR-40 pneumatic gripper with 180° maximum opening angle, with two rubber lined fingers grabs the part with a force of 30 N clamping force at 6 bar. Another pneumatic cylinder from Festo DNCB-32 with 100 mm stroke and self-integrated guiding system from Festo model FENG 32GK slides the gripper and the final assembled set pulls out of the gig, dropping it though a channel. For angle adjustment, a low backlash gearbox from Bonfiglioli VF series with a SEW motor with integrated encoder, self-adjust the extracting system from reference to reference, in order to allow smooth extraction and preventing damages for both the part as for the gig Fig. 5b (F).

### 2.2.4 Sensors Required and Selection

For all the pneumatic cylinders, magnetic sensors from Festo SM8 are integrated, to ensure reliability and reduce complexity. To control the force applied by the pneumatic cylinders, as the system need to be accurate, all pneumatic valves are proportional ones, controlled by the main PLC, which can set the working pressure individually, and change it from reference to reference. The main goal is to have high sensibility on the system, tuning it to prevent defective parts.

Linear position is also measured on station Fig. 5b (C) where the gig is identified by a Balluf BTL6 precision linear position sensing, that read the thickness of the gig, with a maximum accuracy of $\geq 5$ µm and send the measured value to the main PLC, identifying that the gig match the current working reference. The same system is used to measure the linear movement from the cylinder that slides the grooved rubber bushing inside the hole on the main part, so we can stop the system when the process is finish to prevent damage on the bushing, but also for identify possible defects on one of the components by cross-checking current pressure with linear position.

On the operator safe, a safety light barrier from Schneider Electric model XUSLDMQ6A0920T was installed, informing the main PLC that the operator are in the working position, and preventing the rotation of the index table while he is fitting the main part into the gig. Also all the maintenance doors have safety magnetic sensors, also from TURK, that inform the main PLC if there are any door open.

The quality inspection and control will be fail-safe through an external Artificial Vision System Fig. 5b (E), that acquires on photo each final component, through a color DALSA Spyder 3 camera with 1,024 $\times$ 1,024 resolution and pixel size of 14 µm, provided with a special lens, sending it to the main computing station that runs a preprogrammed script to compare the image with the expected standard image, and return a Boolean value, ok/not ok, to the main PLC. The parts tagged as not ok are sent automatically to a different box.

### 2.2.5 Global Control Solution

To control all the hardware an industrial PC from Siemens SIMATIC series with a soft-plc will take the logic and safety of all system. There is a safety relay, where all safety devices plug, that closes the electrical circuit in case of safety failure, or

**Table 1** Pre-requirements for operating mode

| Mode | Pre-requirements | Operation |
|---|---|---|
| Setup | Emergency buttons closed | Manually |
| Manual | Doors closed, emergency buttons closed, operator outside working light barrier | Manually step by step |
| Automatic | Doors closed, emergency buttons closed, operator outside working light barrier, gig locked, part in gig | Fully automatic |

emergency button push. The following modes are available through the control panel, stopped, setup, manual, or automatic (see Table 1). When in setup mode, all automatic motions are disabled and it is possible to move all the actuators from the machine manually thought control panel, or in case of the locking releasing cylinder and table rotation through two pushbuttons near setup door, allowing to change all gigs without leaving the setup position. In this mode, it is also possible to setup the rubber bushing and screw plus washer set, adjusting the rails safely. Manual mode is a diagnosis/tuning mode, where each assembly task is made step by step. In fully automatic mode all working steps are automatic, so while machine is fed with main parts, rubber bushing and washer plus screw sets, will work continuously. For quality control, artificial vision check for key assembly points, measures, colors, and shapes, ensuring the right match of main part, rubber bushing, and screw plus washer sets. All this quality parameters are recorded in a Microsoft SQL database, and they can be accessed by any external software either for statistical, alarming or certification data.

## 2.3 Final Solution

Parts supplied by the client are delivered in boxes, Fig. 5b (M) from where they are picked up and inserted into a unique gig by an operator, as soon as the operator remove his hands from the main part and outside the working zone, the PLC automatically gives the order to rotate the table one step delivering a new empty gig to the operator place. All others working places are performing simultaneous tasks, on stage C, a rubber bushing is being assembled, on D screw plus washer are being fitted, on E the camera is acquiring and processing image and station L is removing a complete set from the gig.

With this solution, we can add real value to the process, not only in productivity and quality, but also in human health and safety. All operator based tasks or setups are easy, error proof, safe, and ergonomics. Assembly time was reduced to 7 s for each part and data can be collected, stored, and documented for each part, ensuring responsibility in the overall process. The main drawbacks of this system are the wide range of gigs needed to be fabricated, stored, and controlled, and the high costs of advanced artificial vision and intelligence systems.

## 3 Conclusions

This work allows to draw a new equipment able to ensure all the purposes required by the manufacturer, in order to increase the productivity, ensuring both repeatability and better ergonomic conditions for workers, making the final product more reliable and competitive. Thus, the follow conclusions should be drawn:

- Using many automation devices, the assembling operations that we are talking about in this work were deeply improved, ensuring an intermediate phase between the full manual and full automated assembling process;
- The setup operations are controlled by PLC, ensuring reduced periods of time spent in these operations;
- All the worker safety and ergonomic aspects were conveniently safeguarded;
- The desired flexibility was ensured by introducing a gig system, able to accommodate all the complex main parts;
- The worker activity was restricted to put the main part into the gig, which conditioning the cycle time of the assembly process. Despite of this, the cycle time was reduced from 11 to 7 s, as expected;
- In the future, when social issues are overcome, the worker should be replaced easily by a robot, maintaining the equipment as drawn.

This work allows to solve an industrial problem and shows how the modularity of the automation can be useful, when conveniently used, in order to overcome many industrial problems, reducing the costs and increasing the reliability of the final products, allowing yet the desired flexibility, attending the large range of references that this system is able to assembly.

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## References

1. Chakravarty AK, Balakrishnan N (2001) Achieving product variety through optimal choice of module variations. IIE Trans 33(7):587–598
2. Klapper D (2005) An econometric analysis of product variety impact on competitive market conduct in consumer goods markets. OR Spectrum 27(4):583–601
3. Benjaafar S, Kim J, Vishwanadham N (2004) On the effect of product variety in production-inventory systems. Ann Oper Res 126(1–4):71–101
4. Kahn B (1998) Dynamic relationship with customers: high-variety strategies. J Acad Mark Sci 26(1):45–53
5. Holweg M, Greenwood A (2001) Product variety, life cycles and rates of innovation: trends in the UK automotive industry. World Automotive Manufacturing, pp 12–16

6. Carvalho E (2005) Globalização e estratégias competitivas na indústria automobilística: uma abordagem a partir das principais montadoras instaladas no Brasil. Gestão Produção 12(1):121–133
7. Lancaster K (1990) The economics of product variety: a survey. Marketing Sci 9(3):189–206
8. Nagorny K, Colombo AW, Schmidtmann U (2012) A service- and multi-agent- oriented manufacturing automation architecture: an IEC 62264 level 2 compliant implementation. Comput Ind 63:813–823
9. Carpanzano E, Jovane F (2007) Advanced automation solutions for future adaptive factories. Ann CIRP 56(1):435–438
10. Michalos G, Makris S, Papakostas N, Mourtzis D, Chryssolouris G (2010) Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP J Manuf Sci Technol 2:81–91
11. Fisher M, Ittner C (1999) The impact of product variety on automobile assembly operations: empirical evidence and simulation analysis. Manage Sci 45(6):771–786
12. Salvador F, Forza C, Rungtusanatham M (2002) Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions. J Oper Manage 20(5):549–575
13. Thonemann UW, Bradley JR (2002) The effect of product variety on supply-chain performance. Eur J Oper Res 143(3):548–569
14. Ribeiro L, Barata J (2011) Re-thinking diagnosis for future automation systems: an analysis of current diagnostic practices and their applicability in emerging IT based production paradigms. Comput Ind 62:639–659
15. Hunter SL (2001/2002) Ergonomic evaluation of manufacturing system designs. J Manuf Syst 20(6):429–444
16. Shikdar AA, Hadhrami MA (2005) Operator performance and satisfaction in an ergonomically designed assembly workstation. J Eng Res 2(1):69–76
17. Shikdar A, Al-Hadhrami M (2007) Smart workstation design: an ergonomics and methods engineering approach. Int J Ind Syst Eng 2(4):363–374
18. Shinde GV, Jadhav VS (2012) Ergonomic analysis of an assembly workstation to identify time consuming and fatigue causing factors using application of motion study. Int J Eng Technol 4(4):220–227
19. Battini D, Faccio M (2011) New methodological framework to improve productivity and ergonomics in assembly system design. Int J Ind Ergon 41:30–32
20. Thun J-H, Lehr CB, Bierwirth M (2011) Feel free to feel comfortable—an empirical analysis of ergonomics in the German automotive industry. Int J Prod Econ 133:551–561
21. Saptari A, Lai WS (2011) Jig design, assembly line design and work station design and their effect to productivity. Jordan J Mech Ind Eng 5(1):9–16
22. Deros BM, Khamis NK (2011) An ergonomics study on assembly line workstation design. Am J Appl Sci 8(11):1195–1201
23. Isidori A (2009) Automation is for humans and for our environment. In: Nof SY (ed) Handbook of automation. Springer, Berlin, pp 7–9
24. Williams TJ (2009) Advances in industrial automation: historical perspectives. In: Nof SY (ed) Handbook of automation. Springer, Berlin, pp 5–11
25. Jenkins H (2005) Manufacturing automation. In: Kurfess TR (ed) Robotics and automation handbook. CRC Press, Boca Raton
26. Wiendahl H-P, Rybarczy A (2003) Using air streams for part feeding systems. J Mater Process Technol 138:189–195

# P-SOP Agent Generator for Flexible Manufacturing

**Bo Svensson, Anders Nilsson and Fredrik Danielsson**

**Abstract** In a flexible manufacturing industry the production planner may need to make an updated description of the control strategy every day. The description contains all possible routing paths and is based on actual circumstances. It varies depending on, e.g., rebalancing due to market changes, scheduling of available operators, introduction of new parts, and rerouting due to a machine break down or planned service. A Part oriented Sequence of Operation (P-SOP) description language has been formulated to assist the production planner to be able to handle these flexible manufacturing scenarios. Multi-agents to control the manufacturing are automatically generated from the P-SOP description language. The P-SOP agent generator creates IEC 61131-3 PLC code that can be executed on standard PLC's. An agent consists of a head, a communicator, and a body. The head and the communicator are the automatically generated part with a predefined interface against the physical body, e.g., the mechanical/electrical structure of a robot. This feature eliminates the need for an external expert in PLC programming. The head contains many small sub-sequences for all operations that are defined for the specific body. The purpose of the communicator is to communicate with surrounding neighbor agents to form a multi-agent system. The formulated language and the P-SOP agent generator has been successfully tested and evaluated in an industrial environment.

## 1 Introduction

In the design phase of a part, as well as in the manufacturing phase, there are a number of well-established computer aided tools widely used in industry. However, the process planning phase in-between has not reached the same level of

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computer aid and still requires much work of qualified personnel, due to enormous complexities associated with task of the process planning, Xu et al. [1]. The production planner determines the sequence of individual manufacturing operations needed to produce a given part. The results of the planning are a sequence of operation (SOP) containing a step-by-step work instructions of the production operations and associated machine tools for assembly or process. The process planning is based on the production planner's experience and knowledge of production facilities, equipment, their capabilities, processes, and tooling. Manual process planning is very time-consuming and results are based on the skills of the individual person performing the planning, Stryczek [2]. Also, the planned SOP is dedicated to a specific production scenario and fixed sequence. In automated manufacturing with low volume or short product lifetime the effectiveness of the process planning is essential. The time to market and production equipment utilization rate are crucial for survival. The manufacturers need to respond quickly to a dynamic and changing market. The manufacturers need to be productive in all predicted and unpredicted situations. If, for instance, one machine in the process chain breaks down, it is necessary to immediate re-plan the production. The production need to continue until the broken machine is replaced or up and running again.

An arrangement of production equipment grouped to effectively process a set of parts is by Jang et al. [3] defined as a manufacturing cell. An industrial manufacturing cell is, according to Larin [4], defined from the single machine level to the area level which consists of hundreds of machines. Figure 1 illustrates an example of an automated manufacturing cell containing a conveyor, four robots, five machines, and a number of storage places. In an automated manufacturing cell, the operations such as material handling, machining, and assembly are performed by automated equipment such as robots and NC machines under control of a cell controller, typically a Programmable Logic Controller (PLC). PLC's are common in industry because of characteristics such as reliability, modularity, multiple I/O channels, fast response time, and cost efficiency. They are used to coordinate and synchronize cell equipment (SOP control) as well as motion control, process control, data management, and intra- and inter-cell communication, Johnson [5]. PLC's are well known to be robust and easy to program and re-program following the IEC 61131-3 standard [6] for PLC code. However, the code validation is typically done by direct testing of the PLC through piecewise implementation. Because of the complexity of the PLC code and the manufacturing cells themselves, the implementation and validation are time consuming and expensive. Furthermore, PLC programming is often performed by external experts, which may be hard to access and cause further time delay to production start.

The aim of the research presented in this paper is to describe a multi-agent based control method to handle production with high flexibility. Another aim is to automatically generate these from a high-level description. To be useful in automation an agent generator must be able to generate robust deadlock free code directly from the description. Since PLC is common in manufacturing it is desirable to generate agents in IEC 61131-3 structure text code. The overall aim is

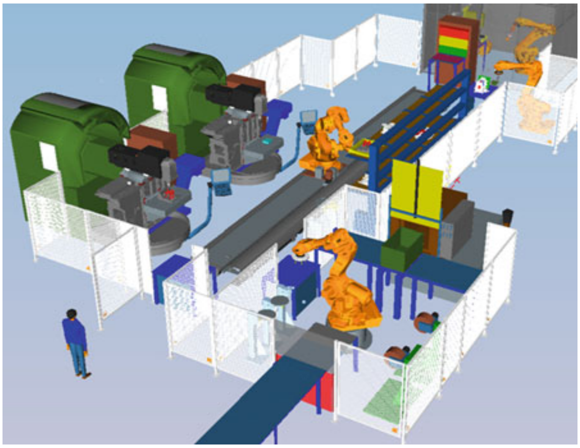

**Fig. 1** Example of an automated manufacturing cell containing conveyor, robots, machines, and storage places

then to create possibilities for a production planner to change, rebalance, and introduce new parts into a manufacturing cell avoiding code optimized for a specific scenario, i.e., a non-adaptable solution with a "single point of failure."

A Part oriented Sequence of Operation (P-SOP) description language has been formulated to assist in the production planner's daily work and eliminate the need for an external expert in PLC programming. P-SOP is designed to handle and program PLC's at manufacturing cell level up to plant level in a multi-agent based way. Consider the following scenario: On daily basis the production planner makes a general description for the part routing in the manufacturing plant in a graphical planning tool. The general description contains all possible routing paths in the plant. The description is based on actual circumstances, e.g., introduction of new parts, rebalancing of manufacturing cells due to market changes, scheduling of operators, and rerouting of the production if one machine breaks down or needs service. Given this description, multi-agents are generated to control the manufacturing plant. An agent is a compilation of the P-SOP description and is a self-maintained piece of software. Multi-agent is the set of all agents controlling the manufacturing plant. This paper presents the P-SOP description language, Sect. 3, and the agent generator that generates the IEC 61131-3 PLC code, Sect. 4. Additionally, related works are summarized in Sect. 2 and test case study results are presented in Sect. 5.

## 2 Related Works

Castillo and Smith [7] present a survey and a comparison of several important formal modeling methodologies that have been used for manufacturing cell control. Formal modeling methodologies provide a framework that supports formal verification and validation techniques. They are directed toward integrating the requirements specification, the design, and the implementation of the cell controller into a consistent process, supported by efficient analysis and development tools. A formal model is defined, by Castillo and Smith [7], as an unambiguous, complete, verifiable, and consistent specification of a manufacturing cell in an implementation-independent language with precisely defined syntax and semantics. The search for a single methodology powerful enough to span all the stages of the development life cycle of a formal model capable of replacing existing non-formal practices, however, has been proved to be more difficult than expected. In practice the use of formal modeling methodologies for manufacturing cell control remains limited. The design is typically based on flow charts or textual control specifications. Furthermore direct testing of the cell controller through piecewise implementation is far more common than verification and validation using formal modeling methodologies. Formal modeling methodologies in the manufacturing cell control domain should support a thread from requirements specification to implementation to be useful in practice. Silva et al. [8] present a survey of modeling methodology creations for Petri Nets compatible with the IEC 61131-3 standard. They did not find any creation that present a completely compatible methodology with the standard. To handle this, Silva et al. [8] present an extended GHENeSys Petri Net model to develop PLC applications. This extended version, with added functions etc. in the Petri Net, allows the creation of a hierarchical model with high-level modularity, similar to IEC 61131-3 PLC code. However, it is only tested in laboratory practices. Though it claims to not require an industrial specialist, it is not obvious to be useful in industry.

An interesting approach of using an object oriented graphical program language to generate IEC 61131-3 PLC code is presented by Vogel-Heuser et al. [9]. They used the Unified Modeling Language for Process Automation (UML-PA), a development of the standard UML. A prototype has been developed, which generates IEC 61131-3 structured text and SFC code automatically from the UML-PA model created with an UML tool. However, the benefits of object orientation as well as bottlenecks have not yet been demonstrated. They will become apparent during application in a more complex system, e.g., a real manufacturing cell. Thapa et al. [10] present an approach with the objective to reduce the development time of cell controller by automating the task of code generation. They applied t-MPSG (Timed Message-based Part State Graph), an extended version of conventional MPSG, Smith et al. [11], with temporal properties embedded. The method deploys the t-MPSG to generate a generic PLC code. The similarity in the hierarchical structure of the t-MPSG and the IEC standard has made it convenient to transform from one form to another. However, only an experimental example is presented, no implementation in real industry has been done.

A new sequence planning approach, where sequences are viewed based on the relations among operations instead of manually constructing the sequence is proposed by Lennartson et al. [12]. In order to obtain a unified information flow from early product design to final production, an integrated framework for product, process, and automation design has been developed. The framework is based on SOPs and includes a formal relation between product properties and process operations. A formal graphical language for hierarchical operations and SOPs is introduced and defined based on automata extended with variables. Since the operations are self-contained they can be grouped and viewed from different point of views, e.g., from a product or a resource perspective. One approach to limit the negative influence of uncertainty and unpredictable behavior on manufacturing performance is to use real-time manufacturing information and intelligence in order to perform at a higher level with a minimum of unscheduled downtime. Wang et al. [13] research objective is to develop methodologies for distributed, adaptive, and dynamic process planning as well as machine monitoring and control, using event-driven Function Blocks (FBs). They utilize the concept of FBs as defined in IEC 61499 [14]. The concept of FBs enables the use of real-time information for dynamic distributed decision making, and possesses dynamic control capabilities that are able to handle different kinds of uncertainty.

A Holonic Manufacturing System (HMS) enables the possibilities to reach a flexible and robust manufacturing cell, Gou et al. [15]. A HMS is a system where elements, such as machines, parts, operators, carriers, etc., are modeled as holons. A holon is characterized by autonomy and cooperation, and consists of a physical component and an informational component. A multi-agent based solution can handle disturbances and failures in the manufacturing cell, Valckenaers and Brussel [16], and thus avoid "single point of failure," i.e., one single failure stop the entire cell from working.

## 3 P-SOP Description Language

The goal with this research is to create possibilities for a production planner to change, rebalance, and introduce new parts into a manufacturing cell like the one in Fig. 1, or indeed a manufacturing plant. With this approach the planner carries out process planning tasks to achieve a more flexible manufacturing. To be flexible it is also desirable to avoid the potential risk "single point of failure," e.g., handle break-downs and other failure scenarios in the PLC code and to adapt to the new upcoming situation. A "single point of failure" is that one single failure stops the entire manufacturing plant or cell from working. This flexibility is possible to reach with a multi-agent based approach, Gou et al. [15]. Tools like Sequence Planner, [12], and Supremica, [17], can be used to provide a formal method to generate the SOP, to guarantee an optimal and deadlock free solution. The goal is to simplify the description work even more and to avoid code optimized for a specific scenario, i.e., a non-adaptable solution with a "single point of failure." The P-SOP agent generator will generate a robust deadlock free code for agents in IEC 61131-3 structure text code directly from the description. The P-SOP description language is prepared for a graphical interface in purpose to simplify the definition work even more, however this is not covered in this paper.

A P-SOP description is mainly focused on the part routing tasks i.e., the material handling to transfer the parts between the different resources. A complete

P-SOP description contains two main sections, declarations and sequences, where the declarations must precede the sequences. The declaration section of the P-SOP description contains declarations of the set of all resources, $R = \{SOURCE, SINK, CARRIER, PROCESS, BUFFER\}$, the set of all parts, $P = \{PART\}$, and all variables that belongs to the actual manufacturing.

- *SOURCE*: a set of all point-of-entry of parts.
- *SINK*: a set of all points for outgoing parts.
- *CARRIER*: a set of all resources able to transport parts from one place to another, e.g., robots, operators, conveyors, cranes, and AGV's.
- *PROCESS*: a set of all activities that refines the part or carrying out work on a part, e.g., CNC, operators, and milling machines.
- *BUFFER*: a set of all part storage locations, e.g., tool magazine, and intermediate storage.
- *PART*: a set of all parts, e.g., parts that will be produced, tools, fixtures.

For all resources $r \in R$ it is optional to declare the maximum number of locations the actual resource possesses, default value is one. All parts $p \in P$ must be declared with an identity, $p.id$. Although each part $p \in P$ is an element in a set, we take the freedom to define properties for such elements with a dot operator. The unique identity number is used as a signal to the API function blocks described later. The declarations section needs only to be changed when the cell is rebuilt, e.g., after installing of a new resource or when a new part is introduced in the manufacturing.

The sequence section of the P-SOP description contain all sequences, $S = \{s_1, s_2, \ldots, s_n\}$, and forms the complete control strategy for the manufacturing system. Each specific sequence, $s_i \in S$, describes all $m$ tasks to be carried out on a defined subset of parts, $sp_i \in P$. Each single task in sequence $s_i$ is denoted $s_{i,j}$, where $j = 1$ *to* $m$, and is defined by

$$s_{i,j} := \langle LABEL_{i,j}, sc_{i,j}, sf_{i,j}, st_{i,j} \rangle.$$

where, $LABEL_{i,j}$ is a user-defined label for identification (it has nothing to do with the sequence order), $sc_{i,j} \in CARRIER$ is a subset of carriers, $sf_{i,j} \in R$ is a subset of resource "locations from," and $st_{i,j} \in R$ is a subset of resource "locations to." Each task, $s_{i,j}$, contains a subset of operations $op_{i,j} \in OP$, where $OP$ is the set of all possible operations.

An example to illustrate the P-SOP description language is shown in Fig. 2 illustrating the sequence for two parts, ProductA and ProductB. The sequence of ProductA is divided in two tasks a and b. Task a: from Input to MachineA, carried by RobotA, and then processed by MachineA. Task b: from MachineA to Output, carried with RobotA ***or*** RobotB. The sequence of ProductB is divided in three tasks c, d, and e. Task c: from Input to MachineA, carried by RobotA and then processed by MachineA ***or*** from Input to location 1 ***or*** 2 at MachineB, carried by RobotA and then processed by MachineB. Task d: from MachineA to Output,

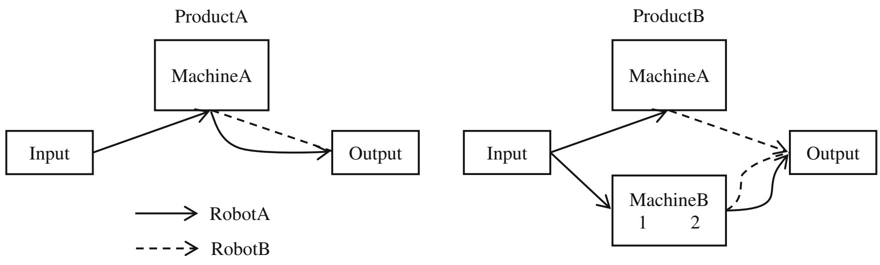


**Fig. 2** Sequence example for two parts, ProductA and ProductB, in one manufacturing cell

carried with RobotB. Task e: from location 1 ***or*** 2 at MachineB to Output, carried with RobotA ***or*** RobotB.

The P-SOP description of the sequences in Fig. 2 is shown in Fig. 3. In the declaration section, on the left side, all resources and parts are declared. Every part $p \in P$ must be declared with an identity, $p.id$, e.g., ProductA [1] and ProductB [2]. All resources are default declared with one location, however, in this example, MachineB has two load/unload locations and are therefore declared as MachineB [2]. The P-SOP description sequence section of the example is on the right side in Fig. 3. When it is necessary to pick or place from a specific resource location it has to be defined in the sequence, e.g., MachineB(1) and MachineB(2). However, if all locations of a resource can be used, the * operator can be used, e.g., MachineB(*). The * operator is a general operator and can be used whenever the entire set is selected. Other general operators to select from a set exist.

## 4 P-SOP Agent Generator

The P-SOP agent generator automatically generates a robust deadlock free code for agents in IEC 61131-3 structure text code out from the P-SOP description. An agent contains a compilation of the P-SOP description and is a self-maintained piece of software for each specific resource $r$. The generated code will work against predefined structures as an API to function block that works as device

```
/* P-SOP declaration */
/* Resources */
SOURCE  {Input};
SINK    {Output};
CARRIER {RobotA, RobotB};
PROCESS {MachineA, MachineB[2]};
/* Parts */
PART    {ProductA[1], ProductB[2]};
```

```
/* P-SOP sequences */
SEQUENCE(ProductA)
{a: RobotA           Input -> MachineA;
 b: RobotA / RobotB  MachineA -> Output;
};
SEQUENCE(ProductB)
{c: RobotA  Input -> MachineA /MachineB(*);
 d: RobotB          MachineA    -> Output;
 e: RobotA / RobotB  MachineB(*) -> Output;
};
```

**Fig. 3** P-SOP description of sequences example in Fig. 2, declaration section on *left* side and sequence on *right*

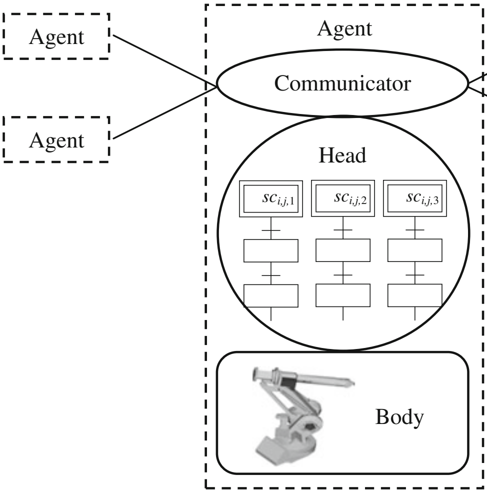


**Fig. 4** Agent description and its communication with neighbor agents forming a multi-agent system. The agent head consist of all sub-sequences for all tasks $s_{i,j}$ that are defined for the specific agent body

drivers that are customized to the hardware (body). An agent consists of a body, head, and communicator, see Fig. 4. The head and the communicator are automatically generated from the P-SOP description language with a predefined interface against the body, e.g., the mechanically structure of a robot. The purpose of the communicator is to communicate with surrounding neighbor agents allowing collaboration status updated and sharing of process information to form a multi-agent system. The head contains many small sub-sequences for all tasks $s_{i,j}$ that are defined for the specific resource $r$. The intention is to make the agents, and by that the whole manufacturing cell more robust and flexible. Hence, there exists no common global sequence. Such a global sequence is hard to restart after a failure and has many potential "single point of failures." Due to the robustness of the P-SOP generated agents it is possible for the manufacturing system to handle complex situation with multiple parts and resources. The robust sub-sequence in the agents contains a precondition $c^{\uparrow}_{i,j}$, a pretask function $f^{\uparrow}_{i,j}$, a task function $f_{i,j}$, a postcondition $c^{\downarrow}_{i,j}$, and a posttask function $f^{\downarrow}_{i,j}$.

## 4.1 Precondition

A task $s_{i,j}$ can only be executed if the precondition $c^{\uparrow}_{i,j} \in C^{\uparrow}$ is fulfilled. $C^{\uparrow}$ is a finite set of all physical and logical preconditions. A single precondition $c^{\uparrow}_{i,j}$ is a logical expression of: part available at "location from," $af_{i,j}$, available carrier, $ac_{i,j}$, available "location to," $at_{i,j}$, and that no available deadlock, $ad_{i,j}$, exist. This can be expressed as,

$$c^{\uparrow}_{i,j} = \left(af_{i,j} \neq \emptyset\right) \wedge \left(ac_{i,j} \neq \emptyset\right) \wedge \left(at_{i,j} \neq \emptyset\right) \wedge \left(ad_{i,j} = \emptyset\right).$$

where,

$$\begin{aligned} af_{i,j} &= \left\{r \in sf_{i,j} | \left(r.l.bk = FALSE\right) \wedge \left(\{p \in sp_i | p.id = r.l.id\} \neq \emptyset\right)\right\}, \\ ac_{i,j} &= \left\{r \in sc_{i,j} | \left(r.l.bk = FALSE\right)\right\}, \\ at_{i,j} &= \left\{r \in st_{i,j} | \left(r.l.bk = FALSE\right) \wedge \left(r.l.id = \emptyset\right)\right\}, \\ ad_{i,j} &= \left\{d \in sd_{i,j} | \left(d(R,P,S) = TRUE\right)\right\}. \end{aligned}$$

Two properties, booked and id, are defined for all resources $r \in R$. The property booked, $r.l.bk$, is a Boolean property, where $r.l.bk = FALSE$ corresponds to location $l$ of resource $r$ available, and $r.l.bk = TRUE$ corresponds to location $l$ of resource $r$ booked. The property id, $r.l.id$, is the identity of current part $p$ handled by the resource $r$ at location $l$.

A method for deadlock avoidance has been implemented in P-SOP. Deadlock avoidance functions, $d \in D$, are automatically generated from the specification. A specific function $d$ is evaluated according to $d(R,P,S) \in \{TRUE, FALSE\}$. If $d$ yields true, $d(R,P,S) = TRUE$, it indicates that a deadlock situation will occur. All deadlock avoidance functions, $D$, are used to guarantee that deadlock situations never occur. For each single task, $s_{i,j}$, there exist a subset of deadlock avoidance functions $sd_{i,j} \in D$.

## 4.2 Pretask Function

When the precondition $c^{\uparrow}_{i,j}$ is fulfilled a pretask function, $f^{\uparrow}_{i,j}\left(af_{i,j}, ac_{i,j}, at_{i,j}, u, v, w\right)$, will be fired and it executes the following bookings to secure a robust behavior:

$$\begin{aligned} af_{i,j,u}.l.bk &:= TRUE, \\ ac_{i,j,v}.l.bk &:= TRUE, \\ at_{i,j,w}.l.bk &:= TRUE. \end{aligned}$$

where, $af_{i,j,u}$ is the single element $u$ of $af_{i,j}$, $ac_{i,j,v}$ is the single element $v$ of $ac_{i,j}$, and $at_{i,j,w}$ is the single element $w$ of $at_{i,j}$. The P-SOP description language has an implemented priority function to decide the values on $u$, $v$, and $w$. The function to select $u$, $v$, and $w$ can be designed to prioritize different scenarios, e.g., rush orders and balancing. However, the priority function is not in focus in this paper.

### 4.3 Task Function

When the pretask function is done, a task function, $f_{i,j}(sp_i.id)$, is executed. The task function carries out the resource physical operations, e.g., robot motion, machining, welding. A task function consists of two operations (one per agent), one carrier operation, $f_{sc,i,j}(sp_i.id)$, and one resource operation, $f_{st,i,j}(sp_i.id)$.

### 4.4 Postcondition

The task function is ready when the postcondition $c^{\downarrow}_{i,j} \in C^{\downarrow}$ is fulfilled. $C^{\downarrow}$ is the finite set of all physical postconditions, e.g., part placed at the "location to," welding operation done, inspection finished.

### 4.5 Posttask Function

A posttask function, $f^{\downarrow}_{i,j}\left(af_{i,j}, ac_{i,j}, at_{i,j}, u, v, w\right)$, is fired after postcondition $c^{\downarrow}_{i,j}$ is fulfilled, it executes the following release of agents concerned:

$$
\begin{aligned}
af_{i,j,u}.l.bk &:= FALSE,\\
ac_{i,j,v}.l.bk &:= FALSE,\\
at_{i,j,w}.l.bk &:= FALSE.
\end{aligned}
$$

Explanatory sketch of two generated sub-sequences, described in two charts, from one task $s_{i,j}$ can be found in Fig. 5. Observe that in Fig. 5 the task $s_{i,j}$ is now dived in two separated sub-sequences since they belong to two different agents. At the left side a sub-sequence for a single carrier, $sc_{i,j,k1} \in sc_{i,j}$, and on the right side a sub-sequence for a single resource location, $st_{i,j,k2} \in st_{i,j}$, each with adherent precondition, pretask function, task function, postcondition, and posttask function. Note that the carrier return to its idle state when done, i.e., ready to perform another carry operation meanwhile the resource refine the part. The P-SOP agent generator generates similar sub-sequences out from all tasks in all sequences, $S$, of the manufacturing system. Each agent head consist of all sub-sequences for all tasks that are defined for the specific agent body, see Fig. 4.

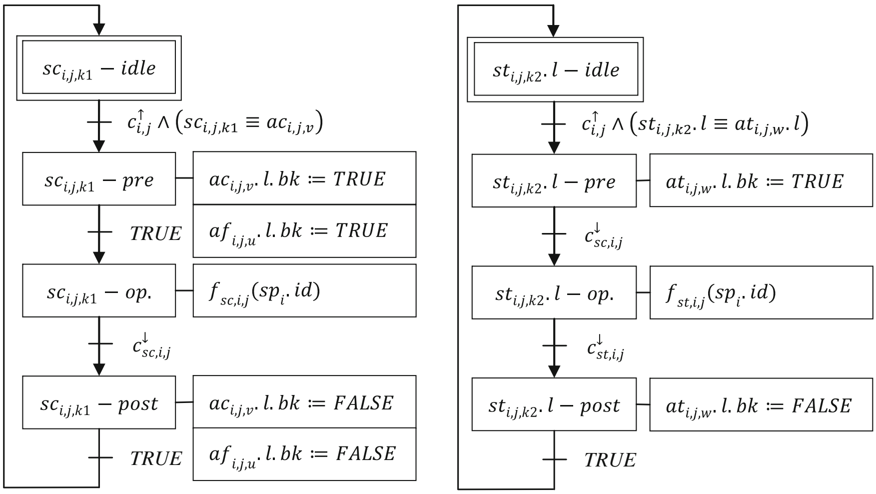


**Fig. 5** Explanatory sketch of two generated sub-sequences described in SFC-like chart. The sub-sequences corresponds to the P-SOP description of the single task $s_{i,j} := \langle LABEL_{i,j}, sc_{i,j}, sf_{i,j}, st_{i,j} \rangle$. The *left* chart describes one sub-sequence for the head of the carrier $sc_{i,j,k1}$. The *right chart* describes one sub-sequence for the head of resource $st_{i,j,k2}$

## 5 Conclusion

A Part oriented Sequence of Operation (P-SOP) description language has been formulated to assist in the production planner's daily work and eliminate the need for an external expert in PLC programming. This is essential to be able to handle high flexibility in automated manufacturing. P-SOP is designed to handle and program PLC's at manufacturing cell level up to plant level in a multi-agent based way. The high-level general description contains all possible routing paths in the plant. Given this description, multi-agents are automatically generated to control the manufacturing plant.

The proposed P-SOP agent generator has been implemented and evaluated in two test case studies, one with a virtual manufacturing cell and one with a real manufacturing cell. The virtual manufacturing cell, shown in Fig. 1, included a conveyor, four robots, five machines, and a number of storage places. The virtual cell was built in the simulation tool Process Simulate and an OPC-interface was used for communication with the PLC. The real industrial manufacturing cell in the second test case is placed at Production Technology Centre in Trollhättan, Sweden. The manufacturing cell includes a conveyor, four robots, two machines, and a number of storage places. The test cases confirmed the applicability of the P-SOP description language and the agent generator. It assist the production planner to be able to handle flexible manufacturing scenarios such as rebalancing due to production changes, introduction of new parts, and rerouting due to a machine break down or planned service. The automatic generation of the robust deadlock free IEC 61131-3 PLC code eliminates the need of a PLC programming expert and reduce the required time dramatically. Re-scheduling and changing of manufacturing part mix in the test cases have been done in a few minutes during on-going production.

Further work will include a more formal test to verify the robustness of multi-agent controlled flexible manufacturing. These tests must verify error handling, restart, rerouting, and introduction of new parts. It is also important to verify that the multi-agent system is deadlock free even if a single agent can be considered as deadlock free within this work.

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## References

1. Xu N, Huang SH, Rong YK (2007) Automatic setup planning: current state-of-the-art and future perspective. Int J Manuf Technol Manage 11(2):193–208
2. Stryczek R (2011) A hybrid approach for manufacturability analysis. Adv Manuf Sci Technol 35(3):55–70
3. Jang J, Koo PH, Nof SY (1997) Application of design and control tools in a multirobot cell. Comput Ind Eng 32(1):89–100
4. Larin DJ (1989) Cell control: what we have, what we need. Manuf Eng 41–48
5. Johnson DG (1987) Programmable controllers for factory automation. Marcel Dekker Inc., New York
6. International Standard (2003) IEC 61131 programmable controller—Part 3: programming languages, 2nd edn
7. Castillo I, Smith JS (2002) Formal modeling methodologies for control of manufacturing cells: survey and comparison. J Manuf Syst 21(1):40–57
8. Silva JR, Benitez I, Villafruela L, Gomis O, Sudria A (2008) Modeling extended petri nets compatible with GHENeSys IEC61131 for industrial automation. Int J Adv Manuf Technol 36(11–12):1180–1190
9. Vogel-Heuser B, Wisch D, Katzke U (2005) Automatic code generation from a UML model to IEC 61131-3 and system configuration tools. In: International conference on control and automation, Budapest, Hungary, pp 1034–1039
10. Thapa D, Park CM, Park SC, Wang GN (2009) Auto-generation of IEC standard PLC code using t-MPSG. Int J Control Autom Syst 7(2):165–174
11. Smith JS, Joshi SB, Qiu RG (2003) Message-based part state graphs (MPSG): a formal model for shop-floor control implementation. Int J Prod Res 41(8):1739–1764
12. Lennartson B et al (2010) Sequence planning for integrated product, process and automation design. IEEE Trans Autom Sci Eng 7(4):791–802
13. Wang L, Adamsson G, Holm M, Moore P (2012) A review of function blocks for process planning and control of manufacturing equipment. J Manuf Syst 31:269–279
14. International Electrotechnical Commission (2005) IEC 61499 Function blocks—Part 1: Architecture, January 2005. [Online]. http://webstore.iec.ch/preview/info_iec61499-1%7Bed1.0%7Den.pdf
15. Gou L, Luh PB, Kyoya Y (1998) Holonic manufacturing scheduling: architecture, cooperation mechanism, and implementation. Comput Ind 37(3):213–231

16. Valckenaers P, Van Brussel H (2005) Holonic manufacturing execution systems. CIRP Ann Manuf Technol 54(1):427–432
17. Åkesson K, Fabian M, Flordal H, Vahidi A (2003) Supremica—a tool for verification and synthesis of discrete event supervisors. In: Proceedings of the 11th mediterranean conference on control and automation, Rhodos, Greece

# Flexible Work Organization and Working Time Flexibility as Flexibility Strategies for Small and Medium-Sized Enterprises

**Ralica Ivanova, Heiko Baum, Jens Schütze and Martina Ganß**

**Abstract** In many countries, economy without small and medium-sized enterprises (SMEs) can hardly be imagined—they offer more jobs than large-scale enterprises and significantly contribute to the economic success in many countries. The globalization pressure, social, economic, and political changes as well as technological innovations force SMEs to alter their organization and their market strategy. In order to survive current situations, SMEs need agile structures and speedy decisions. The following article deals with flexibility strategies and their application in industrial SMEs focusing on the measures of the internal flexibility. Measures like working time models, short time work, job rotation, job enlargement, profit/cost/investment center as well as team and group work particularly belong to this. This article offers an insight into the practice of the internal flexibility of SMEs, indicates which goals are pursued with those measures, which constraints and drivers during implementation and realization are experienced and how satisfied the enterprises are with the measures. Finally, it goes into detail about the application pairings.

## 1 Introduction

In total, small and medium-sized enterprises provide more jobs than large-scale enterprises [1, 2]. Hence, they are an essential source of the economy of most of the OECD countries [3–5]. Like large-scale enterprises, SMEs are faced with an increasing pressure to change due to the high competitive intensity on the globalized market. Further challenges are the diffusion of new technologies as well as

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the social and demographic development. In order to meet these requirements, SMEs selectively and limitedly draws on strategies for the enterprise flexibility [6, 7], while large-scale enterprises use a wider range of strategies [8, 9].

This is the starting point for the project SME*flex*. SME*flex* aims at the ability of SMEs to draw on a range of flexibility strategies without waiving stability aspects. The studies and scientific articles published during the last two decades generally concentrate on individual strategies. With a cross-sectional study, the project SME*flex* tries to focus again on the totality of flexibility instruments and to identify the correlation between the single instruments [10].

The project is structured into the analysis, model development, piloting, and feedback phase. During the creation of project structures and the foundation of the scientific basis, the concept and the conduct of an empirical research belong to the analysis phase as well. At the same time, the empirical research leads over to the model development phase in which a concept for the stability conducing flexibility management will be created. This concept will be tested practically in the subsequent piloting phase and improved continuously based on iterative process steps during the feedback phase. The results of the interviews thus are an important source of insight.

Based on this brief contentual introduction, the following article addresses the peculiarities of the measures of flexible work organization and labor flexibility—especially of the working time flexibility. For this purpose, object-related questions will be created and added to an empirically founded answering. The following questions determine the structure:

- How often are measures of the flexible work organization and of the working time flexibility used by the SMEs?
- What kinds of goals are pursued by these flexibility measures?
- Which constraints and drivers are perceived by the SMEs during the implementation and realization of those measures?
- How satisfied are the SMEs with the measures for the flexible work organization and working time flexibility?
- Which application pairing can be detected during the implementation and realization of those measures?

## 2 Methods

In order to have better understanding of the specific applications of single flexibility strategies in the environment of small and medium-sized enterprises as well as the correlations between the single strategies, it is important to analyze the complete range of applications of industrial flexibility strategies. For this purpose, extensive literature research based systematization was the result for identifying 124 single instruments. Those identified instruments were distinguished into seven applications [11]. The following groups belong to the strategies applied in the inter-enterprise flexibility [12].

- *Flexible work organization:* This group combines all the variants of the flexible use of labor power, for example: job enlargement, team, or group work as well as job rotation.
- *Labor flexibility:* Due to its complexity, the field labor flexibility will be divided into the three subgroups work time flexibility, flexible incentive, and payment system as well as human resource development, further education, and qualification. Single strategies of these groups are, i.e., shift work, flexible weekly hours of work, profit sharing, and target agreements as well as success control of human resource development measures.
- *Flexible technical work equipment:* This group combines all the technical resources for the support of the value added process. Examples are inter alia warehouse management systems, CAD and CAQ systems, industrial robots, flexible manufacturing cells as well as production planning and control systems.

Strategies including external third parties in the context of flexibility measures are grouped as follows [12].

- *Financing:* Flexibility instruments of the financial market facilitating a flexible financial scope of action to the enterprise are subsumed in this group. Financing by means of subsidies, equity financing, credit financing as well as the mezzanine capital and further financing types are examples for instruments within this group.
- *Flexible market strategies:* This group comprehends measures that integrate parts into the enterprise (insourcing) or that outsource parts (outsourcing). Furthermore, platform strategies are summed up in this group.
- *Intercompany collaboration:* This group includes all types of cooperation between enterprises and/or institutions/organizations. For example, this cooperation type can be realized by a joint research project or a common trade show appearance.
- *Temporary employment:* Professional as well as non-professional temporary employment is summarized here. Labor leasing and employee associations are concrete examples for this group.

An essential share of the knowledge acquisition concerning the application of flexibility strategies in SMEs were derived from an extensive empirical research. Therefore, an empirical survey in the form of a cross-sectional study has been conducted in 131 industrial SMEs in Eastern Germany (federal states Saxony, Saxony-Anhalt, Berlin, and Brandenburg) during the period of September 2010 until January 2011. As Fig. 1 shows, the sample includes all three types of SMEs (defined by the European Commission): micro-, small- as well as medium-sized enterprises [13]. The empirical survey is divided into three parts: *brief telephonic interview*, *self-assessment*, and *face-to-face interview* [14]. By means of a *brief telephonic interview* enterprises have been chosen and classified into groups on the basis of the typified features. Typified features for the grouping have been, i.e., the turnover, the total assets, the number of employees and the flexibility strategies used in the past three years. In preparation for the actual interview the chosen

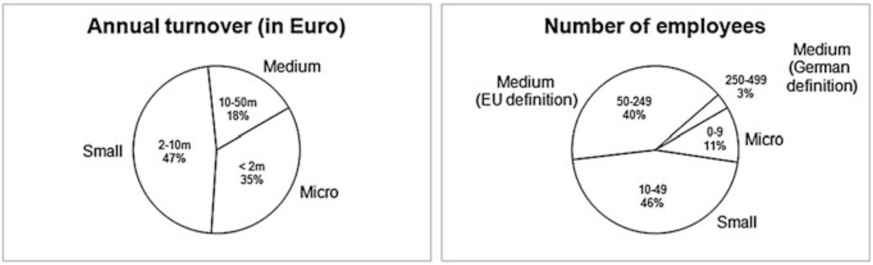


**Fig. 1** Annual turnover and number of employees

enterprise was asked to give information on entrepreneurial details like, e.g., export quota, employment profile, qualification profile and the number of hierarchical levels (*self-assessment*). Due to efficiency and time saving reasons, this data collection took place before the interview. Based on the data of the brief telephonic interview and the self-assessment the actual interview was conducted. The chosen method was the *face-to-face interview* in order to directly and personally gets the information from the manager. The current user behavior of flexibility strategies within SMEs are analyzed here and the constraints and drivers are identified in terms of the decision on the application of such strategies. Additionally, the SMEs had been accompanied during the implementation of strategies in order to uncover potentials of the instruments here. The interviews have been conducted by trained interviewers.

The main goal is to introduce the whole range of potential flexibility strategies to the industrial SMEs. As a result there will be a concept enabling industrial SMEs to choose and use the instruments appropriate for the enterprise [15]. In those works, measures of the internal flexibility like flexible work organization and working time flexibility has an outstanding position.

# 3 Results

## *3.1 Frequency of the Application*

The entrepreneurs were asked in the interview about the flexibility measures they use in their enterprise. It became obvious that measures for the internal flexibility are being applied by the 131 interviewed enterprises. With a result of 92 %, it is most frequently drawn back on instruments of the work flexibility. 86 % of the asked enterprises use forms of the flexible work organization and 77 % flexible technical means of work. In the contrary, the interviewed enterprises less frequently use measures from the fields of the external flexibility like intercompany collaboration (72 %), financing (69 %), flexible market strategies (66 %), and temporary employment (38 %) [16].

A first sign of potential application integration between single flexibility groups is the amount of groups in which enterprises use flexibility measures. The majority of enterprises use measures in more than five groups, summing up to a total of 66 % of enterprises applying flexibility strategies. Only 2 % of the enterprises stated to conduct measures in one group. 6 % of the enterprises use measures in two groups, and 10 % in three groups. In four groups, there are 16 % of the enterprises having flexibility instruments.

## *3.2 Goals of the Application*

The actual reasons for using measures of the groups of flexible work organization and working time flexibility then become obvious when asking about the goals pursued with the implementation and realization of measures of those flexibility strategies in SMEs.

### 3.2.1 Flexible Work Organization

The entrepreneurs named highly economically motivated goals like the increase of labor productivity with 82 %, flexible personnel placement with 77 %, cost optimization with 63 %, and optimized utilization of resources with 60 %. However, goals like reducing the processing times with 63 % as well as an improvement of the adherence to schedules and of quality, higher customer orientation have been indicated often and represent a pursuit of better service. Rather subordinated goals are the encouragement of self-initiative, higher employee motivation, creation of multi-skilled workforces, and innovation support—depending on the nomination, thus summing up to 34 % until 48 % of the enterprises pursuing those goals.

### 3.2.2 Working Time Flexibility

In terms of this flexibility group, aspiring for a better profitability is crucial for the realization of measures in SMEs. An increasing competition, better profitability, and better adjustment of the personnel to the order position received between 52 and 75 % of the statements. Only every third enterprise aims at preventing downsizing, improving the customer service, the reduction of overtime as well as the increase of employer attractiveness.

## *3.3 Constraints and Drivers*

### 3.3.1 Flexible Work Organization

When asked regarding their negative experiences with flexible work organization, 36 % of the enterprises stated to have not perceived any negative factors. Circa every fifth enterprise indicates organizational barriers and internally conflicting goals during the implementation and realization of measures of the flexible work organization. Some enterprises also reported an internal competition, insufficient qualifications of the personnel, inappropriate work tasks or resistance by the employee representative/employees.

In total, the enterprises appear to have made negative experiences only to a relatively small extent. This impression is supported by the look on the positive experiences. Enterprises like flat hierarchies with 71 % and the support of the employees with 68 %. Furthermore, multi-skilled employees are considered to be positive by 40 % of the enterprises.

### 3.3.2 Working Time Flexibility

When asked concerning their negative experiences with working time flexibility, 31 % of the enterprises stated to have not perceived any negative factors. 31 % of the enterprises complained about insufficient time capacities and 29 % about organizational difficulties during the implementation and realization of measures of the working time flexibility. Several enterprises reported as well that internal competition, inappropriate work task or resistance on the side of the employee representative/employees are to be found.

Regarding the positive experiences made by enterprises, 70 % indicated the support of the employees. More than half of the enterprises perceive flat hierarchies (58 %) and highly motivated employees (55 %) as positive. The internal incentives by means of working time flexibility are considered as positive by circa one third of the enterprises. Only 3 % of the enterprises reported to have not made any positive experiences.

## *3.4 Satisfactory During the Application*

### 3.4.1 Flexible Work Organization

The results show that in SMEs the flexible work organization as a flexibility strategy plays an important role. The majority of the interviewed enterprises evaluate their experiences as positive in the dimensions profit for the enterprise (95 %), employee acceptance (88 %), goal achievement (87 %), process of the implementation (77 %), and crises capability (68 %). Only some enterprises, however remaining in the single-digit percent range, perceived negative effects in the named dimensions.

### 3.4.2 Working Time Flexibility

The majority of the interviewed enterprises evaluate their experiences as positive in the dimensions profit for the enterprise (85 %), employee acceptance (83 %), goal achievement (86 %), process of the implementation (72 %), and crises capability (58 %). Only in terms of a few enterprises, ranging in the single-digit percent range and negative effects in the described dimensions had been indicated.

## *3.5 Application Pairings*

Like already mentioned, SMEs in the fields of flexible work organization and working time flexibility use many different measures. In the following, it will be explained by means of selected examples which specific application pairings have emerged in the entrepreneurial practice. For this purpose, based on the dichotomous yes/no answers of the (single) measures, correlation intensities have been calculated. The thickness of the lines of the single measures illustrates the intensity of the correlations. Furthermore, the depicted "filling level" indicates the application frequency of the respective flexibility measures.

### 3.5.1 Flexible Work Organization

A relatively high application frequency as well as a strong application pairing exists between job enlargement and job enrichment (Fig. 2). The correlation coefficient between those two measures is $\Phi = 0.573$, is significant and hence the strongest significant correlation in this group. This strong application correlation contextually originates as follows. Job enlargement means to extend an employee's range of job duties by similar subtasks but remaining on the same job level. The subtasks require the same qualification level. The changing requirements decrease the danger of fatigue or monotony. In order to additionally increase the autonomy of an employee, the application of job enrichment is the logical consequence. Job enrichment includes taking over superordinate tasks and activities like, e.g., planning or controlling subtasks normally fulfilled by direct supervisors. The employee thus receives a higher level of autonomy positively influencing the work motivation. By enriching the task spectrum, performance potentials of employees are used and supported in a better way. In order to even more approach to a flexible enterprise, the use of job rotation, in addition to the application of job enlargement and enrichment, could be realized. Job rotation is a systematic change of the work place within the enterprise

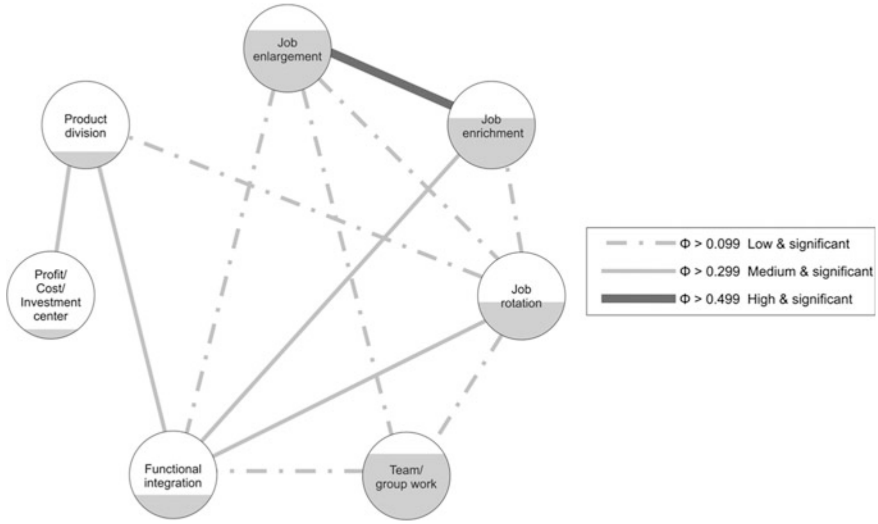


**Fig. 2** Application pairing of the flexible work organization

also enlarging the qualification of the employee. The alteration of the work place can effect in a horizontal or vertical way, meaning tasks with a similar qualification level can be overtaken but also a change toward superordinate tasks is possible. The potential advantages of job rotation regarding varying requirements, changing strains, developing competences, work motivation, and personnel flexibility are eventually opposed by increased expenses for the coordination and the qualification [17]. In terms of vertical position changes, a potentially decreasing motivation has to be taken into account [17]. Those obviously increased expenses however, originate from the relatively low application pairing with job enlargement and job enrichment in the entrepreneurial practice of SMEs. The medium significant correlation between the functional integration on one side and job enrichment ($\Phi = 0.346$) as well as job rotation ($\Phi = 0.423$) on the other side can be interpreted as a certain application bridge. The enterprises try to achieve the economies of scale of a flexible enterprise by combining the functional integration and job enrichment as well as by combining the functional integration and job rotation, which is however, only partly successful in practice. The reason is that especially on-the-job trainings of employees are neglected due to financial and expenses aspects.

A medium significant correlation exists between the pairing of product division and profit/cost/investment center. The coefficient between those two measures is $\Phi = 0.366$. However, it must be considered that the product division and also profit/cost/investment center have a very low application frequency in the entrepreneurial environment of the SMEs. From the organizational perspective, it definitely makes sense to organize, independently from the object range of SMEs, a product division as profit/cost/investment center.

### 3.5.2 Working Time Flexibility

While examining the application pairings of the measures of the working time flexibility, it becomes obvious that strong correlations could not be proven empirically (Fig. 3). The only significant correlation of medium intensity exists between the pairing of flextime and working time accounts ($\Phi = 0.366$). Additionally, both measures are used relatively often in the entrepreneurial environment of the SMEs. In terms of flextime, employees can influence the point and the duration of the daily, weekly or even of the monthly working time. The working time regarding flextime however, consists of a core time with a general compulsory attendance and flextime spans. The earliest start of flextime and latest end of flextime determine the range within which the working time can be variably fulfilled. The agreements on flextime can also include whole days terminating an existing time credit. As the actual working times are irregular in terms of flextime, it makes sense to combine this with a second measure of working time accounts. Here the actually completed work of the employee is registered by writing or electronically and set off against the working time to be done according to the labor contract. The employee then takes care that the working time account is balanced over a period of generally one month or one year.

In addition to the described application pairing of medium intensity, there are several correlations having a rather low intensity but which are significant, like, e.g., between shift work and short time work, shift work and working time accounts, limited contracts and part-time work as well as limited contracts and

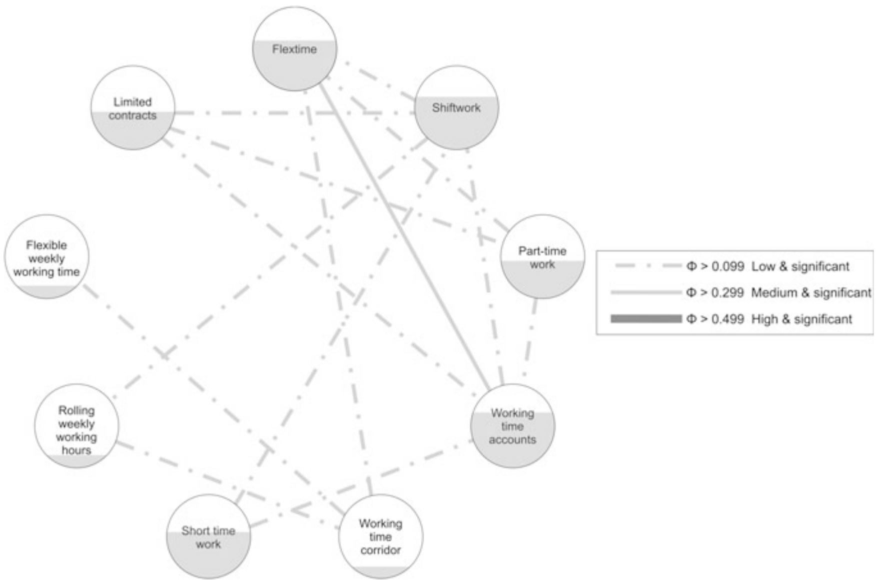


**Fig. 3** Application pairing of the working time flexibility

working time accounts. As the empirical research was conducted in the years 2010/2011, the relatively high application frequency of short time work in SMEs originates from the international financial crisis and its consequences. Also the application frequency of limited contracts and part time work are another indicator of crises-related working time flexibilities in SMEs. The application pairing short time work and working time accounts can be considered a crises-related measure, too. Thus, the overtime documented in the working time accounts is set off against the crises-related absence from work. Hence, the applying enterprise works on slack time before the flexibility measure sets in which is tied to considerably higher labor contractual restrictions for the enterprise.

### 3.5.3 Application Pairings Between Groups

In addition to the application pairings of each flexibility group, cross-group-pairings can be identified as well. Between the groups flexible work organization and working time flexibility two strong and significant correlations are obvious—the profit/cost/investment center correlates with the working time corridor as well as the functional integration with flexible weekly working time. Furthermore, there is a variety of medium strong, significant correlations (Fig. 4).

The application pairing profit/cost/investment center and working time corridor derives from the fact that enterprises running profit/cost/investment centers generally insist on highly autonomously working employees. Hence, for, e.g., profit centers are organizational units with a high degree of responsibility and authority to decide. Those units themselves plan their business within a given scope of action. The core idea is that profit centers think and act like independent enterprises. So it is only logical that this high level of authority within the organization is also represented in the working time conditions. The application of working time corridors, flextime, rolling weekly working time, and flexible weekly working

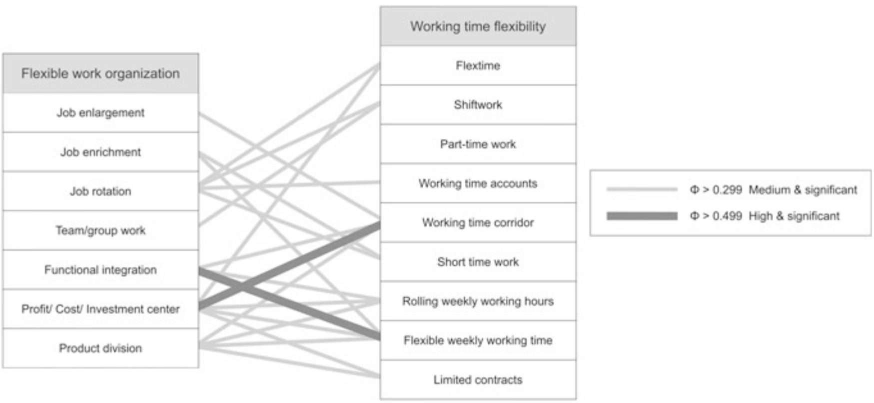


**Fig. 4** Application pairings between flexible work organization and working time flexibility

time are hence appropriate measures to run a flexible organization in the form of a profit/cost/investment center. The pairings related to the product division can be explained similarly. As product divisions are mainly organized via profit/cost/investment center, the same realization arguments like in the already described pairing apply.

Job rotation is a form of the flexible work organization in the field of the operative tasks characterized by a wide qualification profile of the executing employee and this is also appropriate to combine with working time models with a high employee responsibility. Flextime and working time accounts are appropriate time models for this type of work organization. Also this application pairing represents the influence of crises on the internal organization of the SMEs. Hence especially the work forms of the operative tasks, e.g., job rotation and job enrichment are strongly affected by the crises-related short time work.

## 4 Summary

Based on the results of the empirical survey and the latest research works it can be concluded that the application of the flexibility strategies of the flexible work organization and working time flexibility in SMEs are relatively wide spread; in contrast to the measures rather relating to the external flexibility. The goals for realizing measures of the internal flexibility rather dominate economically motivated goals meaning in general those measures are realized in order to achieve competitive advantages and to increase work productivity as well as to decrease the costs. Goals like improving the image of the enterprise by, e.g., family-friendlier working time models are rather of subordinate meaning.

Regarding the constraints and drivers the enterprises believe that the positive experiences outweigh the negative ones. In terms of the implementation of measures of the flexible work organization, organizational barriers and internally conflicting goals most likely have been considered disturbing—hence of every fifth enterprise. Flat hierarchies and the support of the employees with more than 60 % have been counted to the positive experiences. This is likely the same with the working time flexibility—nearly one third of the enterprises have not made negative experiences, only circa one third complains of insufficient time capacities and organizational difficulties. Positive experiences here were the support and the high motivation of the employees as well as the flat hierarchies within the enterprise.

Regarding the satisfactory with the measures, enterprises are relatively comfortable with the realized measures. The enterprises are the most satisfied in the dimensions profit for the enterprise, employee acceptance, and goal achievement. It is noticeable that the enterprises evaluate the measures of the flexible work organization and working time flexibility after their implementation and realization only limitedly suitable for crises.

**Acknowledgments** This work has been supported by the German Federal Ministry of Education and Research (BMBF) and the European Social Fund (ESF) under reference number 01FH09147. It has been developed in the scope of the German research project SME*flex* (www.smeflex.info) and the European WORK-IN-NET Coordination Action (www.workinnet.org).

## References


1. Davis SJ, Haltiwanger JC, Schuh S (1996) Job creation and destruction. MIT Press, Cambridge
2. Messina J, Vallanti G (2006) Job flow dynamics and firing restrictions—evidence from Europe. European Central Bank Frankfurt am Main
3. Acs ZJ, Audretsch DB (1991) Innovation and small firms. MIT Press, Cambridge
4. Audretsch DB (2004) SME in Europe 2003. Office for official publications of the European Communities
5. Ayyagari M, Beck T, Demirguc-Kunt A (2007) Small and medium enterprises across the globe. Small Bus Econ 29(4):415–434
6. Obermann D (1996) Eine Analyse der Beschäftigungsprobleme kleiner Unternehmen. Peter Lang Frankfurt am Main
7. Flüter-Hoffmann C, Solbrig J (2003) Arbeitszeitflexibilisierung—Erfolgskonzept auch für kleine und mittlere Unternehmen. Dt. Inst. Verlag Köln
8. Kiel U, Kirner E (2002) Innovative Arbeitsgestaltung in Unternehmen und öffentlichen Einrichtungen. Rainer Hampp Verlag München/Mering
9. Preis U (ed) (2005) Innovative Arbeitsformen—Flexibilisierung von Arbeitszeit, Arbeitsentgelt, Arbeitsorganisation. Verlag Dr. Otto Schmidt Köln
10. Schütze J, Baum H, Ganß M, Ivanova R, Brückner W (2010) Stabilitätsförderliche Flexibilisierungsstrategien in industriellen KMU. In: Möslein KM, Trinczek R, Bullinger AC, Danzinger F, Lücking S (ed) BALANCE Konferenzband—Flexibel, stabil und innovativ: Arbeit im 21. Jahrhundert. Cuvillier Göttingen, pp 181–190
11. Müller E, Schütze J, Baum H, Ganß M, Ivanova R (2011) Business flexibility in small and medium enterprises—an empirical study. In: 21th international conference on flexible automation and intelligent manufacturing (FAIM 2011), Taichung (Taiwan)
12. Baum H, Schütze J, Ganß M, Ivanova R, Müller E (2012) A contribution to the development of the flexibility theory. In: Proceedings of the FAIM 2012, 22nd international conference on flexible automation and intelligent manufacturing, Helsinki, Finland. Tampere University of Technology, pp 253–260
13. European Commission, Commission Recommendation (2003/361/EC) of 6 May 2003 concerning the definition of micro, small and medium-sized enterprises, Official Journal of the European Union, L 124/36, 20 May 2003
14. Ivanova R, Ganß M, Baum H, Schütze J (2011) Flexibilisierungsstrategien als Instrument der innovativen Arbeitsgestaltung. Mensch, Technik, Organisation—Vernetzung im Produktentstehungs- und -herstellungsprozess, 57. Kongress der Gesellschaft für Arbeitswissenschaft, GfA-Press, pp 409–412
15. Ganß M, Baum H, Schütze J, Ivanova R (2011) Ein Beitrag zur Entwicklung einer Flexibilitätstheorie. In: Müller E, Spanner-Ulmer B (ed) Nachhaltigkeit in Fabrikplanung und Fabrikbetrieb—TBI'11. Tagungsband, Wissenschaftliche Schriftenreihe des IBF, Sonderheft 17, TU Chemnitz, pp 451–460
16. Ganß M, Baum H, Schütze J, Ivanova R (2011) Flexibility instruments in SME: an empirical study. In: 21st international conference on production research (ICPR), Stuttgart
17. Schlick CM, Bruder R, Luczak H (ed) (2010) Arbeitswissenschaft 3. Aufl., Springer, Berlin

# Agent-Based Service-Oriented Architecture for Heterogeneous Data Sources Management in Ubiquitous Enterprise

**L. Y. Pang, Ray Y. Zhong and George Q. Huang**

**Abstract** In a ubiquitous manufacturing environment, different devices such as radio frequency identification (RFID) technology are used to collect real-time data. Additionally, data is used by different enterprise information systems for supporting managerial decision making. Since data sources from applications and devices are characterized by multiple types of heterogeneities such as communication channels, blinding methods, and developing environments, the difficulty in managing heterogeneous data sources is greatly increased. This paper proposes an innovative Application Information Service (AIS) that serves as a middleware for information exchange in between different applications. The AIS possesses several key contributions. Firstly, AIS provides a centralized platform to manage distributed heterogeneous data sources so as to reduce the data duplications, increase consistency, and accuracy. Secondly, it combines software agent technologies with service-oriented architecture (SOA) so that services are capable of accomplishing tasks in an autonomous way without human intervention. Thirdly, agent-based service-oriented architecture paradigm is proposed to cultivate a collaborative environment to integrate different data sources as well as third party application providers.

## 1 Introduction

Enterprise Information Systems (EISs) play an important role in the enterprise. EISs provide a platform for organizations to integrate and coordinate their business processes and activities such as warehousing, manufacturing, inventory control, etc. The objectives of EISs are to increase organization agility, follow the market

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changes, improve the relationship between business partners, and enhance the enterprise competitiveness. Since different EISs provide various functions, different types of EIS may be adopted within a single enterprise based on the enterprise situation. Also, recent advances in Auto-ID technology for supporting operations have increased the demand for ubiquitous data exchange among Auto-ID devices and EISs [1]. An enterprise equipped with distributed and simultaneous information processing capacity is termed as ubiquitous enterprise. Under the ubiquitous enterprise, decision makers need comprehensive information for high-level or managerial decision making.

This paper is motivated by real-life problems from a collaborating company which encounters problems in managing different EISs. The collaborating company is a public warehouse providing logistics and value added services for its manufacturing partners. The company has a small production line for repacking manufacturers' finished product according to the customer requirements. The packaged product will then consolidate and ship to customers. The company is facing some problems in managing different EISs. Firstly, the company adopted several EISs to support their daily operations. However, operating data are inputted and stored in various EISs separately and independently. Thus, data is usually asynchronous, inconsistence, and inaccuracy in between EISs. Secondly, transactions and data exchange between the company and its customers are handled by employees manually. Human errors at this time are unavoidable and require a lot of time and efforts to ensure the data correctness. Also, the format and structure of information from different customers are various. The company pays a lot of human resources in order to ensure data consistence between EISs. This increases the operating costs and the responsive time and hence affecting the company image. Thirdly, the company uses a lot of Auto-ID devices such as RFID, barcode devices to improve the performance of inventory management. However, the outputting format and structure of Auto-ID devices are highly irregular. The company found that it is difficult for them to integrate real-time data and existing static information to support decision making.

To address the above problems, significant research progresses have been made in enterprise information integration. The objective of enterprise information integration is to provide a uniform access to various data sources [2]. Sujansky summarized four significant representational heterogeneity differences for aggregating data; they are structural differences, naming differences, semantic differences, and content differences [3]. A lot of methods have been proposed for data integration. Halevy summarized and categorized data integration in 6 directions [4]. (1) Using mediated schema to map multiple data sets to one schema. (2) Developing an adaptive query language to query multiple data sources. (3) Using XML to integrate data. (4) Developing models to provide algebra for manipulating and mapping different data sources. (5) Using peer-to-peer technology to share data or files. (6) Using artificial intelligence technologies to semi-automatically generates semantic mapping for data integration. A lot of frameworks have been proposed to integrate and merge enterprise information system systematically [5–7]. Artificial intelligence technologies such as software agent technology have been widely adopted in information system integration [8]. Software agent technology is an important branch of artificial intelligence and has been widely accepted and adopted in different areas such as supply chain, manufacturing, and product design for it characteristics of autonomy, interoperability, flexibility, re-configurability, and scalability [9–11]. Agent-based approaches have played an important role to achieve outstanding performance with agility in various kinds of applications such as resources management [12], planning and scheduling [13], and information processing [14]. Foundation for Intelligent Physical Agents (FIPA) provides an overview and guide to design and develop heterogeneous interact agents and agent-based systems [15]. Java Agent Development (JADE) framework that compliant to FIPA specifications is a common framework for agent applications under JAVA environment [16]. The recent movements of enterprise information integration are focusing on the integration of web service technology and artificial intelligence technologies [17–19]. Web services technology provides a higher-level interoperability for leveraging business activities across the web either within an enterprise or among collaborating enterprise. Web Services technology and Service-Oriented Architecture (SOA) have provided a new and excellent solution to the data integration among heterogeneous and distributed systems. Agents and web services are integrated together to provide a more flexible and dynamic solution [20]. However, the knowledge requirements and technology threshold of implementing these technologies are very high. Small and middle enterprise may not have enough knowledge and expertise in developing these complicated systems.

Therefore, several research problems are addressed in this paper. Firstly, how to integrate and manage the heterogeneous data sources, such as EISs and Auto-ID devices, in ubiquitous enterprise such that they are usable by non-technical end-users? Secondly, how to wrap and integrate the multi-types data sources and export the result to a common format so that data can be easily shared? Thirdly, how to manage the agents and its services through web services technologies in order to make them be easily registered, discovered, and invoked by users, decision support systems, or other applications? The aim of this research is to design and develop an agent-based application information service (AIS), which adopted SOA, for managing heterogeneous data sources in ubiquitous enterprises. The objectives of this paper are firstly, it is to develop a framework of AIS platform that users can integrate and manage heterogeneous data sources. Secondly, it is to develop a mechanism that wraps heterogeneous data sources so that international standards such as ISA-95 can be easily applied to standardize data enquiry, format, and structure. Thirdly, it is to integrate agents with web services that promote services intelligence and collaboration. Also, it enhances agents so that they are easily be registered, discovered, and invoked. This research adopts and develops three important concepts. Firstly, intelligence agent technology is used as a mediator that provides translation of queries and data between heterogeneous data sources. Secondly, web service technology is used for promoting agent operations to agent services that enhance the software agent characteristics. Thirdly, an agent-based service oriented architecture that adopts SOA in designing the agent architecture for efficient integration of different AIS agents. The rest of the paper is organized as follows. Section 2 is the overview of the agent-based data source management. Section 3 is the framework of the AIS. Section 4 is the design of agent-based SOA. Conclusion and future works are given in Sect. 5 to summarize this research.

## 2 Overview of Agent-Based Data Sources Management

Under the ubiquitous enterprise, several EISs are usually used in an enterprise to support their daily operations. Information stores in different EISs separately. If there is no systematic mechanism for data management, information become asynchronous, inconsistence, and disperse in different EISs. Therefore, an agent-based AIS platform is proposed to assist users in managing heterogeneous data sources. The overview of Agent-Based Application Information Service is shown in Fig. 1. AIS acts as a middleman in between data consumers and data providers to provide several services. The first service is to manage different data sources within the enterprise. The second service is to integrate data from different data sources in order to provide comprehensive information for decision making. The third service is to ensure data is consistent, non-duplicated, and accurate in different data sources. Finally, it is to provide a set of visual tools for general users to (re)configure and manage the AIS platform and various data sources.

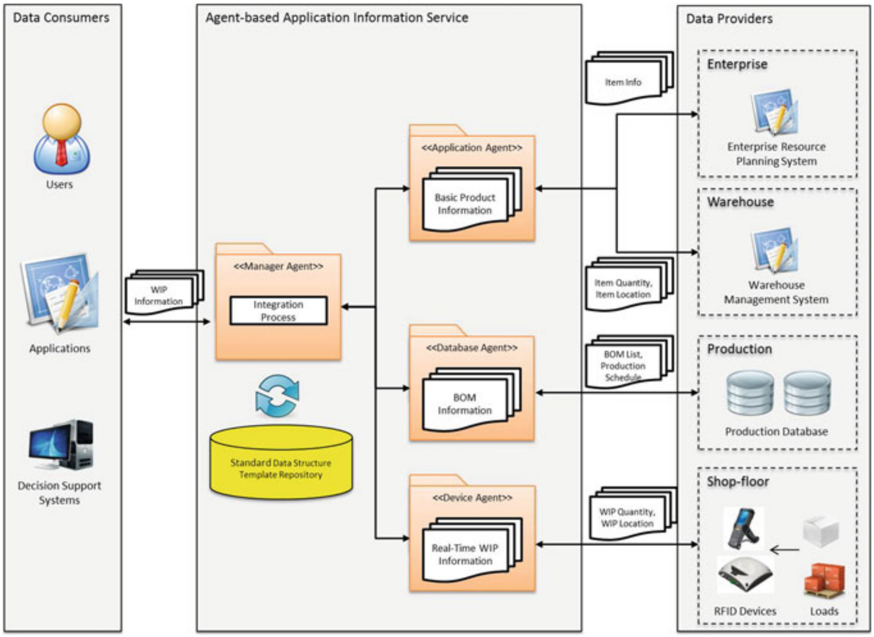



**Fig. 1** Overview of agent-based application information service

An example is selected to illustrate the situation. Work-in-progress (WIP) is important information for decision making within the manufacturing enterprise. WIP information is used to (1) calculate total inventory value, (2) plan the production schedule and (3) monitor the production progress. However, WIP is comprehensive information which usually consists of four sets of basic information. It includes item information from ERP system, item quantity and location from warehouse management system (WMS), scheduling and planning information from MES, and real-time production such as WIP quantity and location information from shop-floor. The data consumer such as decision support systems sends the data request token to the AIS Platform. The token indicates what information is needed to retrieve. This information is defined in the standard data structure template repository which acts as a library for different information sets. After the Manager Agent receives the request, it will find and invokes different data sources agent which responsible for accessing and collecting request data from different data sources. Finally, the Manager Agent integrates all data pieces and sends the result back to the data consumers.

## 3 Framework of Agent-Based Application Information Service

Different data sources are driven by different communication methods such as class libraries, communication protocols, and invoking methods. In this regard, professional programming knowledge and expertise are obviously needed. Moreover, a tiny change of business processes and requirements may need to redesign and recoding the existing applications in order to collect right information. It is, therefore, necessary to configure and manage the heterogeneous data sources following a uniform and flexible model to reduce the technical difficulties. For the above purpose, the proposed AIS is to integrate the concepts of software agent and web services. Figure 2 shows the framework of agent-based AIS. It aims to provide a framework for agent management services, and a platform for agent message transport. The purpose of AIS is to help data consumers collect data from different data providers and integrate those data to meaningful information with standard data structure. Inside the AIS, software agent technology is adopted for managing and accessing different data sources. It is used for wrapping various heterogeneous data sources to form a uniform architecture. The most innovative features of AIS is to provide a standard data structure template library for users to customize the output data format and wrap heterogeneous data sources to a uniform interface for data capturing. The design of agent application in AIS is compliant with the FIPA specification. The agent-based AIS includes four main modules.

1. AIS Agents
   This module is the collection of agents and their related services. There are three types of agents. They are Manager Agent, Data Source Agents (DS

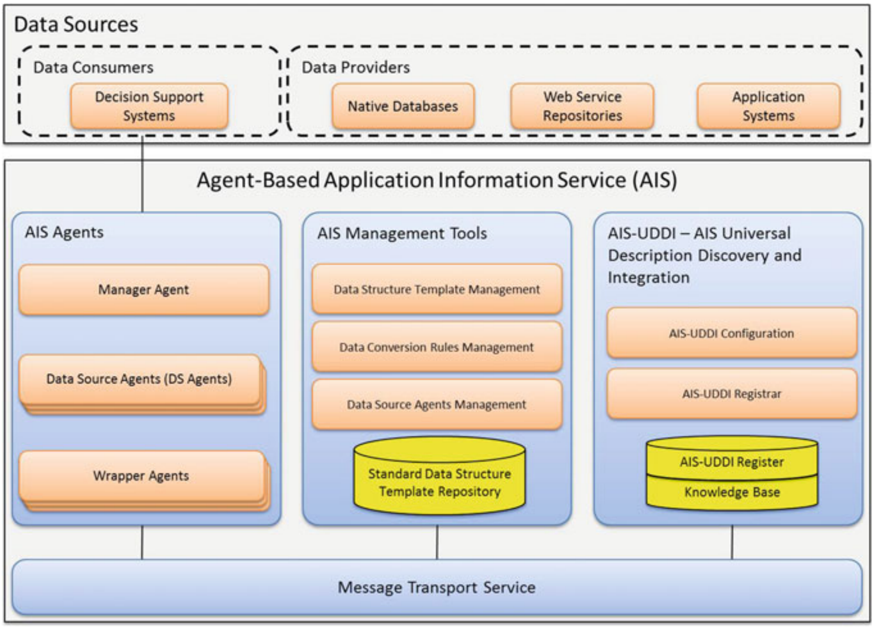



**Fig. 2** Framework of agent-based AIS

Agents), and Wrapper Agents. The Manager Agent is the mediator between data consumers and other agents. The AIS manager has three purposes. The first purpose is to handle requests from data consumer. The second purpose is to communicate different DS agents to retrieve data from data providers. The third purpose is to convert different data sets to standard data structure and return the result to data consumers. The purpose of DS agents is to access different data sources that are wrapped by Wrapper Agents. The purpose of Wrapper Agent is to wrap non agent-based data sources to a uniform interface and join the agent-based AIS platform.

2. AIS Management Tools
   The main purpose of this module is to provide visual tools and APIs to manage and configure the AIS platform and AIS agents. There are three tools in this module. The first one is Data Structure Template Management tool. This tool allows uses manage the standard data structure template repository. This repository is a library for outputting data format. Data retrieve from different data source may contain different data structure, table name, column name, etc. Users can use this tool to standardize the data structure that they want to retrieve. The second tool is Data Conversion Rules Management. After users establish the standard data structure, users need to use this tool to create the converting rules or the matching table for translating data from the original data format to the requiring data structure. The third tool is Data Source Agent Management which enables users to manage AIS Agents manually and checks

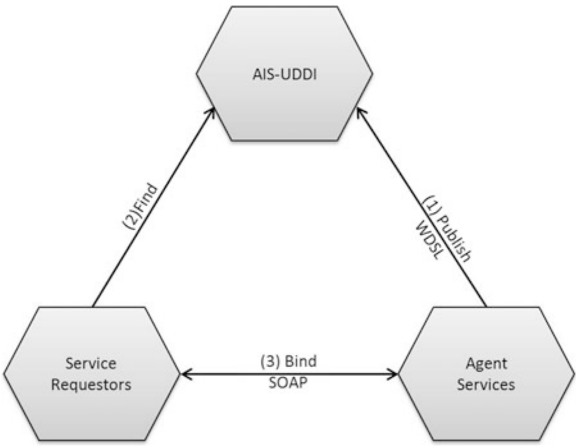
AIS Agents status. The AIS management tool exerts supervisory control over the whole AIS platform.

3. AIS-UDDI
   This module is an agent directory facilitator that provides a yellow pages directory services to agents and their services. An AIS-UDDI platform, which is XML-based registry, is developed and used for agent services describing and discovering through internet. The detailed structure will be introduced in the next section.
4. Message Transport Service
   This service is used for delivering message between agents within the agent platform and to agents that on others agent platform. The communication between agents is through agent message which consists of a message envelope and a message body. Agent messages will be routed and handled between agents according to the specific transport requirements such as transport protocol.

## 4 Architecture of AIS Agents and Services Directory

As discussed above, AIS agents are exposed as web services form. The SOA is adopted to design the AIS agent directory facilitator. The SOA cultivates a loosely coupled environment that supports dynamic binding agents or services during run-time, and standardizes the different agents' communication protocol. The Fig. 3 shows the architecture of AIS Agents and Services Directory. An AIS-UDDI platform, which is XML-based registry, is developed and used for agent services describing and discovering through internet. In the implementation level, web services, WSDL, and SOAP provide such capacities as discovery, deployment and communication to realize such architecture. Web services are commonly adopted to develop internet accessible applications. The services, which are provided by

**Fig. 3** The architecture of AIS agents and services directory



AIS Agents, are composed and encapsulated in web service format in order to standardize the accessing protocol and invoking methods. WSDL describes the operations correspond to the action supported by the agents. SOAP is a platform-independent communication protocol for exchanging XML-based message via HTTP protocol. This relationship of web services, AIS-UDDI, WSDL, and SOAP cultivate a SOA for AIS Agents and Services Directory.

A complete process of using AIS-UDDI involves three main phases: service registration, searching, and binding. In the registration phase, after deploy agents in web services format, the information of agents and its related services should be registered to the AIS-UDDI to indicate its availability, capability, location, as well as the interfacial description. Then, the registered agents and their provide services can be searched by other agents. In the search phase, other agents or sub-agents can discover and obtain other agents information. The AIS-UDDI provides two ways for web services discovery, programmatically, or through the service searching explorer GUI. The former means the discovery could be triggered by SOAP message sent from the program of a remote requestor, while the latter means the requestor could use the service searching explorer to manually, perform the service discovery. The searching result will indicate the following information: (1) the uniform resource identifier (URL) of the agent location/provider. (2) the remote service(s)/method(s) name for invoking. (3) the input and output parameters data types. In the binding phase, once the request prepares proper input data for intended the agent service, it starts binding the service URL and invoking the service method. The communication between requestor and receiver is via SOAP request message. The receiver agent decodes the message, executes action, and returns the XML-based result. The request agent parses the result for its own process.

## 5 Agent-Based Application Information Service Data Processing Process

In this section, a product information requesting scenario is envisaged to demonstrate the agent-based AIS data processing procedure. Product information is important and critical information required for upper level decision making in manufacturing enterprises. Enterprises require product information in calculating the inventory value, costing, production planning, and scheduling. Production information in manufacturing enterprise commonly consists of four sets of information. They are basic production information form ERP, product quantity and location from warehouse management system (WMS), product BOM list and production progress from MES, and WIP information from shop-floor. Detailed procedure of the aforementioned processes is shown in Fig. 4.

From the perspective of processes, the AIS Agents consist of three different levels of agents, from the top to down, are Manager Agent, Data Source Agents

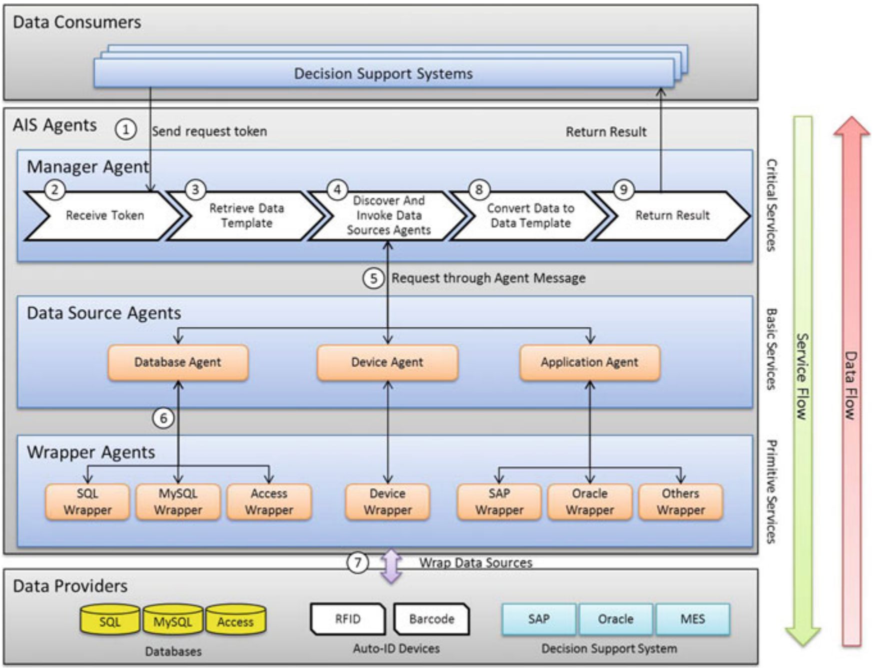



**Fig. 4** AIS agents data processing procedure

(DS Agents), and Wrapper Agents. The higher levels of agents provide more complex services and the lower level of agents provides more basic and primitive services. Different levels of agents have different objectives to achieve. The AIS Manager is mediator between data consumer and data source agents. The purpose of the Manager Agent is to coordinate the sub level data source agents and integrate data which retrieves from DS Agents to a standard data structure. The purpose of DS Agents provide basic services for communicating different types of data sources such as database, devices, or application systems because the parameters input are very similar. The purpose of Wrapper Agents act as an adaptor function to encapsulate non-agent data sources and allow DS agents to access them as an agents via a standard communication protocol. Also, the DS Wrappers provide two functions. The first function is to integrate the drivers, class library, and communicate protocol that related to the data sources. The another function is to convert the agent message to query language such as SQL for database, SOAP message for web services, and other dedicated invoking methods for Auto-ID devices. The steps of Data Processing Procedure are described as follows. First, the data consumers such as decision support systems will send a request token to Manager Agent. The request token is XML based and information includes three types of information, the required data structure template to retrieve, the target data providers, and filtering parameters. Second, the Manager Agent receives token and translates the token. Then, the correspondence data template is loaded from the native data template repository. Forth, according to the data structure template, the AIS manager searches and invokes different type of DS Agents to collect information from different data sources. Fifth, the DS Agent parses the message and discovery suitable Wrapper Agents to access the target data source. Sixth, the Wrapper Agent translates the message to corresponding query language with proper condition parameters. Then, the wrapper agent accesses the data sources with suitable class library, protocols, and methods to connect and retrieve information from the data source. The result finally transfers back to the Manager Agent. Eighth, after the Manager Agent collects all required information from DS agents, all piece of information will be integrated together based on the specifications of data structure template. Finally, the result sends back to the data consumer for further processing or decision making.

## 6 Conclusions and Future Work

In a ubiquitous manufacturing, data is usually stored in heterogeneous data sources. Since each data source has its own data structure and format, unmanaged information easily becomes inconsistent, duplicated, and inaccurate. There are an increasing number of data sources with need for uniform query interfaces to access and manage distributed data across diverse source. This paper has proposed an agent-based application information service to manage heterogeneous data sources in ubiquitous manufacturing. A standard data structure library is established for storing the data output structure template. AIS Agents are developed and used for accessing heterogeneous data sources and integrating data from different data sources according to the selected data structure template. The united data format enable data interchange between applications. The use of agents enhances the flexibility and scalability of the AIS.

The agent-based AIS demonstrates several key contributions. Firstly, AIS provides a centralized platform to manage distributed heterogeneous data sources so as to reduce the data duplications, increase data consistency and accuracy. Also, the use of standard data structure template library is to enable users self-customized the output data structure. Standard schema can be added to the data template library easily. The use of standard schema facilitates the information interchange between applications as well as enterprises. Secondly, it combines software agent technologies with SOA so that services are capable of accomplishing tasks in an autonomous way without human intervention. Services provided by AIS agents are wrapped by web services that provide a standard communication interface for communication among agents. This can enhance the agents' communication and cooperatively in cross-platform and cross-enterprise environment. Thirdly, the design and development of AIS-UDDI provides a platform to register, publish, search, and bind the AIS agents and their related services. The implementation of AIS-UDDI realizes the SOA and cultivates a collaborative environment to integrate different data sources as well as third-party applications. Operation processes are created by linking up different individual services. Therefore, IT-engineers are easy to reconfigure, rearrange, and reuse different services. This maximizes system integrity and scalability.

The current work will be further extended in the future research form several aspects. Firstly, the data source agents and wrapper agents will be extended to support more type of data sources through accommodating more drivers and API library. Secondly, the standard template library will be extended to support more international standard in logistic and manufacturing domain. Therefore, more efforts are necessary to better understand these standards for better exploitation. Finally, ontology will be implemented in the agents to help for integrating data between data sources. Data syntactic, schematic, and semantic heterogeneities are main barriers affect the data integration process. The next step is to implement ontology methods to solve this type of problem.

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## References

1. Mohsen A (2007) RFID: an enabler of supply chain operations. Supply Chain Manag Int J 12(4):249–257
2. Halevy AY et al (2005) Enterprise information integration: successes, challenges and controversies. In: Proceedings of the 2005 ACM SIGMOD international conference on management of data 2005, ACM, Baltimore, pp 778–787
3. Sujansky W (2001) Heterogeneous database integration in biomedicine. Comput Biomed Res 34(4):285–298
4. Halevy A, Rajaraman A, Ordille J (2006) Data integration: the teenage years. in VLDB'2006: Proceedings of the 32nd international conference on very large data bases. VLDB Endowment
5. Ronald EG (2004) A framework to review the information integration of the enterprise. Int J Prod Res 42(6):1147–1166
6. Lenzerini M (2002) Data integration: a theoretical perspective. In: Proceedings of the twenty-first ACM SIGMOD-SIGACT-SIGART symposium on principles of database systems, ACM, Madison, Wisconsin, pp 233–246
7. Woelk D et al (1993) Using Carnot for enterprise information integration. In parallel and distributed information systems. In: Proceedings of the second international conference on 1993
8. Gorton I, Liu A (2004) Architectures and technologies for enterprise application integration. In: Software engineering, ICSE 2004 Proceedings of 26th international conference on 2004
9. Sikora R, Shaw MJ (1998) A multi-agent framework for the coordination and integration of information systems. Manage Sci 44(11):S65–S78
10. Gek Woo T, Hayes CC, Shaw M (1996) An intelligent-agent framework for concurrent product design and planning. Eng Manag IEEE Trans 43(3):297–306
11. Jiao J, You X, Kumar A (2006) An agent-based framework for collaborative negotiation in the global manufacturing supply chain network. Robot Comput Integr Manuf 22(3):239–255

12. Bastos RM, de Oliveira FM, de Oliveira JPM (2005) Autonomic computing approach for resource allocation. Expert Syst Appl 28(1):9–19
13. Weiming S, Lihui W, Qi H (2006) Agent-based distributed manufacturing process planning and scheduling: a state-of-the-art survey. Syst Man Cyber C Appl Rev IEEE Trans 36(4):563–577
14. Bayardo RJ et al (1997) Info Sleuth: agent-based semantic integration of information in open and dynamic environments. SIGMOD Rec 26(2):195–206
15. http://www.fipa.org. Accessed May 2012
16. Bellifemine F, Rimassa G (2001) Developing multi-agent systems with a FIPA-compliant agent framework. Softw Pract Exper 31(2):103–128
17. Huhns MN (2002) Agents as web services. Int Comput IEEE 6(4):93–95
18. Dale J et al (2003) Implementing agent-based web services. In: AAMAS 2003 workshop on challenges in open agent environments, Melbourne Australia. Citeseer
19. Huhns M (2003) Software agents: the future of web services. In: Carbonell et al J (ed) agent technologies, infrastructures, tools, and applications for E-services, Springer, Berlin, pp 1–18
20. Brazier FMT et al (2009) Agents and service-oriented computing for autonomic computing: a research agenda. Int Comput IEEE 13(3):82–87

# Implications of Interoperability for Factory Planning

**Sebastian Horbach**

**Abstract** Enterprises operate in an increasingly turbulent environment. In order to stay competitive, more and more complex decisions have to be taken. Production systems are not relatively closed systems any more, but often part of supply networks with a high number of resulting interfaces. Planning and operation of factories are tightened together. At the same time virtual reality, as the mean of modern factory planning, merges with the real world. The processes of planning and operation are supported by a variety of software tools. With reference to operation of enterprises a lot of effort is put in integrating the different tools, while there is a deficit concerning the integration of factory planning tools. Therefore, the paper will look at the current state of interoperability in factory planning. The requirements and use cases of data exchange between tools for factory planning as well as other enterprise software, are discussed. Thereby, challenges and opportunities resulting from better hardware performance, faster communication networks and a wide range of new types of devices are listed. The consequences of trends like cloud computing and big data are classified. Conclusions are derived for possible architectures of software systems. The role of the Digital Factory in the whole development is investigated.

## 1 Introduction

Enterprises operate in an increasingly turbulent environment. A multitude of methods and tools has been developed for managing production systems with an ever-growing complexity. The result is a heterogeneous world of enterprise software. A solution would be to use a monolithic system by one provider who

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guarantees a high degree of integration. This is not appropriate if an enterprise wants to work with best-in-class tools. In the case of collaboration, the problem gets urgent, if the participants work with different software tools. Then the interoperability of these tools becomes mandatory.

Much research has been invested in the interoperability of the tools accompanying the product life cycle in the operational domain as part of Computer Aided Engineering (CAE). This starts from the Computer Aided Design (CAD) over the Computer Aided Process Planning to the NC-programs of the machine tools [1–3]. As a matter of fact, since 2000 of the European Commission has funded several projects through the Framework Programs (FP7) about enterprise interoperability, such as ATHENA, INTEROP, or ENSEMBLE. A good overview is given by Ducq, Chen and Doumeingts [4].

Less attention was given to the issue of interoperability with tools for factory planning as a strategic management task [5]. Therefore this paper will look at the current state of interoperability in the context of the planning of production systems.

Emerging technologies present opportunities which should be also exploited in factory planning. This refers to both software and hardware. Topics like cloud computing, data warehouse, or NoSQL-Databases come to mind. People now not only use PCs or laptops for computer work, but also a whole bunch of new devices which have become popular in the last few years, such as smart phones or tablets in different sizes. Since increasingly enterprises encourage the concept of "bring your own device," enterprise applications should be able to run on such equipment. It is no science fiction any more that the production manager uses an advertisement break to check on his Smart-TV the utilization of the machinery he is responsible for. The performance of computers and communication networks has also grown all the time.

## 2 Terms

Interoperability is defined as "the ability for a system or a product/service to work with other systems or products/services without special effort of the user" [6]. If two or more per se incompatible systems are desired to work together an interoperability problem appears [7].

Enterprise Application Integration (EAI) is the concept of connecting typical software systems of one or more companies, such as ERP, CRM (Customer Relationship Management), or document management applications. It should include the integration of the business processes, especially if different companies are involved. EAI is usually realized by web services. Even though EAI doesn't get much attention anymore the issue of Enterprise Integration (EI) is still a widely discussed topic.

By definition of the US-American National Institute of Standards and Technology (NIST) "Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" [8]. The extent of the provided resources is differing, the definition lists three service models.

- Software as a Service (SaaS): The provider hosts software applications to which the user provides input data while the applications returns result data. The interface of the application can be a web page.
- Platform as a Service (PaaS): The user is provided with a platform on which he can deploy his own applications, according to the programming languages, software libraries, tools etc. on the platform.
- Infrastructure as a Service (IaaS): The provider allocates computing capacity to the user, who can run arbitrary software, which could even include operating systems.

Deployment models are proposed, which differ in the degree of privacy of the services.

"Digital factory is the generic term for a comprehensive network of digital models, methods, and tools—including simulation and 3D visualiation—integrated by a continuous data management system. Its aim is the holistic planning, evaluation, and ongoing improvement of all the main structures, processes, and resources of the real factory in conjunction with the product" [9]. The purpose of the Digital Factory is to move planning decisions to an earlier stage since conclusions can be drawn from digital models. Integration of the different planning tools is a prerequisite for the implementation of the Digital Factory. The main tools of the Digital Factory from the point of factory planning are Simulation and Virtual Reality (VR).

## 3 Requirements and Use Cases of Interoperability

This chapter explains the use cases in which interoperability in connection with factory planning is needed. These use cases point to requirements on interoperability between factory engineering tools. It can be concluded, which data is affected and which synchronization tasks have to be executed. In another section obstacles for the realization of interoperability are listed.

### *3.1 Scenarios of Interoperability in Factory Planning*

The process of factory planning is supported by different types of tools, even though the main tool often enough turns out to be Microsoft Excel®. Thereby, factory planning is an iterative process. Especially in early stages good planners consider a number of possible solutions, develop them, and drop some as they gather more information. These variants have a considerable subset of common data, which makes data management harder insofar that a change in that basic data applies to all variants. More difficulties arise from the fact, that factories are commonly planned by a team. Such a team is distributed, since it might be not efficient that all planners work on site. But every planner has to be informed about occurring changes as soon as possible. Additional difficulties arise from the fact, that the planning process is iterative, i.e., planners might need to go back to earlier stages to revise assumptions. Since planning processes are required to get faster all the time, the planners have to work increasingly simultaneously.

When a factory planning project starts, data has been already produced, that can be input for factory planning tools. This could be the product data from the designer, the data of the resources from the producer, or the data of the process from the process planner. As the planning process goes on, specialized factory planning tools will be deployed. One tool builds on the output of another tool. In conclusion, interoperability is decisive for implementing the Digital Factory in a holistic way.

At the point when the planning process enters the implementation stage, the produced data has to be transferred to the software tools for factory operation, particularly the ERP system. Even if only restructuring was done and data about products, processes, and resources were taken from ERP a new master schedule might be adopted. As another example, data might need to be announced to the quality management system.

Planning of production systems is not anymore a once in a while task, but a permanent issue faced by the management [10]. In result, a constant data exchange between the tools for manufacturing operation and the tools of production systems planning is required. The operation side provides the system load to the planning party. The planning side uses the data as input for optimization tools. The approved results are finally returned to the operation software.

The development of the vast majority of factory planning solutions starts in the virtual world. The eventually preferred solution is implemented in the real world. Now the environment will change, not all initial assumptions can be held. Changes and experiences should be applied to the virtual model, which is re-evaluated on the new situation. New solutions again need to be implemented in the real world. Therefore, a better interweaving of virtual and real world is desired.

A stronger interlinking of virtual and real world is provided by augmented reality. On the one hand, this means that virtual objects are projected to the real world or to camera mappings of it. On the other hand, equipment can connect by apps to a portable device, which can receive important information about the equipment, such as utilization or downtime.

Nowadays hardly any enterprise can operate without being integrated in Supply Chains or Networks. Supply Networks depend on a good communication between the participants. Planning decisions of one participant have consequences for others. In order to obtain planning solutions which are satisfying for all participants, data exchange is necessary. It can't be assumed that all partners use the same software toolset.

It has to be kept in mind, that the disclosure of data understandably faces a lot of reservation. Xu observed a strong reluctance of enterprises in storing sensitive data on the cloud [11]. Loss of sensitive data can have fatal consequences for enterprises.

### *3.2 Obstacles for Interoperability*

There are several obstacles hindering interoperability. The planning objects evolve in certain levels of abstraction and elaboration. At the beginning the planner can use templates (components, building blocks) which contain general information. As the processes are designed concrete types of resources are determined. After the point of purchase, instances of resources, which should have a unique ID, have to be considered. So in the course of planning, templates have to be replaced by resource types and then particular resources.

The carrying of identifiers for objects can be a serious obstacle. There are tools which don't work with identifiers, while many others automatically generate identifiers, what can lead to overwriting of IDs or ambiguity of data. There might be even special conventions which prevent the usage of identifiers already assigned by other systems. A typical example is the maximum length of a data field. Further problems originate in the use of different measuring units. It is not always obvious which units a system uses.

Barriers for interoperability origin in the specifics of the information certain applications are using. Examples are the graphical data used for storing layouts or simulation software. It has been attempted to create the relevant models from textual data, which is the result of early planning stages. This refers especially to the automatic generation of simulation models [12, 13]. However, a lot of manual fine tuning is needed. But this is often also desired, since the designing of a production system remains a highly creative process.

Prerequisite for interoperability are adjusted business processes between enterprises. The procedures for factory planning are only roughly defined, so that detailed reference processes, which determine the needs for data exchange, are missing.

## 4 Architectures for Interoperability

Hypothetically, interoperability and flexibility seem to exclude each other. Standards seem to hinder freedom and independence of vendors. A complex, monolithic software system provides good integration but the cost of adapting the toolset to special customer requirements is high. Contrary, a collection of tools, which come at a relatively low price, offers a high degree of flexibility, but the integration of the different tools gets expensive.

The framework for the integration of factory planning tools has been provided by the Digital Factory [9]. For the DF, it has been demanded that "the data integration required for ensuring better data quality must be realized with the use of databases" [9]. A concept of small tools connected through a central database was developed with the Net Planning Assistant [14]. Experience has shown that the database is subject of a growing complexity which results in expensive maintenance. For the multitude of different formats of data different storing techniques might be appropriate, a Relational Database Management System (RDBMS) not always being the best solution.

The trend goes increasingly to architectures consisting of services, provided through the internet. The modularization of software systems is growing, software solutions can consist of a grid of dozens of independent services. Cloud Computing is seen as a major enabler for manufacturers [11]. Cloud computing is seen as a promising approach for factory planning applications [15].

A possible scenario (see Fig. 1) is that a consulting enterprise provides optimization algorithms as web services which are stored in the cloud. Companies, which want to optimize their production, call the service from their ERP-system or MS Excel. Alternatively the service could be accessed through a web page.

The project Virtual Factory Framework (VFF) [5] researches an architectural concept for the whole lifecycle of a factory. The approach is extending Product

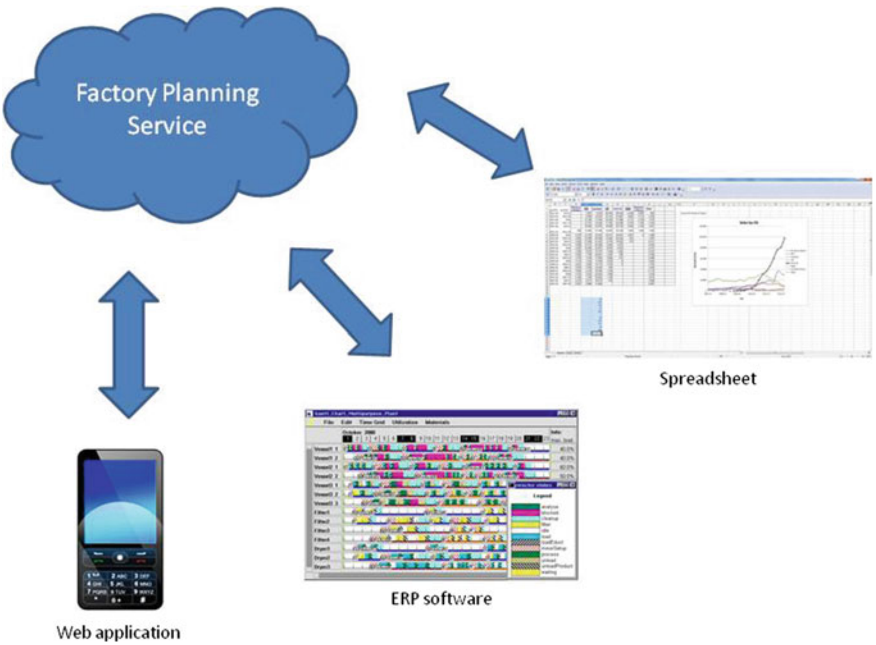


**Fig. 1** Factory planning functions as web services

Lifecycle Management (PLM) concepts to the factory as a complex product, having the purpose of manufacturing other products [16]. The VFF provides an integrated virtual environment for the support of design and management of the various factory entities for all types of factories, including supply networks.

## 5 Data Management

Reference models for enterprise data as base for interoperability were developed with standards like GERAM, GRAI, etc., [17–19]. These models only partly address the requirements of factory planning.

Nowadays a lot of data is collected in production systems. Main source is the Manufacturing Execution System (MES). Other possible sources are RFID readers or sensors, the latter being used, e.g., for monitoring energy consumption. This data gives a good insight in the evolution of the production system. It is important input for factory planning decisions. However, first the data needs processing. Techniques to handle extreme amounts of data are summarized under the keyword "Big data" [20–22].

Again it needs to be kept in mind that normalized relational databases are not the ideal tools for data analysis. So data warehouses are not normalized in order to achieve a better performance and avoid too complex queries. The process of analyzing the data is known as Data Mining. Widely popular is Online Analytical Processing (OLAP) [23].

Besides Relational Databases other ways of storing data are becoming popular. Due to the restricted flexibility of relational databases and the Structured Query Language (SQL) as interface for applications NoSQL databases are increasingly deployed, especially for web applications on a freeware basis. There are different types of NoSQL databases.

The extended markup Language (XML) gains a growing importance for data exchange between applications. It dominates the format of data used for communication with web services. XML-Documents follow a few basic rules for their structuring, but allow the definition of arbitrary tags and attributes. The structure of a XML-Document can be restricted by a specification, which is often embodied by a XML-Schema-Document. Popular examples for formats derived from XML are XHTML, MathML, or SysML as well as the aforementioned AutomationML. Another format with importance for web programming is the JavaScript Object Notation (JSON).

Data is no longer only stored in large monolithic databases.

The synchronization of different data models for realizing interoperability is supported by different tools, both commercial and freeware, such as Talend Open Studio or Sybase Power Designer.

## 6 Summary and Outlook

The paper gave an overview about interoperability issues in connection with the strategic planning of production systems. A lot of effort has been made to improve the interoperability of enterprise application. However, tools for factory planning are often not included in the considerations. Yet developments in hardware, software, software architecture, and data management provide better opportunities to integrate factory planning tools in the enterprise software environment.

The discussed interoperability approaches need to be validated on industrial use cases. At the moment, two applications are under consideration.

First the concepts are evaluated in a laboratory, which connects a small real world factory setup with a virtual factory environment. The laboratory is used for research, student education and also provides the possibility for companies to present emerging technologies. The research about building block for adaptable factory systems was presented at this conference in the past [24].

Secondly the concepts are incorporated in the research for the project Saxon Photovoltaic Automation Cluster (S-PAC) [25]. There, especially the simulation and visualization models for factories producing photovoltaic equipment are connected. Besides factory planning tools correspond through a central data repository with Manufacturing Execution System and software for maintenance management.

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## References

1. Nassehi A, Newman ST, Xu X, Rosso RSU (2008) Toward interoperable CNC manufacturing. Int J Comput Integr Manuf 21(2):222–230
2. Wang XV, Xu X, Hämmerle E (2010) Distributed interoperable manufacturing platform based on STEP-NC. In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing—FAIM 2010, Oakland, California
3. Xu X, He Q (2004) Striving for a total integration of CAD, CAPP, CAM and CNC. Robot Comput Integr Manuf 20(2):101–109
4. Ducq Y, Chen D, Doumeingts G (2012) A contribution of system theory to sustainable enterprise interoperability science base. Comput Ind 63(8):844–857
5. Sacco M, Pedrazzoli P, Terkaj W (2010) VFF: virtual factory framework. In: Proceedings of 16th international conference on concurrent enterprising, Lugano
6. Institute of Electrical and Electronics Engineers (IEEE), 610 (1991) IEEE standard computer dictionary. Compilation IEEE Standard Comput Glossaries
7. Naudet Y, Latour T, Guedria W, Chen D (2010) Towards a systemic formalisation of interoperability. Comput Ind 61(2):176–185
8. Mell P, Grance T (2012) NIST SP 800-145, The NIST Definition of cloud computing: recommendations of the National Institute of standards and technology http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf. Accessed 19 Dec 2012

9. Digital Factory—Fundamentals, VDI-Norm 4499-1
10. Rogalski S (2012) Factory design and process optimisation with flexibility measurements in industrial production. Int J Prod Res 50(21):6060–6071
11. Xu X (2012) From cloud computing to cloud manufacturing. Robot Comput Integr Manuf 28(1):75–86
12. Bergmann S, Strassburger S (2010) Challenges for the automatic generation of simulation models for production systems. In: 2010 international simulation multiconference: Crowne Plaza Hotel, Downtown Ottawa, On, Canada, 12–14, S.l: Omni Press, pp 545–549
13. Weigert G, Horn S, Jähnig T, Werner S (2006) Automated creation of DES models in an industrial environment. In: Lewis H, Gaughran B, Burke S (eds) Proceedings of the 16th international conference on flexible automation and intelligent manufacturing: FAIM 2006, June 26–28th 2006. Department of Manufacturing and Operations Engineering, University of Limerick, Limerick, pp 311–318
14. Müller E, Horbach S, Ackermann J (2009) Tool support for industrial engineering in small enterprises, Proceedings of the 19th international conference on flexible automation and intelligent manufacturing, Middlesbrough, p 195
15. Moch R, Müller E (2011) Planning software as a service—a new approach for holistic and participative production planning processes. In: Proceedings of international conference on digital enterprise technology, pp 93–100, Patras
16. Constantinescu C, Hummel V, Westkämper E (2006) The migration of life cycle paradigm into the manufacturing engineering. In: Proceedings of 13th CIRP international conference on life cycle engineering, Leuven, pp 705–710
17. GERAM (2010) The generalised enterprise reference architecture and methodology. In: Bernus P, Nemes L, Schmidt G (eds) Handbook on enterprise architecture, Springer, Berlin, pp 21–63
18. TOGAF® 9.1 (2012) http://pubs.opengroup.org/architecture/togaf9-doc/arch/ Accessed 14 Dec 2012
19. Chalmeta R, Campos C, Grangel R (2001) References architectures for enterprise integration. J Syst Softw 57(3):175–191
20. Bughin J, Chui M, Manyika J (2012) Clouds, big data, and smart assets: Ten tech-enabled business trends to watch, McKinsey & Company, McKinsey Quarterly http://www.mckinsey.com/insights/mgi/in_the_news/clouds_big_data_and_smart_assets. Accessed 19 Dec 2012
21. Bughin J, Livingston J, Marwaha S (2011) Seizing the potential of 'big data', McKinsey Quarterly https://www.mckinseyquarterly.com/PDFDownload.aspx?ar=2870. Accessed 19 Dec 2012
22. Manyika J, Chui M et al (2011) Big data: the next frontier for innovation, competition, and productivity http://www.mckinsey.com/insights/mgi/research/technology_and_innovation/big_data_the_next_frontier_for_innovation. Accessed 19 Dec 2012
23. Codd EF, Codd S, Salley C (1998) Providing OLAP to user-analysts: an IT mandate http://www.minet.uni-jena.de/dbis/lehre/ss2005/sem_dwh/lit/Cod93.pdf. Accessed 17 Jan 2013
24. Horbach S, Ackermann J, Müller E, Schütze J (2010) Building blocks for adaptable factory systems.In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing—FAIM 2010, Oakland, pp 568–575
25. Horbach S, Schulze R, Ackermann J, Schaarschmidt F, Müller E (2012) Application of methods and tools of factory planning to photovoltaics industry. In: Proceedings of 22th international conference on flexible automation and intelligent manufacturing—FAIM 2012, Ferry Helsinki-Stockholm-Helsinki

# Computer Aided Process Planning: A Comprehensive Survey

**Yusri Yusof and Kamran Latif**

**Abstract** The use of computer technology for process planning was initiated four decades before. Since then, there has been a large amount of research work carried out in the area of Computer Aided Process Planning (CAPP). One of the reasons for this is the role of CAPP in reducing throughout time and improving quality. Now a day's due to dynamic market and business globalization, CAPP research faces new challenges. In this article an attempt is made to provide a comprehensive review on CAPP based on features, knowledge, artificial neural networks, Genetic Algorithms (GA), fuzzy set theory and fuzzy logic, Petri Nets (PN), agent, internet, STandard for the Exchange of Product data (STEP) compliant method, and Functional Blocks (FB) technologies for last five years (2008–2012). The design of paper includes a brief introduction of CAPP and its approaches, methods/technologies of CAPP, snap shot survey of previous research work on CAPP, survey of last five years research work on CAPP, then finally a suggestion for future and conclusion.

## 1 Introduction

The idea of developing process plan using computers was presented by Neibel [1]. Computer aided process planning (CAPP) is the application of the computer to assist process planners in the planning functions. It is considered as the key technology for Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) integration. It consists of the determination of processes and parameters required to convert a block into a finished part/product. The process planning activities includes interpretation of design data, selection and sequencing of operations to manufacture the part/product, selection of machine and cutting

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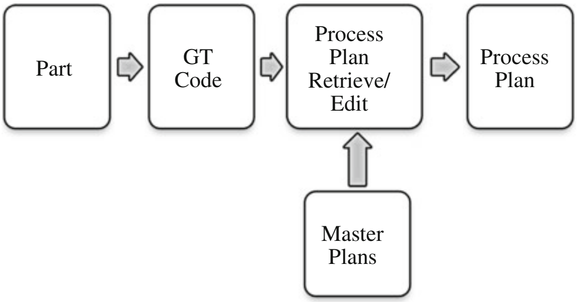



**Fig. 1** Variant CAPP approach

tools, determination of cutting parameters, choice of jigs and fixtures, and the calculation of the machining times and costs.

There are two basic approaches to CAPP: Variant and Generative. Figure 1 shows variant approach to CAPP. Variant approach, also called as retrieval approach, uses a Group Technology (GT) code to select a generic process plan from the existing master process plans developed for each part family and the edits to suit the requirements of the part. Variant approach is commonly implemented with GT coding system. Here, the parts are segmented into groups based on similarity and each group has a master plan. The advantages of this approach is the ease of maintenance but the lack of an on time calculation of manufacturing process and quality of the process plan still depends on the knowledge of a process planner and it still requires manual inputs for the establishment of the mass data into manufacturing processes. Figure 2 shows the generative approach to CAPP. In a generative approach, a process plan for each component is created from scratch without human intervention. These systems are designed to automatically synthesize process information to develop a process plan for a part. These systems contain the logic to use manufacturing data base and suitable part description schemes to generate a process plan for a particular part. Generative approach eliminates disadvantages of variant approach and bridges the gap between the CAD and CAM. The bottleneck of this approach is the difficulty in obtaining useable features, and the difficulty in representing, managing, and utilizing human expertise.

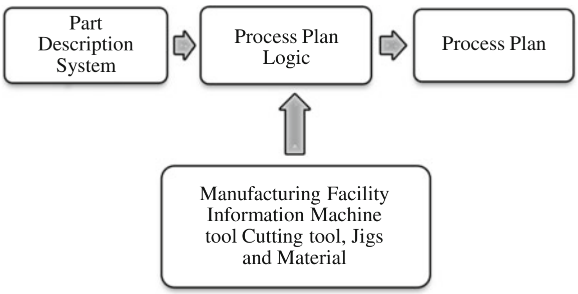



**Fig. 2** Generative CAPP approach

## 2 Established Methods of CAPP

In this research ten established technologies/methods of CAPP are highlighted namely: feature based technologies, knowledge based systems, artificial neural networks, Genetic Algorithms (GA), fuzzy set theory and fuzzy logic, Petri Nets (PN), agent based technologies, internet based technologies, STandard for the Exchange of Product data (STEP) compliant method and Functional Blocks (FB) to overcomes the issues of operation, tool and machine selection and sequencing, features extraction, reorganization, interpretation and representation, knowledge integration, representation, acquisition and sharing, setup planning, energy consumption, linear and non linear planning, integration of product, and manufacturing data etc. Figure 3 shows the use of CAPP in manufacturing cycle.

## 3 CAPP Review

The importance of CAPP in manufacturing facility cannot be underestimated. One of the reasons for this is; it provides a link between design and manufacturing, reduces the time and cost, and improves the quality. The CAPP area has been greatly developed in the last three decades. In this section a snap shot of the past and current survey in the field of CAPP is presented by dividing it into two sub sections: past review and current survey. The aim of this section is to provide a comprehensive review on CAPP technology, past work is discussed in the past review sub section whereas current survey sub section presents the review of last five years work (2008–2012) based on above stated methods/technologies of CAPP.

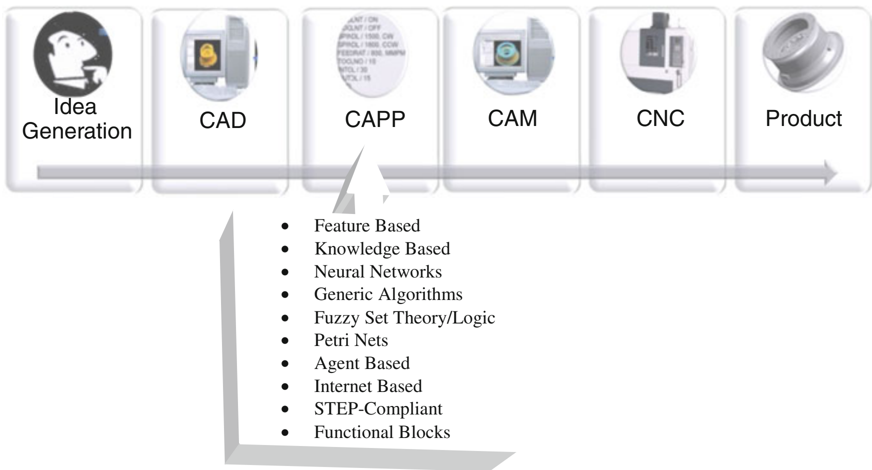



**Fig. 3** Use of CAPP in manufacturing cycle

### 3.1 Past Review

In 1984 the first review article is written by Steudel [2], in this articles scholar has discussed about the approaches and strategies for structuring manufacturing methods and data development for the development of a generative type, automated planning system. This articles also outlined the anticipated development of a 'common language of geometry' to relate a part to the process, and development of CAD/CAM systems that incorporated CAPP. In 1988, Ham and Lu presented an evaluation of the status of CAPP and correctly stated that the direction of future research lies in the integration between design, manufacturing, and the use of Artificial Intelligence (AI) technologies [3]. In the following year (1989) Alting and Zhang presented the most significant survey of the time and indicated that the difficulty in the integration of CAD with CAPP is due to the lack of common methods to represent geometric entities [4]. In this survey the authors also highlighted the issue of interfacing between CAPP and CAM and other computerized production systems such as Numerical Control (NC) tool path, MRP, production simulation, etc. The authors also recognized AI technologies as a crucial technology in the development of an effective process planning system and also pointed out the importance of the learning systems and identified an ideal approach to integrate all the information involved in production of a part into a single data base. In the same year, Gouda and Taraman published a survey of the 128 systems of CAPP and also highlighted the 4 types of CAPP systems: variant, semi-generative, generative, and expert process planning system [5].

In the year 1993 CAPP Working Group of The International Academy Of Production Engineering (CIRP) presented a survey which included the major development thrust in CAPP, evolving trends, challenges, integration of design, and production planning. In that survey authors also addressed the issues of quality and evolving standards [6]. In the same year Eversheim and Schneewind suggested the future of CAPP development is an extension to assembly planning, function integration with NC programming, use of AI methods in decision making, and use of data base sharing for data integration with CAD [7]. In year 1995, Kamrani presented an overview of the techniques and the role of process planning [8]. In that article the critical issues and the characteristics associated with evaluation and selection of a CAPP system are also discussed. In 1996, Leung presented a comprehensive review in which authors observed that solid modeling in CAPP systems is not as adequate as anticipated, hence the revitalization of variant process planning systems [9]. The scholars believed that it is logical that future process planning systems be built on intelligent system architectures with AI techniques. In the following year (1997), Cay and Chassapis presented a research on CAPP from 1990 to 1997 [10]. In this survey scholar provides an overview of manufacturing features and feature recognition techniques with CAPP research. In 1998 Marri presented a review which covers the literature from 1989 to 1996 [11]. In that article the advantages and disadvantages of the systems were discussed with the generative approach highlighted. After 10 years gap Xun Xu, presented an article to provide a comprehensive review on CAPP technologies developed for machining since 1990s but mostly after 2000 [12]. In that article authors provided an up to date review of the CAPP research works, a critical analysis of journals that published CAPP research works, and an understanding of the future direction in the field.

## *3.2 Current Survey*

This sub section presents a comprehensive overview of research work carried out by various researchers from different regions of the world during 2008 to 2012 based on stated methods and Fig. 4 shows the graphical representation of this section.

### 3.2.1 Review of 2008 Research Work

Hu presented extensible Markup Language (XML) based implementation of manufacturing route sheet documents to solve the operation sequencing problem for web based process planning [13]. This method is an extension of the artificial immune system approach and inherits its characteristics from the Maslow's need hierarchy theory related to psychology. Alvares presented an integrated web based CAD/CAPP/CAM system for the remote design and manufacture of feature based cylindrical parts [14, 15]. Sunil and Pande proposed a 12 node vector scheme to represent machining features families having variations in topology and geometry [16]. The data of recognized feature was then post processed and linked to a feature based CAPP system for Computer Numerical Control (CNC) machining. Babic presented a

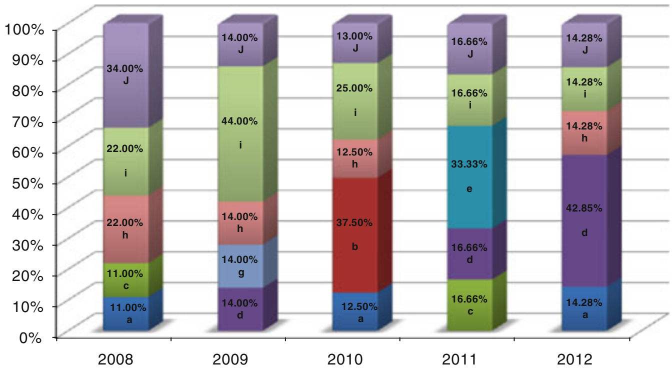



**Fig. 4** Graphical representation of current survey. **a** Feature based technologies, **b** knowledge based systems, **c** artificial neural networks, **d** genetic algorithms, **e** fuzzy set theory and fuzzy logic, **f** petri nets, **g** agent based technologies, **h** internet based technologies, **i** STEP-compliant method, **j** functional blocks

survey on three major feature reorganization problems: extraction of geometric primitives from a CAD model, defining a suitable part representation from feature identification, and feature pattern matching/recognition [17]. Yifei presented an automatic features extraction and process planning system using the STEP Application Protocol (AP) 214 data format and also presented an approach to processing tolerance information by utilization of CAD systems self provided functions for macro recording and editing [18]. Hebbal, Mehta, and Zhang worked on a setup planning. Hebbal and Mehta developed a formalized procedure for automatic generation of feasible setups and selection of an optimal setup plan for machining features of a prismatic part [19]. Zhang presented a mathematical model to describe the tolerance information and datum machining feature relationship based on extended graphics [20].

### 3.2.2 Review of 2009 Research Work

Majority of work carried out on STEP compliant method of CAPP. Rameshbabu and Shunmugam proposed a hybrid approach that uses volume subtraction and face adjacency graph to recognize manufacturing features from 3D model data in STEP AP203 format [21]. Yusof developed a STEP compliant system for the manufacturing of asymmetric parts on CNC turn/mill machine and also provides the structured view of a proposed system framework [22]. Zhao presented an intelligent STEP compliant manufacturing system in which geometric description data described in AP203 or other formats are translated into machining features defined in AP224. The machining feature definitions are used as inputs to macro process planning applications and micro process planning for machining (AP238). Inspections (AP219) are then carried out for each of the application process [23]. Agrawal addressed the Distributed Process Planning (DPP) problem in the e-manufacturing environment. In that article authors presented a multi agent system consist of three autonomous agents: global manager, design, and optimization. These agents are capable of communicating to each other through XML [24]. Salehi and Tavakkoli Moghaddam presented an approach to divide the planning into preliminary and detailed planning stages and applied GAs for process planning in both stages [25]. Jin provided multi objective optimization model for environmentally conscious CAPP. This article outlines a mathematical model that takes into account materials, environmental data, and environmental impact of the materials [26]. Xu and Li combines Jin’s approach and provided a basis for a new goal oriented, multi-parameter approach to representing process parameter selection at multi levels incorporating both micro and macro level decisions and incorporating process knowledge with mathematical logic [27]. Cai presented a GA based adaptive setup planning approach taking into consideration the availability and capacity of machine tools on a shop floor [28].

### 3.2.3 Review of 2010 Research Work

Newman outlined a framework to validate the introduction of energy consumption in the objectives of process planning for CNC machining [29]. In this work the scholars have presented a mathematical representation, and shown that the energy consumption can be added to multi criteria process planning systems as a valid objective. Risal presented an approach to feature recognition using rule based on different characteristics specific to each feature such as total number of faces, edges etc. [30]. The authors have implemented that approach by using Graphic Interactive Programming (GRIP) and unigraphics solid modeler. Shusheng presented an approach driven by process planning to reconstruct the serial Three Dimensional (3D) models for rotational parts [31]. This approach introduced the process planning course and relevant information to implement a dynamic, incremental, and knowledge based reconstruction. Hsin proposed the use of CAPP to reduce processing time and increase efficiency [32]. In this work the authors have developed a CAPP system for numerical control tool path, and this system includes both the automation of auxiliary boundary curve generation and machining strategies. Martin proposed a hybrid procedural and knowledge based approach based on artificial intelligence planning, to address the problems of classic feature interpretation and feature representation [33]. Chen proposed a Parametric Flow Chart (PFC) based on knowledge representation method which efficiently combines parameter information, flow chart technology, and visualization technology to provide user friendly and effective way of representing knowledge [34]. Peng developed a STEP compliant process planning model based on architecture and knowledge by using Ontology Web Language (OWL), and also proposed a novel mechanism to covert STEP into ontology based knowledge [35]. Helgosona proposed a conceptual model which includes an adoption of the Methodology Of Knowledge Acquisition (MOKA) and contains the activities; identify, justify, capture, formalize, package, and activate for sharing and integration of knowledge in process planning to increase the level of efficiency, reliability, and productivity in process planning process [36].

### 3.2.4 Review of 2011 Research Work

Jun Wang introduced the artificial neural network for unstructured manufacturing knowledge model in which knowledge is represented as neural network weight value matrix and the form artificial neural network database to support intelligent CAPP [37]. Lian presented a Cooperative Simulating Annealing (COSA) for the process planning problem to minimize total manufacturing cost. Simulated annealing was utilized to optimize the four components of a process plan individually and sequentially [38]. Lian also investigated the optimization of process planning in which various flexibilities including process, sequence, machine, tool, and tool access direction are considered to minimize total weight sum of manufacturing cost by developing an imperialist competitive algorithm [39]. Lian also proposed a novel optimization strategy for process planning. A Multi Dimensional Tabu Search (MDTS) algorithm based on this strategy is developed to optimize the four dimensions (operation sequence, machine sequence, tool sequence, and toll approach direction sequence) of a process plan [40]. Fernando Garcia introduced a method which utilizes feature based modeling for defining a preprocess plan. Preprocess plan defines the required capabilities on a high level [41]. This method of feature reorganization offers both geometric and non geometric information. Liu Wei Wang proposed an algorithm based on the Pareto genetic algorithm for the cutting parameters selection and optimization to solve the decision making problems of the cutting parameters in CAPP systems [42]. Hu addressed the issue of part fixture planning in CAPP and proposed a clamping planning method based on fuzzy clustering analysis [43]. Zhang proposed a Universal Process Comprehension Interface (UPCI) to regenerate high level process plan from shop floor part programs, and encapsulate the generate plan in STEP compliant data structure [44]. Roman presented a hybrid fuzzy approach for manufacturing analysis to provide solution for knowledge acquisition of expert process planners [45]. In this research special class weighted priority petri nets and genetic algorithms have been used to analyze and optimize the results.

### 3.2.5 Review of 2012 Research Work

Lihui Wanga developed methodologies for distributed, adaptive, and dynamic process planning as well as machine monitoring and control for machining and assembly operations using event driven functional blocks [46]. Jin presented an approach to improve the process planning of Rapid prototyping/manufacturing for complex product models such as biomedical models [47]. Ouyang present a STEP-NC oriented process planning optimization based on hybrid genetic algorithm to solve the non linear process planning problem [48]. The hybrid algorithm was proposed by integrating search of operation precedence graph with genetic algorithm. Shun Cheng presented multi objective decision and optimization of process routing based on genetic algorithm [49]. Tran presented a new approach using ontology and ruled based reasoning to support the integration of products data and manufacturing data [50]. Lian Liu proposed a genetic algorithm for operation sequencing in process planning [51]. Yu Hong presented a CAPP method for rotational parts based on case retrieval [52]. Zhang proposed a method to capture the machining process knowledge from CNC part programs with Universal Process Comprehension Interface (UPCI) and reuse it on new manufacturing resources [53].

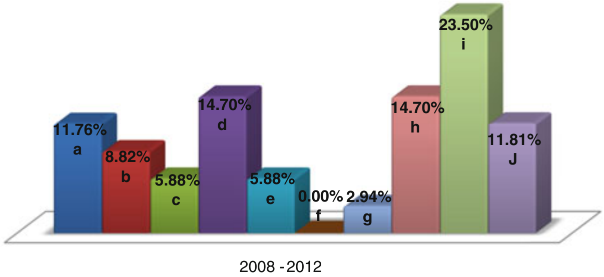
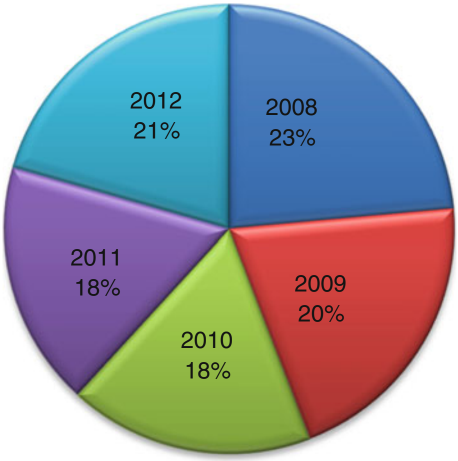



**Fig. 5** Overview of work carried out on CAPP in last five years based on established methods. **a** feature based technologies, **b** knowledge based systems, **c** artificial neural networks, **d** genetic algorithms, **e** fuzzy set theory and fuzzy logic, **f** petri nets, **g** agent based technologies, **h** internet based technologies, **i** STEP-compliant method, **j** functional blocks

**Fig. 6** Overview of work carried out on CAPP in last five years




## 4 Conclusion

As CAPP plays an important role in the Computer Integrated Manufacturing (CIM) systems and it eliminates the gap between CAD and CAM integration. Therefore the need of CAPP is always there in CIM systems. Figure 5 clearly shows the increase and decrease of CAPP work based on stated methods during the last 5 years. From that graphical representation we can easily identify the current trend of CAPP work and the overview of CAPP work carried out from 2008 to 2012 based on this research. Whereas Fig. 6 shows the, percentage of work carried out on CAPP field from 2008 to 2012 based on stated methods.

In this article an attempt is made to provide a review of work carried out on CAPP based on features, knowledge, artificial neural networks, Genetic Algorithms (GA), fuzzy set theory and fuzzy logic, Petri Nets (PN), agent, internet, STandard for the Exchange of Product data (STEP) compliant method, and Functional Blocks (FB) technologies in past and present. From this survey it's founded that most of the CAPP work carried out on machining/manufacturing to resolve the problems/issues of operation, tool and machine selection and sequencing, features extraction, reorganization, interpretation and representation, knowledge integration, representation, acquisition and sharing, setup planning, energy consumption, linear and non linear planning, integration of product, and manufacturing data etc.

## 5 Future Suggestion

Nowadays manufacturing world is moving toward more advance, intelligent, and flexibility so it demands for advance and intelligent CAPP, and due to the global environmental changes environmental issues also becomes an important factor for industry to consider. In near future the key areas of research for CAPP must be toward green manufacturing environment, energy consumption, development of biological applications, nontraditional manufacturing process, extrusion process, sheet metal fabrication, rapid prototyping process, micro manufacturing, nano-manufacturing, welding process, and circuit board processes.

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## References

1. Niebel BW (1965) Mechanized process selection for planning new designs, ASME paper, vol 737
2. Harold JS (1984) Computer-aided process planning: past, present and future. Int J Prod Res 22:253–266
3. Ham I, Lu SCY (1988) Computer-aided process planning: the present and the future. CIRP Ann Manuf Technol 37:591–601
4. Alting L, Zhang H (1989) Computer aided process planning: the state-of-the-art survey. Int J Prod Res 27:553–585
5. Gouda S, Taraman K (1989) CAPP: AAST, present and future. Soc Manuf Eng
6. Elmaraghy HA (1993) Evolution and future perspectives of CAPP. CIRP Ann Manuf Technol 42:739–751
7. Eversheim W, Schneewind J (1993) Computer-aided process planning—state of the art and future development. Robot Comput Integr Manuf 10:65–70
8. Kamrani AK, Sferro P, Handelman J (1995) Critical issues in design and evaluation of computer aided process planing systems. Comput Ind Eng 29:619–623
9. Leung HC (1996) Annotated bibliography on computer-aided process planning. Int J Adv Manuf Technol 12:309–329
10. Cay F, Chassapis C (1997) An IT view on perspectives of computer aided process planning research. Comput Ind 34:307–337

11. Marri H, Gunasekaran A, Grieve R (1998) Computer-aided process planning: a state of art. Int J Adv Manuf Technol 14:261–268
12. Xu X, Wang L, Newman ST (2011) Computer-aided process planning–a critical review of recent developments and future trends. Int J Comput Integr Manuf 24:1–31
13. Hu C, Li Z, Zheng L, Li N, Wen P (2008) An XML-based implementation of manufacturing route sheet documents for context-sensitive and web-based process planning. Int J Comput Integr Manuf 21:647–656
14. Alvares AJ, Ferreira JCE (2008) A system for the design and manufacture of feature-based parts through the Internet. Int J Adv Manuf Technol 35:646–664
15. Álvares AJ, Ferreira JCE, Lorenzo RM (2008) An integrated web-based CAD/CAPP/CAM system for the remote design and manufacture of feature-based cylindrical parts. J Intell Manuf 19:643–659
16. Sunil V, Pande S (2008) Automatic recognition of machining features using artificial neural networks. Int J Adv Manuf Technol 41:932–947
17. Babic B, Nesic N, Miljkovic Z (2008) A review of automated feature recognition with rule-based pattern recognition. Comput Ind 59:321–337
18. Yifei T, Dongbo L, Changbo L, Minjian Y (2008) A feature-extraction-based process-planning system. Int J Adv Manuf Technol 38:1192–1200
19. Hebbal S, Mehta N (2008) Setup planning for machining the features of prismatic parts. Int J Prod Res 46:3241–3257
20. Zhang FP (2008) Research on graph theory-based manufacturing setup planning. J Adv Manuf Syst 7:313–318
21. Rameshbabu V, Shunmugam M (2009) Hybrid feature recognition method for setup planning from STEP AP-203. Robot Comput Integr Manuf 25:393–408
22. Yusof Y, Newman S, Nassehi A, Case K (2009) Interoperable CNC system for turning operations. In: Proceedings of world academy of science, engineering and technology, pp 941–947
23. Zhao YF, Habeeb S, Xu X (2009) Research into integrated design and manufacturing based on STEP. Int J Adv Manuf Technol 44:606–624
24. Agrawal R, Shukla S, Kumar S, Tiwari M (2009) Multi-agent system for distributed computer-aided process planning problem in e-manufacturing environment. Int J Adv Manuf Technol 44:579–594
25. Salehi M, Tavakkoli-Moghaddam R (2009) Application of genetic algorithm to computer-aided process planning in preliminary and detailed planning. Eng Appl Artif Intell 22:1179–1187
26. Jin K, Zhang HC, Balasubramaniam P, Nage S (2009) A multiple objective optimization model for environmental benign process planning. In: Industrial engineering and engineering management IE&EM'09 16th international conference on, pp 869–873
27. Xu H, Li D (2009) Modelling of process parameter selection with mathematical logic for process planning. Robot Comput Integr Manuf 25:529–535
28. Cai N, Wang L, Feng HY (2009) GA-based adaptive setup planning toward process planning and scheduling integration. Int J Prod Res 47:2745–2766
29. Newman S, Nassehi A, Imani-Asrai R, Dhokia V (2010) Energy efficient process planning for CNC machining. CIRP J Manuf Sci Technol
30. Abu R, Md Tap M (2010) Attribute based feature recognition for machining features. Jurnal Teknologi 46:87–103
31. Zhang S, Shi Y, Fan H, Huang R, Cao J (2010) Serial 3D model reconstruction for machining evolution of rotational parts by merging semantic and graphic process planning information. Comput Aided Des 42:781–794
32. Chen HC, Yau HT, Lin CC (2010) Computer-aided process planning for NC tool path generation of complex shoe molds. Int J Adv Manuf Technol 58:607–619
33. Marchetta MG, Forradellas RQ (2010) An artificial intelligence planning approach to manufacturing feature recognition. Comput Aided Des 42:248–256

34. Chen W, Xie S, Zeng F, Li B (2010) A new process knowledge representation approach using parameter flow chart. Comput Ind 62:9–22
35. Li P, Hu T, Zhang C (2010) STEP-NC compliant intelligent process planning module: architecture and knowledge base. Procedia Eng 15:834–839
36. Helgoson M, Kalhori V (2010) A conceptual model for knowledge integration in process planning. Procedia CIRP 3:573–578
37. Wang J, Zhang HL, Su ZY (2011) Manufacturing knowledge modelling based on artificial neural network for intelligent CAPP. Appl Mech Mater 127:310–315
38. Lian KL, Zhang CY, Gao L, Xu ST, Sun Y (2011) A cooperative simulated annealing algorithm for the optimization of process planning. Adv Mater Res 181:489–494
39. Lian K, Zhang C, Shao X, Gao L (2011) Optimization of process planning with various flexibilities using an imperialist competitive algorithm. Int J Adv Manuf Technol 59:815–828
40. Lian KL, Zhang CY, Shao XY, Zeng YH (2011) A multi-dimensional tabu search algorithm for the optimization of process planning. Sci Chin Technol Sci, pp 1–9
41. Garcia F, Lanz M, Jarvenpaa E, Tuokko R (2011) Process planning based on feature recognition method. In: Assembly and manufacturing (ISAM), 2011 IEEE international Symposium on, pp 1–5
42. Taiyong LWW (2011) Optimization of cutting parameters based on Pareto genetic algorithm. Trans Chin Soc Agric Mach 2:046
43. Oba T, Nakamoto K, Ishida T, Takeuchi Y (2011) Development of CAPP/CAM system for 5-axis control machining-application to machining 3-dimensional complicated tiny part. J Jpn Soc Precis Eng 76:90–95
44. Zhang X, Nassehi A, Newman ST (2011) Process comprehension for interoperable CNC manufacturing. In: Computer science and automation engineering (CSAE), 2011 IEEE international conference on, pp 225–229
45. Stryczek R (2011) A hybrid approach for manufacturability analysis. Adv Manuf Sci Technol 35:55–70
46. Wang L, Adamson G, Holm M, Moore P (2012) A review of function blocks for process planning and control of manufacturing equipment. J Manuf Syst
47. Jin G, Li W, Gao L (2012) An adaptive process planning approach of rapid prototyping and manufacturing. Robot Comput Integr Manuf 29:23–38
48. Ouyang HB, Shen B (2012) STEP-NC oriented process planning optimization based on hybrid genetic algorithm. Comput Integr Manuf Syst 18:66–75
49. Fan SC, Wang JF (2012) Multi-objective decision and optimization of process routing based on genetic algorithm (GA). Adv Mater Res 457:1494–1498
50. Vang TA, Jiang PY (2012) Using ontology and rule-based reasoning for supporting automatic process plan for milling prismatic parts. Appl Mech Mater 127:531–536
51. Liu L, Qiao LH (2012) Operation sequencing using genetic algorithm. Appl Mech Mater 163:57–61
52. Yu H, Xing J, Wang X (2012) Research on CAPP method for rotational parts based on case retrieval. Machinery 1:014
53. Zhang X, Nassehi A, Dhokia V, Newman S (2012) Refining process logic from CNC part programmes for integrated STEP-NC compliant manufacturing of prismatic parts, enabling manufacturing competitiveness and economic sustainability, pp 333–338

# Interoperable Data Provisioning and Discovery for Virtual Factories

**Atanas Manafov, Georgi Pavlov, Velimir Manafov and Irena Pavlova**

**Abstract** New generations of collaboration software services supporting Networked Enterprises and Virtual Factories, based on the easily accessible communication facilities, are developed in order to foster the globalization of the business. Still the Interoperability Problem appears to be a bottleneck for their effective functioning. The solution of the problem is of a major importance for their wide adoption. The paper is provides an insight of how the problem was examined and addressed in the project ADVENTURE's Data Provisioning and Discovery services. This work is part of the FP7 EU project ADVENTURE (ADaptive Virtual ENterprise ManufacTURing Environment).

## 1 Introduction

Nowadays businesses more and more intensively use Internet in their attempts to successfully participate in the global market. Utilization of conventional Internet services like: Searching for potential customers and partners; Offering (advertising) products and services on websites; Selling and purchasing products and services in on-line shops; Performing negotiations via email; Exchanging business documents via email, has become an usual practice. Because of their widespread application nobody gains an advantage from exploiting these conventional Internet services. Entrepreneurs strive to overcome this uniformity by introducing more sophisticated means for doing business like Virtual Factories and Networked Enterprises that are now intensively developing in order to foster the business competitiveness, especially for SMEs.

Furthermore, the conventional Internet services have now to a great extent exhausted their exploitation potential and in many cases appear ineffective to bring

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economic value. These services are currently manually exploitable that limits the efficiency of the information processing services used by enterprises for automation of their business. The main problem is like the Tower-of-Babel-Problem, which means that the various services used by different business parties do not understand each other and they need human intervention to help them communicate properly. This problem is known as Interoperability Problem.

The emerging Virtual Factories and Networked Enterprises are expected to increase competitiveness by providing more effective services for supporting the collaboration between different businesses. The current solutions in the area however, are limited in scope at organisational and technological level. They still face obstacles in their attempts to efficiently involve enterprises in the global cross-company distributed business processes [1, 2]. The main barrier in utilizing new services remains the Interoperability Problem and as a consequence—the lack of appropriate means for provisioning and processing real-time information, needed for the efficient involvement of enterprises in global cross-company distributed business processes. The provisioned services do not adequately address the requirements for reliable end-to-end cross partner interoperability and for seamless fuse of dispersed information assets such as processes, data, statuses, and other resources. As a result, small enterprises are not able to influence global business processes neither with passive participation nor with active entrepreneurship.

There is a need for additional efforts in order to cope with the demand for improving the manufacturing services efficiency in the above context. In this regard, the paper is introducing an innovative approach for Data Provisioning and Discovery (DPD) that will seamlessly support the vision of "plug-and-play" Virtual Factories based on cross-organizational interoperability. This work is part of the project ADVENTURE (ADaptive Virtual ENterprise ManufacTURing Environment) that is developed under the "Factories of the Future" objective of the FP7 EU. The project aims at developing an end-to-end IT solution in order to achieve higher management efficiency and foster innovation in networked operations related to manufacturing, as well as to support the emergence of "smarter" Virtual Factories. The project is in its early implementation phase.

The paper is structured as follows: In the second section, we present an overview of the main challenges in contemporary Virtual Factory; In Sect. 3, we present the role of DPD in ADVENTURE's lifecycle model; In Sect. 4 we analyze the interoperability concerns in Virtual Factories and the ADVENTURE approach to address them; In Sect. 5 we outline the technology choices in DPD that support the approach at addressing interoperability issues; Sect. 6 concludes the presentation by exploring the clear advantages the ADVENTURE DPD solution on supporting the ad-hoc involvement of SMEs in Virtual Factories and also in enabling these SMEs to manage such Virtual Factories in the role of entrepreneurs.

## 2 Challenges of Virtual Factories

Manufacturing usually goes through a distributed process, where many different parties provide various products, raw materials, and business services for assembling a single final product. In fact, a number of partners are typically integrated into manufacturing process forming the so-called Virtual Factory.

There are a lot of different definitions of the term *Virtual Factory*, reflecting the different aspects of distributed manufacturing. Virtual Factory is defined in [3] as an integrated simulation model of major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability. It seeks to go beyond the typical modeling of one sub-system at a time, such as the manufacturing model, the business process model and/or the communication network model developed individually and in isolation.

A great number of other definitions of close or related terms Virtual Enterprise, Network Enterprise, Virtual Network, and Virtual Factory are explored in [4]. The resemblance of these concepts under the umbrella designation of Virtual Enterprise is in the distributed operating and the common goal to operate efficiently and flexibly through cooperation.

In this paper, we will refer to the following definition of a Virtual Factory that has a comprehensive emphasize on the key characteristics of contemporary cross-organizational processes and reaches out to capture the motivation, the technology, the autonomy, the process, and the temporal aspect of such endeavors:

***Virtual Factory*** is a temporary alliance of factories from multiple organizations, managed by a distributed, integrated, computer-based system that interfaces with all systems (of the partnering organizations) necessary for the design, production, and delivery of a product [5].

The general requirements emerging from manufacturing companies in the context of a Virtual Factory are at minimum the ability to create flexible manufacturing processes that are controllable and manageable and thus sustain in global, highly competitive markets [6]. A variety of challenges arise with regards to support of such processes. For example:

- Cross-organizational interoperability on different levels that is realized without compromising the required dynamism in the formation and execution of Virtual Factory processes and their efficiency.
- Adequate support for automated discovery and seamless induction of appropriate business partners and formation of partner ecosystems.
- Monitoring and sharing of real-time data, needed to assess the risks and support decisions in distributed manufacturing.
- High adaptation capabilities of a running Virtual Factory to changes in a highly dynamic environment.
- Despite the efforts, the existing solutions have limitations like:
- Limited integration with information sources (e.g., conventional Internet services, ERP systems).
- Lack of interoperability between internal and cross-organizational processes.

〉 Limited interoperability of systems/data across different factories.

One of the biggest issues in that domain is the interoperability and its automation. It is a particularly limiting factor for organizations with limited resources like SMEs for addressing such a complex issue, especially when it is not in their core business. That results in operational inflexibility and inability to react to a fast changing economic and technological environment and ultimately has a detrimental effect on their business.

In addition, the seamless inclusion of enterprises (especially SMEs) is still a big challenge. They often lack means or resources to advertise their capabilities, particularly in their dynamic aspect (e.g., current manufacturing capacity), in a manner that would be acceptable for a Virtual Factory dynamic process [6]. This reduces their chances to be concurrently selected for participating in large cross-organisational processes and both they and their potential partners miss business opportunities. Overcoming and solving these problems bears the potential to support in particular SMEs, which usually neither have the capabilities to control the whole manufacturing lifecycle, nor the market power to enforce their own interfaces and manufacturing standards, to reduce cost, to increase competitiveness, and to generally improve production processes with better insight, predictability, and automation.

## 3 Data Provisioning and Discovery in ADVENTURE Virtual Factory Model

Considering the maturing of technologies and the economic conditions, ADVENTURE introduces a new Virtual Factory model—the ADVENTURE Virtual Factory (*Virtual Factory*). The *Virtual Factory* addresses the competitiveness of businesses in the highly dynamic world where it is vital to be fast in discovering new and responding to emerging business opportunities efficiently and flexibly as well as in adapting to changing operational conditions. The model involves steps of joining the ADVENTURE, searching for appropriate business services, plugging, and playing the *Virtual Factory*.

The Virtual Factory lifecycle requires appropriate technology for data modeling and management that can underpin the phases of formation and operation of the alliance. Since many different independent parties are involved in the virtual manufacturing, that technology is challenged with various interoperability concerns. Research and development of the methods for efficient information definition and maintenance for supporting *Virtual Factory* is of major importance and constitutes a substantial part of the ADVENTURE project. The ADVENTURE technical component that addresses these requirements is called Data Provisioning and Discovery (DPD).

The first step in a Virtual Factory lifecycle model is the *Join* phase. The DPD component defines formal, structured, semantic-driven descriptions of factories, the *Resources* they affect and use, their demands and offers in terms of semantically enriched business services, called *ADVENTURE Services (Services)* and properties, as well as view on dynamic and historical related data. Examples of such properties are skills, locations, standards, regulations, capabilities, current capacities, availabilities, cost, delivery time, carbon footprint, etc. These descriptions are provisioned through the ADVENTURE semantic infrastructure and can be correspondingly found and compared and eventually involved into production processes by the interested parties at the second step—searching. This will ensure that factories can interoperate at technical level and that they can be involved in complex processes based on their abilities to offer competitive services in the next steps of plug and play.

In the second step of the model—searching the ADVENTURE (Searching)—the provisioned Services can be correspondingly discovered and compared and (eventually) chosen and involved into manufacturing processes. DPD provides the necessary interfaces to perform the queries and form the recommendations.

The core of the Virtual Factory is the ADVENTURE Smart Process (Process), which integrates reusable smaller Processes/Services, provided by the Members. The Process is defined by the ADVENTURE Broker (Broker) that plays a central role as entrepreneur and manages the entire Process. The Broker designs the Process defining every step/activity. Further, through the ADVENTURE DPD, the Broker can semantically search and select a number of Members as suitable to participate with their Services in the different steps of the Process that best match the criteria for the concrete step/activity as defined by the Broker.

The *Broker* is able to simulate the *Process* in order to forecast the potential outcome for the worst case, based on criteria like costs, delivery time, carbon footprint, etc. The average potential outcome based on the selected factories can also be calculated, as well as the outcome of adding new factories or setting specific constraints to the process.

Once appropriate *Services* are assigned i.e., pluged to the corresponding steps, the *Process* can be executed i.e., played. A step-by-step execution is performed, tracking on real-time monitoring. At the end of each step, an automatic decision is taken about the execution of the next step in order to optimize the requirements and metrics of the process. This adaptive execution allows for considering unexpected events such as delays in the manufacturing process, strikes, delays in the transportation, etc. Based on the current condition of the process, the most suitable business services will be used for the next step. This can also help to achieve load balancing and therefore to reach a higher stability and compliance of the overall process.

On Fig. 1 the overall enterprise model is presented with the respective steps that constitute the ADVENTURE lifecycle [5]. The corresponding stakeholders and results are also depicted at each step.

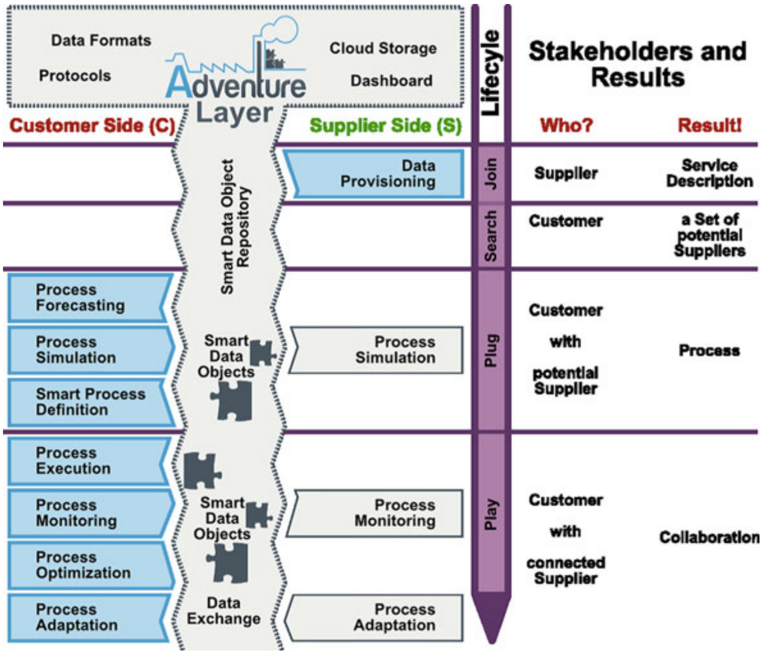


**Fig. 1** Machining features and their tool access directions

## 4 Interoperability Concerns in Data Provisioning and Discovery

ADVENTURE presumes many different enterprises to collaborate intensively through *Virtual Factories* in order to achieve higher manufacturing efficiency. Ensuring effective information exchange for seamless collaboration between diverse enterprises is an obligation of the DPD component. The main problem to be resolved when implementing the DPD functionality is the Interoperability Problem.

*Interoperability* is the ability of services to work with other services, which presumes the information exchange between services without special effort on behalf of the human user. As the concept of “The network is the computer” becomes more and more a reality, *Interoperability* becomes a quality of the highest importance for services. European Commission Interchange of Data between Administrations Community Programme (IDA) [7] recommends that interoperability-oriented systems should support three dimensions of *Interoperability* i.e., technical, semantic, and organisational interoperability. The structure of the problem domain and the challenges are addressed in the IDEAS road-mapping project which is followed by the ATHENA IP [8] and INTEROP NOE [9]. The implementation of *Interoperability* can be based on a number of existing standards, such as the Universal Description Discovery and Integration (UDDI) [10] and eBusiness XML (ebXML) [11] that enable parties to provide business information within the Web. Nowadays the integration of information from heterogeneous origins can be achieved by making use of standards like the Resource Description Framework (RDF) [12] as a data model and the Web Ontology Language (OWL) [13] as a description language, together with powerful engines which can be used to search, to map, and to combine heterogeneous business information [12]. However, it must also be clearly recognized that currently the information is maintained mainly in the form of "run-of-the-mill" relational models and XML schemas.

## *4.1 Semantic Interoperability and Ontologies*

Semantics concerns the study of meanings. In the world of services *Semantics* usually is represented by a number of concepts, constituting the knowledge in a domain area. *Semantic Interoperability* [15] indicates that the meaning of data can be comprehended unambiguously by both humans and services, and that information can be processed in a meaningful way. *Semantic Integration* is the mean to achieve *Semantic Interoperability* and can be considered as a subset of information integration, which includes data access, aggregation, correlation, and transformation. The corresponding interoperability-oriented architecture of services aims at connecting heterogeneous business information origins making use of semantically enriched descriptions in order to achieve logical interoperability between them.

*Ontology* arranges the number of concepts, representing the knowledge in a domain area, in a structure that is suitable and understandable both for human and services. *Ontologies* have become widely used instrument to capture, maintain, and provide the form and the content of the knowledge for the purposes of information exchange and sharing in a certain domain area. Ontology construction, mapping, and evolution are topics of major importance. In particular, in the last years, several EU projects have specifically focused their work in ontology-related matters (the most significant of them is NeOn [16]). When exchanging and processing data in a closed domain area, *Ontologies* are the most convenient instrument for annotating these data with the needed meaning and thus, turning these data into semantically interoperable information.

Unfortunately in the real world and especially in today's globalization, the information exchange in a closed domain area, where *Ontologies* are entirely useful, is uncommon and occasional case. The modern systems/services provide unlimited technical possibilities for communication and as a consequence the information flows all over the world through different domain areas, skipping any kind of boundaries. *Ontologies* are not able to provide the diversity of knowledge constructs, needed to cover the means of every distinct data flow that goes beyond the boundary of a concrete domain. Moreover, in many real cases even from a single domain area, *Ontologies* do not satisfy the specific requirements for appropriate knowledge representation. The main problem is that every *Ontology* represents the domain knowledge from a separate point of view. Thus, we cannot expect a single *Ontology* (no matter how sophisticated it is constructed) to cover the needed *Semantics* in the area of interest that in our case is the *Interoperability* of services in *Virtual Factories*.

## 4.2 Addressing Interoperability in ADVENTURE DPD

The approach for developing light semantic structures based on different semantic origins such as already well defined and widespread used *Ontologies* and classifications, as well as other already in use ADVENTURE semantic construction, reflecting the diversity of different domain areas. A market-driven promotion of *Semantics* seems (like the one employed in project STASIS [17]) very attractive with its natural view on the possibilities every single business party, no matter how big it is, to participate in the global electronic market not only as a passive user, but as an active provider of *Semantics*. This philosophy is fully in line with the entire ADVENTURE intention to make it possible small enterprises to influence the global business via *Virtual Factories*.

ADVENTURE DPD aims at creating reusable semantic assets for a diversity of ADVENTURE (and non-ADVENTURE) applications in different industrial sectors for different kinds of users/entrepreneurs as well as reusable for other kind of business applications. The intention of this development investment is also to improve the quality of the semantic assets, to foster a large community around them, and to ensure critical mass of ADVENTURE adopters. Thus ADVENTURE DPD will contribute in developing global semantic assets knowledge base through the SEMIC.EU/Joinup initiative and other similar common activities.

The *Semantics* to be used in the ADVENTURE infrastructure has several different aspects. It describes both the ADVENTURE business entity (*Member*) providing their *Services* the operational parameters of the offered services. It describes also the operational environment where the ADVENTURE *Processes* take place. All of these aspects should be captured in the ADVENTURE semantic structures and provided by the ADVENTURE platforms' *Data Provisioning and Discovery* component.

The solution for employment of *Semantics* in ADVENTURE presumes semantic constructions on three levels:

〉 *ADVENTURE upper semantic constructions*. This level introduces upper ADVENTURE *Semantics*, presenting concepts that are domain neutral. As an example *semantic constructions* of this kind can be the Business Process Modelling Ontology [18, 19] that defines the core concepts in a *Process* model and can be used to describe an ADVENTURE blueprint, smart process in *Virtual Factory*. All ADVENTURE tools share and understand the concepts in a semantic cluster. Other prominent example of *upper semantic constructions* is Good Relations ontology, which can be used as a lightweight semantics to describe *Members* and their *Services*.

〉 *Domain semantic constructions*. In the real business world the semantics of an entrepreneur often includes concepts from different domain areas. For example, if the entrepreneur produces mixing machines for making bread, he needs a concept “Bolt” (from the mechanical industry domain area). But they probably also need the concept “Nutrient” (from the food domain area). This small example shows that the relation between an entrepreneur business and the ontologies used to describe the business is one-to-many. Within each industry domain there is a defragmentation of the ontologies in use. Where possible, *semantic constructions* per domain will be introduced to reduce the opportunities for “knowledge silos”. A prominent, practical mean to significantly improve the inter- and intra-domain concepts associations is Linked Data [20].

〉 *Broker semantic constructions*. This level reflects the entrepreneur’s internal, business specific *Semantics*. Large enterprises often have developed internal knowledge management through respective own ontologies. SMEs on the other hand rarely invest into this. However, in order to be able to include SMEs into the marketplace for business opportunities offered by ADVENTURE, they need to be semantically described as well. This means that their internal *Semantics* needs to be mapped to the *Semantics* that can be resolved by the ADVENTURE mechanisms. Again a prominent inclusion mechanism here would be Linked Data but unfortunately there seem to be little or no origins for linking data via Linked Data mechanism exposed on the Internet for the manufacturing domain. Thus ADVENTURE might be a pioneer in this.

## 5 Data Provisioning and Discovery in ADVENTURE Virtual Factory

The state-of-the-art and requirements analysis performed in the initial stages of the ADVENTURE DPD project elicited several related key data model concepts that sufficiently describe an ADVENTURE Virtual Factory. These are the *Member Organizations*, *Services*, *Process Models* and *Resources*. Collectively they provide a complete basis to model and explore Virtual Factories from different perspectives and support ADVENTURE’s holistic view on the problem domain. There are a number of other concepts that ‘glue’ them into a coherent domain model (as described on the diagram in Fig. 1) and provide more detail and aspects. These details as well as many of the concrete properties in the domain model are non-normative, leaving it open to each concrete ADVENTURE deployment to adapt it to their own needs.

The domain model supported by DPD (Fig. 2) is very close to the domain models elaborated in focused activities like SEAMLESS [21] and NEFFICS [22] projects. This confirms its validity as generic model that solves organizational interoperability concerns and requires good extensibility options from the modeling technologies that will be employed in order to ensure effective and efficient

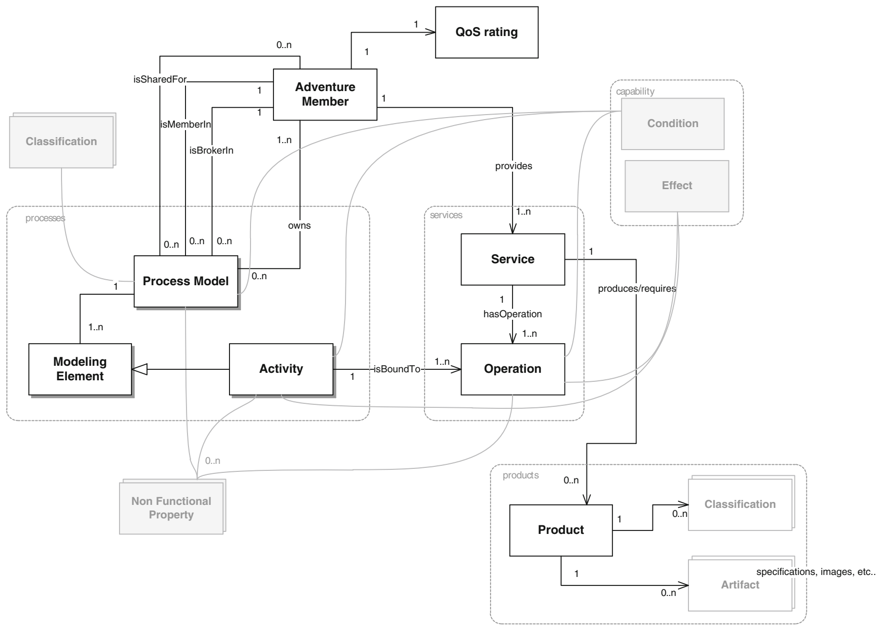


**Fig. 2** ADVENTURE DPD domain model

tailoring to specific domains and needs. Another relevant model is developed by the VFF: "Virtual Factory Framework" project "Error! Reference source not found". While there are similarities between the approaches, DPD seeks for minimalistic modeling driven by the "Factory-as-a-Service" concept considering both business and operational characteristics. Further, DPD targets at mostly reusing existing and well established ontologies and classifications, building on the openness, and the extensibility provided by the LinkedData approach.

From the analysis performed for data models in the related R&D domain it became apparent that Linked USDL, GoodRelations, and Schema.org complement each other nicely to provide a good coverage for most of the DPD domain model concepts and are supported by the technologies that will ensure extensibility and openness, all of which backed up by live communities and large industrial and organizational entities. Since Linked USDL provided the most comprehensive model of the three, it was selected to serve as basis and will be complemented by the rest. The core model is further enriched by references to external established classifications like NACE or UNSPC.

However, it also became apparent that none of the reviewed technologies covers completely the DPD domain model and requirements. For example, organization's processes were barely considered and there's also no applicable ontology for manufacturing task assignments properties like carbon footprint, task durations, etc. Therefore where Linked USDL, GoodRelations, and Schema.org (or others) do not cover the ADVENTURE domain model and no other external and compliant model is available to fill the gap, own (ADVENTURE) vocabularies/concepts will be contributed accordingly.

The DPD module relies on RDF to represent the data model technology due to the fact that most of the classification systems, taxonomies, and ontologies that would be of interest to ADVENTURE (NACE, UNSPCS, e@class, etc.) are or can be provided as RDF and will naturally form a common information space with the core DPD domain model. In addition RDF provides the excellent, non-disruptive extensibility mechanism.

Recognizing the reality that the majority of the data around is managed in relational databases and either converted to RDF and managed via SPARQL, or more recently published on the web via the OData protocol, and in an attempt to reach for maximum adoption DPD is designed to support also OData access to a relational model and semi-structured data models like JSON and XML.

DPD is designed as a service, with SPARQL and OData interfaces as well as a simplified own REST API. It features a user interface that exemplifies how the services can be consumed, lowers the adoption barrier with a ready to use human-oriented interface and is designed according the same guidelines for lightweight, web citizenship. The SPARQL service endpoint of the DPD service is a generic, machine interpretable interface to the managed metadata. Using the SPARQL 1.1 Query protocol gives opportunities to build very complex queries and derive information beyond the obvious and consequently construct highly useful decision-support, autonomous applications. In the case of the DPD use cases this will constitute the backbone of important features like the recommendations mechanism for finding suitable partners for an activity.

In addition to using popular, contemporary technologies like jQuery, it will take advantage of the emerging HTML5 Microdata standard, and in conjunction with web vocabularies like schema.org will enrich semantically the UI presentation.

## 6 Industrial Applicability, Future Work, and Conclusions

The ADVENTURE Data Provisioning and Discovery (DPD) introduces a customizable and extensible model for describing ADVENTURE members and their ADVENTURE-related assets (e.g., services) into a common, coherent information space, supporting the other ADVENTURE tools in their information retrieval needs. It provides tools for provisioning of new members information into the system during their join phase and tools for discovery of existing ADVENTURE members and services matching selection criteria during the play phase or to find potential partners.

The scientific contribution of DPD is in building on concepts and methods from the field of Service Oriented Computing and Semantics, benefiting from the progress that has been made in these domains during the last years, and advancing these concepts and methods in direction of their efficient application in supporting the virtual factories dynamic establishment. DPD uses the most advanced state of-the-art in collaborative organizations modeling and presents an innovative general-purpose SaaS (Software as a Service) model management implementation. It is designed using edge technologies for maximum effect and adoption. The component will serve all requirements defined by ADVENTURE and also has the ambitious goal to provide a valuable contribution that spans way beyond the ADVENTURE project boundaries and lifetime, and to fill the gap that became apparent during the state-of-the-art analysis. Within the above context the main scientific and technological contributions can be summarized as follows:

The DPD model is designed, based on recent research and development in the field such as Linked USDL Core ontology, Schema.org, and GoodRelations and seeks to combine those for best results along with own contributions. The model also uses established taxonomies and classifications like UNSPSC, NACE, or ISICv4 (non-normative list) and are generally open which one to select. Technically, the model is serialized in the highly extensible RDF technology that underpins currently the efforts for a global Web of data.

The DPD software is designed to provide access to the model via well-defined protocols and most of all with wide adoption in mind. It exposes a set of popular REST-oriented service interfaces that implement the most popular protocols in the field—SPARQL and OData, as well as a lightweight UI. The software is designed for cloud platforms (i.e., delivered as SaaS) primarily, but can also be adopted as a tightly integrated component in a system.

This approach ensures the delivery of a highly consumable software solution for modeling collaborative organizations that will create even more business opportunities than ADVENTURE itself when seen as standalone Web datasource.

As planned future work and in order to prove its viability and applicability the ADVENTURE DPD solution is going to be validated through a real industrial case study in the automotive domain. The validation will occur with real data for hundreds of organizations of different magnitude and their operations, originating from a genuine supply chain ecosystem. Thus, the DPD solution will prove its effectiveness in the establishment, partner profiles management, run-time adaptation, and interoperability of dynamic manufacturing processes in automotive virtual factories.

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## References

1. Mohr J, Spekman R (1994) Characteristics of partnership success: partnership attributes, communication behavior, and conflict resolution techniques. Strateg Manag J 15:135–152
2. Abbott P, Zheng Y, Du R (2013) Innovation through collaborative partnerships: creating the MSN news for iPad app at Vance info technologies. J Inf Technol Teach Cases, Online publication 15 Jan 2013
3. Jain S, Choong NF, Aye KM, Luo M (2001) Virtual factory: an integrated approach to manufacturing systems modeling. Int J Oper Prod Manage 21(5/6):594–608

4. Cunha MMC, Putnik GD (2006) Agile virtual enterprises. Implementation and management support. Idea Group Inc, Hershey
5. ADVENTURE (2011) Project vision consensus, ADVENTURE, FP7 FoF—Contract N 285220, Deliverable D2.1
6. Bititci U, Maguire C, Gregory I (2012) Adaptive capability—a must for manufacturing SMEs of the Future http://ebookbrowse.com/bititci-maguire-gregory-adaptive-capability-pdf-d136477043
7. Enterprise Interoperability Research Roadmap (European Commission DG INFSO, July 2006)
8. ATHENA FP6 Project http://www.fines-cluster.eu/fines/jm/FInES-Private-Information/athena.html
9. INTEROP (2007) Enterprise interoperability-framework and knowledge corpus, Final report, INTEROP NoE, FP6—Contract n 508011, Deliverable DI.3, 21st May 2007
10. UDDI v3 http://uddi.org/pubs/uddi_v3.htm
11. ebXML http://www.ebxml.org/
12. RDF http://www.w3.org/RDF/
13. OWL http://www.w3.org/TR/owl2-overview/
14. Pavlov G (2009) Repository infrastructure for community-driven ontologies management support. In: Proceedings of the 1st international conference software service and semantic technologies (s3t) Sofia,pp 28–29, Oct 2009
15. Pedrinaci C, Domingue J (2010) Web services are dead. long live internet services, SOA4All White Paper http://soa4all.eu/file-upload.html?func=startdown&id=217
16. NeOn EU Project http://www.neon-project.org/
17. STASIS (2007) Vision and technical consensus statement, FP6-2005-IST-5-034980, Deliverable D2.1
18. Cabral L, Norton B, Domingue J (2009) The business process modelling ontology. In: Proceedings of the 4th international workshop on semantic business process management, June 01 2009
19. Business Process Modelling Ontology http://www.ip-super.org/ontologies/process/bpmo/v2.0
20. Linked Open Data http://linkeddata.org/
21. SEAMLESS (2007) Ontology and multilingual support technical specification, SEAMLESS Project FP6-2004-IST-4-026476, Deliverable D2.1.2
22. NEFFICS http://neffics.eu/
23. VFF http://www.vff-project.eu

# Designing of Cloud-Based Virtual Factory Information System

**Yuqiuge Hao, Rafael Karbowski, Ahm Shamsuzzoha and Petri Helo**

**Abstract** In the manufacturing industry, customers' requirements vary all the time, a way that to increase capacity and add capabilities of factories without investing in new infrastructure becomes essential. An advanced information management system to share valuable information and knowledge among collaborative factories is demanded. The concept of "Cloud" can encompasses subscription-based or pay-per-use service that, in real time over the Internet, extends factories existing capabilities. Cloud Storage can be used to share data is a flexible manner. With such perspective, a cloud-based Virtual Factory Information System (CloudVFIS) design is proposed in this research. This new system will provide a concrete tool for SMEs (Small and Medium Enterprises) to realize the integration of factories based on the idea of Virtual Factory. In this paper, the Cloud VFIS architectural framework and the cloud storage in manufacturing management are illustrated.

## 1 Introduction

Under the pressures of global competition, there is a need for highly flexible business relationship between enterprises. Many enterprises concentrate on their core competencies while adopt themselves to participate in emerging interenterprise formations following the virtual enterprise (VE) paradigm [1]. VE is a form that offers high flexibility, agility, and resilience for enterprises to survive and prosper in the globalized economy.

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Although the concept of VE has already existed over decades, there is a lack of efficient IT systems to support its inherent functionalities. Many researchers proposed different approaches to establish VE, but the challenges with VE are flexibility, adaptability, and agility [2]. Especially for Small and Medium sized manufacturing companies, they are lack of efficient communication when cooperate with other enterprises. Therefore, it is very necessary to find a solution to support and improve the VE activities.

Cloud computing is a new overloaded IT term. With the advent of cloud computing, more and more business are taking advantages of cloud computing. The flexibility of cloud computing makes it easier for companies to scale their services according to the user demands. One major characteristics of cloud computing is load balancing, which means the computation loads get balanced on-the-fly as the number of requests increase or decrease [3]. This load balancing service maximizes throughput, minimizes response time, and avoid overload, therefore it ensures the system performance [3].

In the business environment, our concern is: how could the concepts of Virtual Enterprise and Cloud Computing be deployed and integrated? A new strategy for Cloud based Virtual Factory Information System (VFIS) design is proposed in this research. This CloudVFIS design aims at setting up process-based collaboration network, and leveraging the information exchange between different manufactories by utilizing different Cloud Storages. The Storage provided by cloud model is named as Storage as a Service [4]. There are several different types of Cloud Storage Services. The major differences among these different Cloud Storages are how the customer uses the storages and how the users access the storages [3]. The main focus in this paper is to introduce a new methodology to use Cloud Storage to support the Cloud based Virtual Factory Information System and to support the virtual factory activities.

In this paper, CloudVFIS reduces the limits of collaboration between SMEs in the manufacturing domain. This is performed by providing companies with tools and methods to interact with other companies within virtual factory and distributed manufacturing processes.

The rest of this paper is organized as follows: Section 2 describes some related work and existing literature; Sect. 3 shows how to design CloudVFIS; the following section illustrates how to implement Cloud storage by an example. The concluding section summarized the entire paper.

## 2 Literature Review

### *2.1 Virtual Factory and Information System*

The term of Virtual Enterprise (VE) is used to form a temporary collaborative network of independent enterprises. Many geographically dispersed enterprises often structure this type of business collaboration to meet various market objects agile. The goal of VE is to achieve a particular business requirement and obtain more opportunity [1, 5] for small and medium enterprises. The benefit of enterprises cooperation in the VE is to ensure the enterprises can focus on their own core business while leverage their competencies, resources, or the skills.

Industrial manufacturing is a typical application area of VE concept, which also our focus in this paper. In this turbulent global economic environment, the manufacturing processes can be hardly accomplished by only one manufacturer, but multiple manufacturers. Manufacturers must be viewed in the context of their contribution to the total value chain [5]. It's very important for manufacturers to focus on their core competences and join efforts with others, in order to fulfill the new products' requirements [6]. Therefore, we label this particular virtual enterprise as Virtual Factory (VF). More specifically, VF is dynamic, ad-hoc, and temporary, and exists only for the lifetime of a specific business opportunity in the manufacturing. Each manufacturer in VF is independent operation agency, but the management of VF is logic concentrated and physical distributed [7].

The success of VF is highly relying on Information System. Advances in modern technologies, such as internet, workflow management system etc., have made Information System is possible to enable enterprises to cooperate with each other [8]. VE structure is information system centered. The core competence which has to be developed is an information system working with different organizations. However, there are many challenges related to technology when implement Information System to support VE. The structure of VE has to face different technical constraints [9]. Particularly for VF the challenges could be: (1) selection of proper manufacturing enterprises; (2) rapid integration of the manufacturing processes; (3) dynamic reconfiguration of system; (4) change introduced by various factors such as joining and dropping of partners, market, and context changes.

## *2.2 Data Storage of Virtual Factories Information System*

One issue in realizing VE is the information/data exchange among different application systems in this virtual activities environment [10]. ICT support systems have to allow enterprises to share information, by guaranteeing data-consistency and establishing synchronized and collaborative processes [11]. The difficulty and problem is when different actors are working together at the same time, how to handle real-time communication [9]. Information/data exchange between different software tools is a common problem. Efficient data management is the most critical issue to obtain the agility and it improves the competitiveness of virtual enterprises [10].

Cloud computing gains a lot of attention currently. More and more business are taking advantages of cloud computing. In this virtual environment, users can access computing resources remotely and all the required data is transferred throughout the cloud [12]. According to the definition of the National Institute of Standards and Technology (NIST), the cloud-based services can be divided into three layers: Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), and Infrastructure-as-a-Service (IaaS) [13]. Cloud storage belongs to IaaS layer and it is becoming a very popular research field. One reason is that it's the basic level of the whole cloud system to support the functions of other layers above it (SaaS, PaaS). Another reason is more and more data-intensive applications are being attracted by the clouds.

Cloud storage can provide high scalability, availability, fault tolerance, security, and cost-effective data services for those applications [14]. Typically in the cloud storage, users will know neither the exact location of their data nor the other sources of the data collectively stored with theirs. Cloud-based data storages provide several advantages in contrast to former data center solutions. Therefore, cloud-based storage solutions are applied within this paper for the cataloging and processing various data, like the incorporation of eternal system's data, and production status information, inter-organizational data, etc. This way, an overall repository for manufacturing process-related data can be provided.

## 3 Cloud Storage in CloudVFIS

In this paper, we propose a CloudVFIS (Cloud-based Virtual Factory Information System). In the virtual factory information system, technology used to communicate data must be cost-effective, flexible, and portable [15]. Since the considerable benefits of cloud data storage, it plays an important role in this CloudVFIS implementation.

### *3.1 Cloud Based VFIS Working Environment*

The working environment for a virtual factory proposed in Fig. 1. This solution helps virtual factory and the cooperating manufacturing enterprises move beyond existing operational limitations by providing concrete tools and approaches for leveraging the information exchange between enterprises. The centralized control enterprise is named as manufacturing broker. They are responsible to collect customer orders, design process model, and describe the manufacturing process and then assign appropriate manufacturing enterprises (in this scenario, they are called as partner factories) to accomplish the manufacturing processes. Therefore the clients in this CloudVFIS are two parts: brokers who propose the virtual factory and partner factories. Moreover, all the information storing and data performing are taking place in cloud storage.

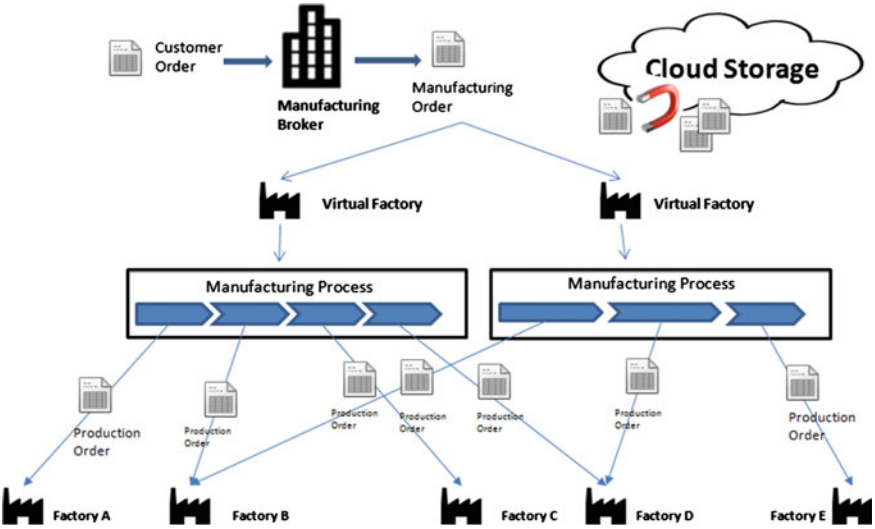



**Fig. 1** Cloud VFIS working environment

In order to satisfy orders in a short time and avoid bottlenecks, the controlling over the whole manufacturing process carried out in a form of virtual factory. The brokers benefit from this CloudVFIS by following activities:

- Brokers can describe the (semantic) description of companies, their production facilities, and products.
- Brokers can design a process to produce specific products and describe the constraints, e.g., regarding environmental and ethical questions, lead time, costs.
- Brokers can assign different partner factories to each process step. This CloudVFIS can suggest the best fit partner factory to each step in order to optimize the manufacturing process.
- Brokers can simulate the well designed process and then execute the process.
- Information about the current status of the manufacturing process is given in real-time. Furthermore, information from different ICT systems of the partner factories is also integrated into process monitoring.
- When unforeseen events happen and change the outcome of the manufacturing process (e.g., delay and costs increase), an automatic adaption of the process will take place.

Based on this scenario described, a new architecture to implement all these functionalities is designed in the following section.

## 3.2 Cloud Based VFIS Architecture

Three-tier architecture model is the fundamental framework for virtual enterprise information system. In both research Bergamaschi et al. [11] and Chen et al. [7], authors propose three-tier model architecture to implement the Virtual Enterprise Information System. However, the traditional three-tier architecture is suitable mostly for applications with a predictable number of users, following a small number of usage patterns and a reduced number of load spikes [16]. In other words, this architecture runs into problems with the need for high scalability and elasticity of modern web applications such as for virtual factory implementation. Furthermore, traditional web applications use relational databases for their data tier. This database system is difficult to scale or to replace in case of failure and any change in the database schema requires some downtime. Also, performing queries on these databases is slow [16]. In order to solve these issues in three-tier architecture, we provide a new solution. In this paper, this three-tier architecture needs to be modified with two additional services components. The architecture is presented as Fig. 2.

- Presentation Layer: this layer remains the same functionalities as traditional presentation layer to interact with users. This user interface can be customized based on users different needs and users can use any devices with web browser to access the Cloud based VFIS. The user interface for brokers and partner factories are different.
- Business Layer: this layer consists of business rules. It is responsible for implementing the manufacturing process. It contains six distributed components: Process Design, Process Simulation, Process Optimization, Process Execution, Process Monitoring, and Process Adaptation. Although these components are designed separately, they interact with each other. The interplay of these components is used to manage the manufacturing process in order to fulfill the customer orders. These components mainly used by brokers, but when signing the partner factories to the manufacturing process, the system will send notification to the partner factories. Although the partner factories don't have active interact with these components, they are important part of the manufacturing process.
- Data Layer: The data layer contains cloud storage. This Cloud Storage serves as central data storage. It allows the business layer to pass by different types of data (binary, semi-structured, structured, and semantic) and will ensure high scalability for data storage processes. Within this cloud storage, scalability, and reliability both have a higher priority than speed. Because there are many different types of data in CloudVFIS, the cloud storage should support all of them by different cloud providers.
- Load Balancer Service: This service distributes user requests to different components in the business layer instances in order to avoid overload and minimize response time.

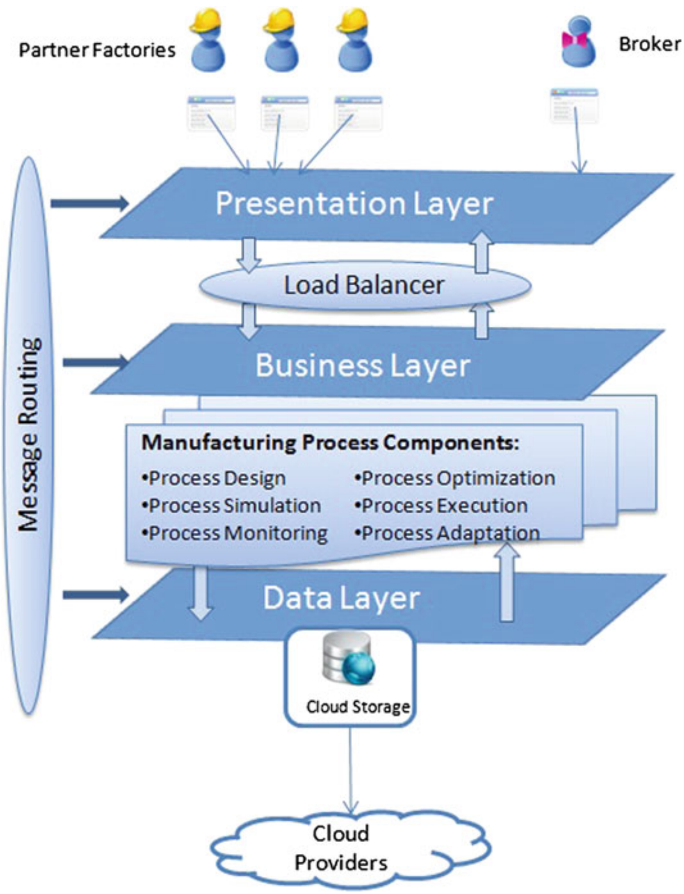



**Fig. 2** Overview of cloud VFIS architecture

- Message Routing Service: This service is needed which connects the different tiers and which manages the communications between each tier. This service routes valuable information and ensure the scalability.

## 4 Cloud Storage Implementation

CloudVFIS applies the cloud storage to support virtual factory information system. It allows manufacturers to share information about production/products over the cloud platform. In this section, we only focus on cloud storage implementation.

The data layer supports several types of data. For instance, *semi-structured* data storage such as XML or JSON data, *structured* data used internally by different components in business layer, *semantic* data for semantic company descriptions and also *binary* data, which is documents such as specifications. Therefore, different cloud storages are needed to different types of data. This Cloud Storage will be based on the concept of buckets, which are specific isolated storage spaces managing data for different data type. These buckets can be thought as independent databases to store and retrieve different types of data in different databases. Thereby, the data types decide their databases and how it stores the data.

Within this solution, a set of four different bucket types for semi-structured, structured, semantic, and binary data will be implemented. Designing in this way can ensure the flexibility. If other bucket types are needed, such as a SQL bucket, they can be added easily. The Cloud Storage will support a basic set of CRUD (create, read, update, delete) operations for all bucket types in a suitable data format (e.g., OData for structured data).

## *4.1 Cloud Storage Structure*

In order to realize this integrated Cloud Storage, it is needed to identify adequate technologies to store structured, semi-structured, binary, and semantic data. One unique feature of the business model in cloud is that different services are provided by multiple operators [4]. Therefore, different cloud storage providers will be selected to provide different types of cloud storages. For managing those data types, a lot of proven technologies exist. In this paper, the well tested and good performance technologies are selected. It is presented in Table 1.

Based on the selection of technology on different types of bucket, the Cloud Storage can be decomposed into a detailed structure. Figure 3 illustrates the structure of Cloud Storage.

- Message Routing: It is used to realize the communication within CloudVFIS. It receives message from other components in business layer to this data layer.
- Cloud Storage Facade: this is the message interface and virtual controller of this Cloud Storage. It manages the buckets, interprets the messages, and executes the commands sent in the message. Additionally, it checks, whether the data has to be transformed and if the needed access rights are granted. To achieve this it uses the Query Translator and the Access Control.
  - Query Translator: It is used to convert the data from the messaging format into the specific database query format and back.
  - Access Control: it is used to check if components in business layer are authenticated to access a specific bucket. It also checks whether the users have the rights to access specific binary data. Access Control List will be stored in the Semi-Structured Data Storage.
- Buckets: Buckets are independent data storages that can be created and used by components. Depending on the type they are realized as own database instances,

**Table 1** Description of different bucket types and the technology selection

| Bucket types | Type of data | Requirements | Selected technology |
|---|---|---|---|
| Structured | Typical application data such as setting or administration data | Table based structure on top of relational databases | MySQL |
| Semi-structured | Typical data in a document-oriented way without a fixed data schema, such as XML or JSON data | It executes the semi-structured (for example for NoSQL databases) queries and returns the results to the Cloud Storage Facade | MangoDB |
| Binary | A document-centric storage for binary data (e.g., Store videos, PDFs, etc.) | Queries will be based on the document name or ID, e.g., by requesting the content of the document "company description.pdf" | Amazon S3 |
| Semantic | Storage of semantic information, e.g., for managing semantic factory descriptions | Queries will be based on a semantic query language such as SparQL | Sesame |

separate tables, or keys with are specific prefix. Each component can create an own separate bucket, so the Cloud Storage has to manage several buckets of each type, as it can be seen as an example in Fig. 3, where two binary buckets exist in Binary Data Storage.

## 4.2 Create Bucket

This is an example when a component, for instance Process Design, in business layer sends a message to data layer to create a binary bucket. The Process Design component sends a message with the bucket type, component identifier, and the command to create a bucket to the Cloud Storage. Then the responsible Cloud Storage provider creates the bucket and sets the corresponding value in the ACL that the component can access the bucket. In the end, the Cloud Storage sends the message with the bucket ID back to the component that sends the message to create the bucket (Fig. 4).

The Message Routing Service throws an event that a message has been received. The Cloud Storage Facade checks this message, which kind of bucket has to be created. A Binary bucket will be created in Amazon S3 and returns a BucketID. Then the Cloud Storage Facade sets the needed write and read rights for the component that has sent the message and it returns the BucketID to it. For instance, Process Optimization component has the right to access Process Design's buckets with read and write access. But some other components only have

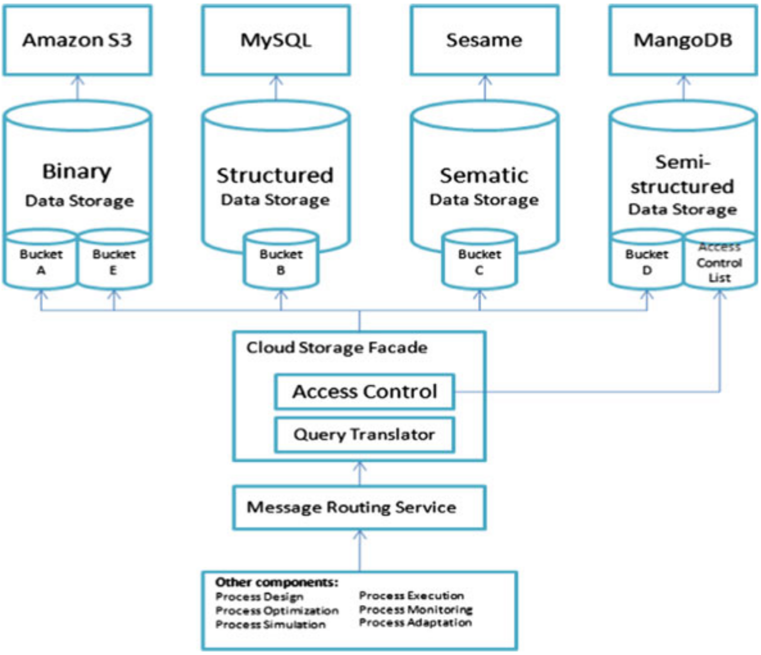
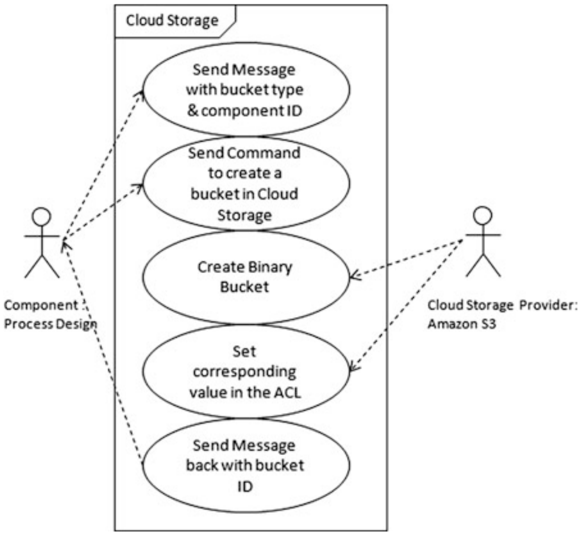



**Fig. 3** Cloud storage structure

read-only access. Also, Process Design and Process Execution can share a bucket to store the process models (Fig. 5).

This method will create a new bucket for an application for managing data:

**Fig. 4** Use case for bucket creation



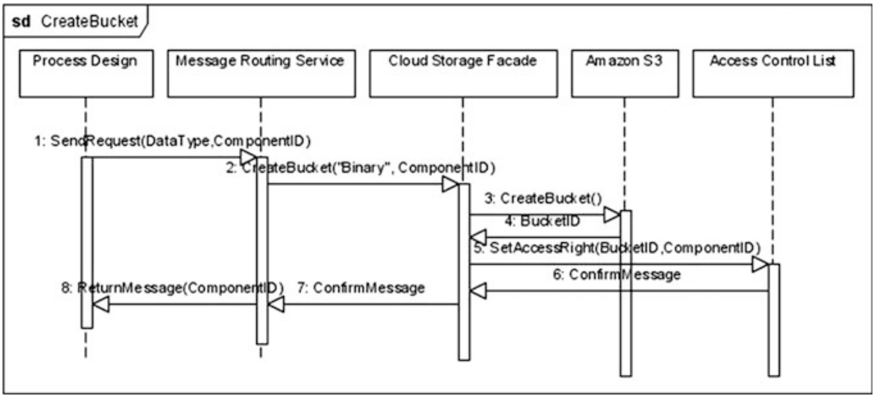



**Fig. 5** Sequence diagram for bucket creation

## 5 Conclusions

In this paper, a new solution for using Cloud Storage in Virtual Enterprises is introduced. This CloudVFIS will enhance the conceptual framework that virtual factory use to make decisions about their manufacturing process. More important, it will contribute to fill the gap in knowledge about the use of Cloud storage in virtual enterprise. There is an acknowledged lack of studies about adoption and implementation processes for virtual enterprise platforms in SMEs. Consequently, we provide a concert tool to support the Virtual factory activities.

In this CloudVFIS, the three tier architecture offers many advantages to virtual factory. It is easily expandable and has a high degree of scalability. Two additional layer load balancer and message routing complete the architecture and it supports virtual factory environment. Components in the business layer that need a high amount of processing power in short time can be virtually duplicated easily achieved by load balancing. The use of cloud-based data storage also implies a high scalability in terms of data throughput and storage capacity. This CloudVFIS relies on a number of cloud storage providers to ensure a highly elastic data storage. In this solution, the data is managed based on the different data types. Moreover, the communication of the components and these three tiers will be routed via the Message Routing service.

Cloud computing is changing the way to do business in many industries. However, this paper mainly focuses on cloud storage implementation. With earlier adoption of cloud storage to access/manage data will help enterprise stay ahead, and it is very crucial to the small and medium size enterprises' existence.

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## References


1. Browne J, Zhang J (1999) Extended and virtual enterprises similarities and differences. Int J Agile Manage Syst 1(1):30–36
2. Goel A, Schmidt H, Gilbert D (2009) Towards formalizing virtual enterprise architecture. In: Enterprise distributed object computing conference workshops, 2009. EDOCW 2009. 13th, pp 238–242
3. Fredriksson J, Augustsson K (2011) Cloud service analysis-choosing between an on-premise resource and a cloud computing service. Chalmers University of Technology, Göteborg, Sweden
4. Hwang J et al. (2011) A business model for cloud computing based on a separate encryption and decryption service. 2011 International conference on information science and applications (ICISA)
5. Helaakoski H, Iskanius P, Peltomaa I (2007) Agent-based architecture for virtual enterprises to support agility. Establishing the foundation of collaborative networks: IFIP TC 5 working group 5.5 eighth IFIP working conference on virtual enterprises, pp 299–305, Guimaraes, Portugal, 2007
6. Camarinha-Matos LM, Afsarmanesh H (2006) Virtual enterprise modeling and support infrastructures: applying multi-agent system approaches. Multi-Agent Systems and Applications, Lecture Notes in Computer Science 2086:335–364
7. Chen D, Huang H, Ji C (2008) Research on virtual enterprise workflow modeling and management system implementation, WiCOM '08. 4th international conference: Wireless communications, networking and mobile computing, 2008
8. Zhang Y, Shi M (2003) A method describing the cooperative relationships evolution of virtual enterprise. The 8th international conference on computer supported cooperative work in design proceedings, 2003
9. Martinez MT et al (2001) Virtual enterprise- organisation, evolution and control. Int J Prod Econ 74:225–238
10. Yoo SB, Kim Y (2002) Web-based knowledge management for sharing product data in virtual enterprises. Int J Prod Econ 75:173–183
11. Bergamaschi S, Gelati G, Guerra F, Vincini M (2005) An intelligent data integration approach for collaborative project management in virtual enterprises. Springer Science+Business Media, Inc, The Netherlands
12. Kaufman LM (2009) Data security in the world of cloud computing. IEEE security and privacy, 2009
13. Mell P, Grance T (2009) A NIST notional definition of cloud computing. The National Institute of Standards and Technology. http://csrc.nist.gov/groups/SNS/cloud-computing/cloud-def-v15.doc, [Last access: 2010-11-28]
14. Huo Y et al. (2011) A cloud storage architecture model for data-intensive applications. International conference on computer and management (CAMAN), 2011
15. Hardwick M, Spooner DL, Rando T, Morris KC (1996) Sharing manufacturing information in virtual enterprises. Commun ACM 39(2):46–54
16. Petcu D et al. (2012) Portable cloud applications—from theory to practice. Future generation computer systems. Available online 27 Jan 2012

# Enabling Virtual Manufacturing Enterprises with Cloud Computing: An Analysis of Criteria for the Selection of Database as a Service Offers

**Ronny Hans, David Dahlen, Sebastian Zöller, Dieter Schuller and Ulrich Lampe**

**Abstract** In our globalized world, small- and medium-sized enterprises in the manufacturing domain face a highly competitive environment. They are subject to various challenges, such as very short product life cycles and a strong price competition with companies from low-cost countries. To remain competitive in such an environment, new forms of collaborations, like Virtual Manufacturing Enterprises, are required. An essential part of virtual organisations is data provisioning. Thereby, data from various sources like factories' ERP systems or data provided by sensors need to be processed and stored. In this context, data storage is a crucial architectural element that influences both functional aspects and competitive aspects, especially costs, of Virtual Manufacturing Enterprises. For realizing Virtual Manufacturing Enterprises with low up-front investments, the application of new technologies, such as Cloud Computing, is required. For storage of information in databases, Database as a Service offers from the Cloud can be exploited. However, since there is a huge amount of providers acting on a non-transparent market, it is difficult to find appropriate "Database as a Service" offerings. To overcome this problem, we provide a criteria catalog for the selection of providers and their services. Further, we show how different offers, which at the first glance look very similar, could cause very different expenses. With our work, we simplify the selection and evaluation of Cloud storage providers and provide an evaluation of current Cloud storage service offers.

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Lecture Notes in Mechanical Engineering, DOI: 10.1007/978-3-319-00557-7_35,

## 1 Introduction

These days, Small and Medium Enterprises (SMEs) in the manufacturing domain face various challenges such as short product life cycles. Further, customers request a high degree of customization at low costs. To remain successful, companies need to find a way to cope with challenges effectively [9]. On the one hand, SMEs play an important role regarding economic growth, employment, and innovation. All over the world they contribute 54 % to the GDP of the countries on average [3, 30]. On the other hand, SMEs do not have the financial strength like large companies to handle all the challenges individually. To remain competitive and fulfill customer expectations, SMEs need to focus on their core competencies, and thus have to collaborate with other companies. Hence, the success of an enterprise depends on the individual capability as well as efficient collaborations in well-defined value chains across enterprises [6]. To address the mentioned challenges, Agile Manufacturing (AM) is a popular concept. In this context, agility means the exploration of competitive bases through the use of reconfigurable resources in order to provide products and services regarding customer needs in a quickly changing environment [32]. Thereby, AM focuses on setting up whole organizations for production including different enterprises [16]. A basic building block to achieve AM is the concept of "Virtual Manufacturing Enterprise" (VME) [16, 32]. A VME is created by at least two companies [26] and is the enabling element for process sharing across organizational boundaries [7, 20]. The different companies within a VME share costs, skills, and competencies to produce goods which are beyond the capability of individual companies. Thus, VMEs may be equally powerful as big enterprises, but are still equipped with the ability of small enterprises to react quickly to changes of market circumstances [26].

An essential part of the VME infrastructure is Information and Communication Technology (ICT) [11]. Because of the fact that SMEs do not have the same financial power like large companies, an ICT infrastructure is required that can be established with reasonable costs. To achieve that, we suggest the use of Cloud Computing (CC). CC offers different advantages, such as cost reduction, charging in a pay-per-use manner [4], flexibility, and scalability [2]. With these characteristics, the corresponding ICT infrastructure can grow or shrink according to the business needs. Further, CC offers the access to data independently from the location of the user [13]. Within an ICT architecture for VMEs, data storage plays an outstanding role, e.g., all monitoring data, product information, and data from sensors need to be stored and provided. All possible types of storage services offered by Cloud providers are referred to as the common term *Data Storage as a Service (DaaS)* [31]. Database functionality, as a specific subset of DaaS, is referred to as *Database as a Service (DBaaS)* [19]. Among the various offers in the market, an appropriate choice is difficult because of the large amount of cloud service providers, a low market transparency, and tedious access to relevant information [27]. Thus, we provide a criteria catalog to qualitatively evaluate DBaaS offers. As the application of the derived criteria catalog, we provide a qualitative and quantitative evaluation of three popular offers from Amazon, Microsoft, and Google.

The paper proceeds as follows: In Sect. 2, we derive a criteria catalog with essential functional and non-functional criteria, which puts SMEs in the position to select Cloud storage offers effectively under consideration of their specific needs. In Sect. 3, we apply the criteria catalog to selected DBaaS offers from Amazon, Microsoft, and Google. Furthermore, we calculate the costs of these offers depending on different load profiles. We show that similar looking accounting models can cause extremely different costs. Related work is presented in Sect. 4. Finally, conclusions and an outlook on future work are provided in Sect. 5.

## 2 Development of a Criteria Catalog

In this section, we identify key criteria in order to enable the comparison of different DBaaS offers. Based on a literature review we find, identify, and describe potential criteria for selecting appropriate offers. The references indicating the usage of such criteria are provided in Table 1.

To begin with, the *pricing model* describes how the cost for a cloud storage offer is calculated. That is, it represents the key parameters that determine the total usage cost. In order to be able to assess the cost arising from performing IT projects, a certain degree of *cost transparency* is indispensable. If an IT project is to be realized using the own data processing center, costs for servers, electricity, maintenance staff, network, and facilities have to be considered [5]. Referring to the Cloud, different parameters come into play, depending on the pricing model applied by a cloud storage provider. A high degree of cost transparency thereby enables solid decisions with respect to selecting a certain cloud storage offer for a concrete project. Further, a comparison of these costs with the cost of providing these IT resources in-house is enabled. For assessing the cost transparency of a

**Table 1** References for cloud storage selection criteria

| Criteria | Repschläger et al. [27] | Hetzenecker et al. [14] | Cryans et al. [8] | Jatana et al. [17] |
|---|---|---|---|---|
| Pricing model | X | X | | |
| Cost transparency | X | X | | |
| Data model | X | | X | |
| Scheme | | | X | |
| Indexing | | | | X |
| Scalability | X | X | X | X |
| Service level agreement | | X | | |
| Data security and compliance | X | X | | |
| Encryption | X | X | | |
| Performance | X | X | | X |

cloud storage offering, mainly two factors are of importance. On the one hand, the complexity of the pricing model has to be considered. If, for instance, lots of parameters are required for determining the total cost, the complexity of the pricing model is rather high, resulting in a lower cost transparency degree. On the other hand, the predictability of the mentioned parameters plays a role.

Another criterion which should be considered when a DBaaS offer has to be selected is the *data model*. In addition to the typical, relational architectures, further data models exist, commonly referred to using by the term "NoSQL" [28]. Obviously, different data models are differently appropriate for concrete tasks and problem instances, respectively. Thus, the applied data model should serve as a key criterion for the selection of a certain cloud storage offer. Depending on the concrete application scenario, different *schemes* with advantages as well as disadvantages need to be taken into account to distinguish cloud storage offerings from each other. Relational databases generally require exact definitions of data structures, while flexible schemes are allowed by NoSQL databases [10]. In order to speed up the access to datasets, *indices* are commonly used. Thereby, the access pattern of the application logic determines the selected indices. In this respect, it has to be noted that the creation and application of indices may be either limited or required by different cloud storage providers. Amazon's DynamoDB1[1] and Microsoft's Azure Table Storage,[2] for instance, do not support user defined indices [1], [21]. This may require for the user to adapt an existing application logic. Therefore, indices should be considered as additional cloud storage selection criterion.

Another criterion is given by the *scalability* of offered services. In this respect, we aim to assess the ability of a DBaaS offer to satisfy the need for fast scalability. In general, databases may be scaled in two ways, i.e., vertical versus horizontal scaling. While vertical scaling is performed by enhancing the performance of the according database server, horizontal scaling refers to interconnecting several, different database servers [18]. The criterion of scalability thereby should indicate which type of scaling is supported in which way. In order to assess, whether a Cloud storage offer satisfies the requirements of an IT project, dedicated information regarding the offered *performance* are needed. This criterion aims at collecting and providing observations on the performance of different Cloud storage offerings in order to enable comparisons among them. In this context, evaluation data as well as benchmarks are commonly applied. With respect to the domain of databases, the benchmarks of TPC [29] are predominant for relational databases.

Cloud providers might make use of *Service Level Agreements (SLAs)* in order to provide their customers with guarantees concerning different non-functional properties, such as availability or response time. As there is no dedicated, individual contract between a cloud user and the respective provider, the provisioning of such prescribed guarantees and may support the trustworthiness of a cloud

[1] http://aws.amazon.com/de/dynamodb/

[2] http://msdn.microsoft.com/en-us/library/windowsazure/ee924681.aspx

provider form a customer's perspective. With respect to data transmission and storage of data, legal regulations as well as company internal requirements exist and have to be adhered to. For instance, the German Data Protection Act[3] specifies and provides mentioned legal regulations. As data is handed over to the Cloud and thus, a third party, it has to be ensured that the respective cloud provider adheres to the according guidelines. For this, the criterion *data security and compliance* should indicate whether a cloud storage provider has undergone formal certification, indicating whether mentioned legal and company internal requirements are met. Whether *encryption* is used for transmitting and storing data and which encryption algorithm thereby is applied, may also be prescribed according to organizational or legal requirements. For instance, the German Data Protection Act requires taking "appropriate" actions for the protection of personal data. For this, the criterion *encryption* should indicate whether the data communication as well as the storage of data supports encryption.

## 3 Evaluation of Cloud Storage Offers

In the following, we exemplarily apply the criteria that were deduced in Sect. 2 to three selected DBaaS services. We focus on DBaaS offers from three major providers in this context, namely Amazon DynamoDB, Google App Engine Datastore,[4] and Microsoft Windows Azure Table Storage. First, we provide a qualitative analysis of the DBaaS offers based on the criteria catalog from Sect. 2. After that, we conduct a quantitative analysis of the selected DBaaS offers with a special focus on monetary costs associated with the offers for an example scenario, since monetary costs constitute one of the most relevant decision criteria in the very cost-sensitive manufacturing domain. Thus, we provide not only a guideline on how to employ our criteria catalog in the selection process for a DBaaS provider, but also a comparison between the services offered by prominent providers that are currently active in this market.

### *3.1 Qualitative Analysis*

In the following, we provide an exemplary analysis of Microsoft's Windows Azure Table Storage service according to our criteria catalog from the previous section. We conducted this analysis as well for the Amazon DynamoDB and the Google App Engine Datastore services. An overview of the results can be found in Table 2. However, as the quantitative analysis in Sect. 3.2 outlines, Microsoft's

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[3] http://dejure.org/gesetze/BDSG

[4] https://developers.google.com/appengine/docs/python/datastore/

**Table 2** Qualitative analysis of DBaaS offerings

| | Amazon DynamoDB | Microsoft windows Azure table storage | Google App engine datastore |
|---|---|---|---|
| **Pricing model** | Storage space, reserved read/write-throughput, outgoing data transfer | Storage space, API calls, outgoing data transfer | Storage space, I/O-operations, outgoing data transfer |
| **Cost transparency** | + | + | – |
| **Data model** | Key-tuple | Key-tuple | Key-tuple |
| **Scheme** | No fixed scheme, only primary key fixed | No fixed scheme, only primary key fixed | No fixed scheme, only primary key fixed |
| **Indexing** | Only primary key | Only primary key | Any |
| **Scalability** | Horizontal | Horizontal | Horizontal |
| SLA | No SLA provided | 99.9 % availability | 99.95 % availability |
| **Data security and compliance** | | | |
| – *Datacenter locations in EU* | Ireland | Ireland, Netherlands | Confidential |
| – *EU location for datacenter selectable* | Yes | Yes | Yes (surcharge) |
| – *Safe harbor support* | Yes | Yes | Yes |
| – *Applicable law* | USA | Ireland | USA |
| – *Data owner* | User | User | User |
| – *Data usage by service provider* | No | No | No |
| **Encryption** | No | No | No |
| **Performance*** | N/A | N/A | N/A |

* To the best of our knowledge, there is no comparable analysis of the performance available

service seems very promising from an economic point of view. In consequence, we present the details of its qualitative analysis in more depth here. With respect to this highly dynamic area and the fast changing offers of Cloud provides, it has to be noted that all used information and considered data have been collected in October 2012"*Pricing Model*: Pricing depends on three parameters, namely, the storage space used in a month, the number of memory transactions, and the outgoing data transfer. The basis for the storage space accounting is the average daily storage space allocation. Depending on the arranged level of redundancy, costs between US$ 0.093 and 0.125 per month and GB accrue, with discounts for data volumes over 50 TB. Memory transactions cost US$ 0.01 per 100,000 transactions. Further, the outgoing data transfer is charged with US$ 0.12 up to US$ 0.19 per month and GB depending on region [23].

*Cost Transparency*: As the costs for the usage of the service depend on the three mentioned parameters of storage space, number of memory transactions, and outgoing data transfer, their respective predictability is the main indicator to estimate the cost transparency of the service. As the costs for data storage rise proportionally to the used data storage, this parameter can be predicted quite well. The number of memory transactions correlates to the number of queries and the query types with the number and size of returned datasets. Thus, this parameter is rather hard to estimate. The same holds true for the outgoing data transfer, which is also dependent on type and number of queries and hence rather difficult to estimate.

*Data Model*: The Windows Azure Table Storage service relies on a NoSQL database of the key-tupel type [24].

*Scheme*: Windows Azure Table Storage has no fixed scheme. Name, number, and data type are individually assigned for each dataset. However, each dataset has to possess the three mandatory attributes "*PartitionKey*", "*RowKey*", and "*Timestamp*". PartitionKey allows distributing a table over different servers to realize load balancing. RowKey allows to uniquely identifying a dataset within a partition. Timestamp is an internally used field. The service offers the possibility to specify up to 252 user-defined attributes [24].

*Indexing*: Data is stored as a clustered index based on a primary key, which consists of the attributes PrimaryKey and RowKey. User-defined indices are not supported [24].

*Scalability*: Windows Azure Table Storage provides automatic horizontal scaling with respect to data volume by partitioning datasets according to their PartitionKey. Datasets related to multiple PartitionKey values can be stored on one server. However, scalability directly relating to the system load is not foreseen.

*SLA*: A Service Level Agreement is provided with the service, which guarantees an availability of 99.9 %. A refund of 10 %, respectively 25 %, of the monthly fee is provided in case the availability drops between 99 and 99.9 %, respectively below 99 %. The availability is calculated as the difference between 100 % and the mean error rate in the accounting month for the memory transactions of the customer for the respective booked offer [22].

*Privacy and Compliance*: The locations of stored data can be specified as to be restricted to Europe. The customer remains owner of the data all the time. Microsoft takes part in Safe Harbor and the Windows Azure Table Storage service is certified with ISO27001 and ISAE3402 Type 2 [25].

*Encryption*: Stored data is not encrypted, but the data access via the API is realized via HTTPS [24].

*Performance*: In several tests, a latency of 18 ms per read and 24 ms per write operation for a dataset has been reported [12]. Hill et al. [15] could register in one of their test setups an average performance of ca. 1,150 datasets per second for CRUD-operations[5] reaching a maximum of 1,525 datasets per second.

### *3.2 Quantitative Analysis*

In order to evaluate the monetary efficiency of the three mentioned DBaaS offers from Amazon, Microsoft, and Google, we devised an exemplary application scenario and calculated the monetary costs arising within this scenario.

[5] CRUD: Basic operations on data storage; acronym for: create, read, update, delete.

**Table 3** Load levels employed in the example scenario

| Load level | Average number of monitoring datasets per day | Average number of views of the data source websites per day | Peak load of number of monitoring datasets per second | Peak load of number of views of the data source websites per second | Initially registered data sources | Initially stored monitoring datasets |
|---|---|---|---|---|---|---|
| 1 (Low) | 500 | 1,000 | 1 | 5 | 100 | 182,500 |
| 2 (High) | 50,000 | 100,000 | 100 | 500 | 10,000 | 18,250,000 |

Furthermore, the gathered monitoring data shall be stored in the data store, as well. We assume a maximum length of the monitoring data of 140 characters, with an average length of 70 characters.

The mapping of the monitoring data to its source shall be supported. It shall be possible to create new monitoring datasets, read datasets, and delete datasets. Furthermore, all datasets associated with a certain source shall be retrievable arranged according to their timestamps, with the newest on top. The data storage solution should provide an availability level of 99.9 % and a Web interface with a dedicated website for each data source, along with its identifier and description as well as its last 20 datasets. Regarding the Microsoft Developer Network,[6] we assume an average size of 514 Byte for a source dataset, 188 Byte for a monitor dataset, and 200 Byte for the protocol overhead per transaction. Regarding the prices for the western region we calculated US$ 0.01 per 100,000 transactions, US$ 0.125 per GB stored data per month, and US$ 0.12 per transferred GB.

Based on two different load levels (cf. Table 3), we calculate the total price of each mentioned DBaaS offer for 1 month of operation. This allows drawing conclusions on the cost efficiency with regard to scalability and the impact of different usage parameters. The individual results of our calculations can be found in Table 5. Figure 1 provides a comparison with respect to the monetary costs arising in the example scenario with the different load levels for the three analyzed DBaaS offers Amazon DynamoDB, Google App Engine Datastore, and Microsoft Windows Azure Table Storage (Table 4).

Our results show that for the different load levels in our sample application scenario, the overall costs highly differ. Notably, for load level 1, the Amazon and the Google DBaaS service can be used for free, whereas the Microsoft service incurs minimal costs. A significant difference between the offered services is found by analyzing load level 2. In this scenario, the costs when employing the Microsoft solution are nearly negligible, whereas the usage of the Google service would incur costs of roughly US$ 50 and the Amazon service would even incur costs of roughly US$ 200 per month.

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[6] http://blogs.msdn.com/b/windowsazurestorage/archive/2010/07/09/understanding-windows-azure-storage-billing-bandwidth-transactions-and-capacity.aspx

**Table 4** Monthly resource consumption in the example scenario

| DBaaS offers | Load profile | Employed storage | Employed writes | Employed reads | Outgoing data transfer |
|---|---|---|---|---|---|
| Amazon DynamoDB | 1 | 31.7 MB | 1 | 8 | 65.7 MB |
| | 2 | 3.1 GB | 100 | 750 | 6.4 GB |
| Windows Azure Table Storage | 1 | 20.6 MB | 75,000* | | 93.7 MB |
| | 2 | 2.0 GB | 7,500,000 | | 9.1 GB |
| Google App Engine Datastore | 1 | 31.2 MB | 60,000 | 630,000 | 73.4 MB |
| | 2 | 3.0 GB | 6,000,000 | 63,000,000 | 7.2 GB |

* With Windows Azure Table Storage, write and read transactions are not differentiated. Thus, the values provided here comprise the number of consolidated memory transactions

**Table 5** Monthly costs in the example scenario

| DBaaS offers | Load profile | Costs for employed storage | Costs for employed writes | Costs for employed reads | Costs for outgoing data transfer | Sum |
|---|---|---|---|---|---|---|
| Amazon DynamoDB | 1 | US$ 0.00 | US$ 0.00 | US$ 0.00 | US$ 0.00 | US$ 0.00 |
| | 2 | US$ 3.39 | US$ 77.29 | US$ 120.41 | US$ 0.65 | US$ 201.74 |
| Windows Azure Table Storage | 1 | US$ 0.13 | US$ 0.01† | | US$ 0.00 | US$ 0.14 |
| | 2 | US$ 0.25 | US$ 0.75 | | US$ 1.10 | US$ 2.10 |
| Google App Engine Datastore | 1 | US$ 0.00 | US$ 0.00 | US$ 0.00 | US$ 0.01 | US$ 0.01 |
| | 2 | US$ 0.49 | US$ 5.25 | US$ 43.58 | US$ 0.86 | US$ 50.18 |

† With Windows Azure Table Storage, write and read transactions are not differentiated. Thus, the values provided here comprise the number of consolidated memory transactions

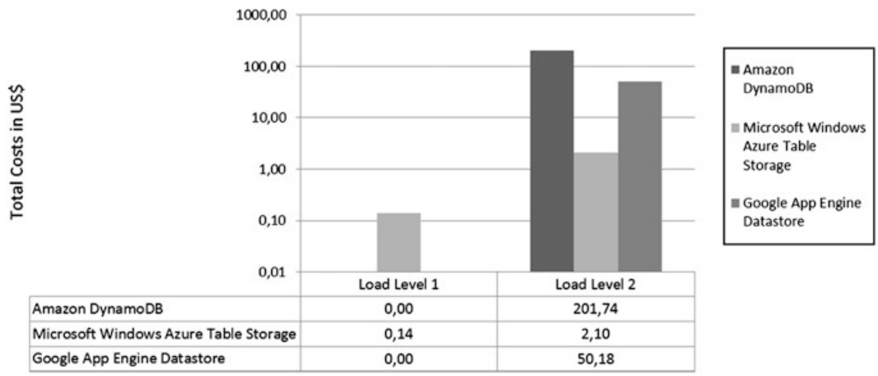


**Fig. 1** Cost comparison for DBaaS offerings for the introduced example application scenario

In consequence, it is essential to spend sufficient time on a thorough analysis of the application scenario and the respective current and estimated future requirements for the data storage solution to be employed. Due to very different pricing schemes, one solution can be cost-efficient in a certain application scenario, but in another scenario, its employment can be disadvantageous and result in significant additional spendings. Nevertheless, a selected service needs to fulfill both qualitative and quantitative requirements. For example, DBaaS offers that are not in accordance with data security and compliance requirements are not of interest for enterprises, even if they are the cheapest solution.

## 4 Related Work

Repschlaeger et al. [27] developed a classification framework for comparison and selection of Infrastructure as a Service (IaaS) providers. Their findings are based on a literature analysis, on an analysis of current cloud service offers, and on expert interviews. The authors aim to simplify the cloud provider selection process and to increase the market transparency. Hetzenecker et al. [14] developed a model of requirements to asses CC providers. Their findings based on a literature analysis, on expert interviews, and on an online survey. The provided model should help CC users to identify the individual needs and evaluate providers regarding their requirements. Cryans et al. [8] present new database technologies based on Hadoop, a scalable distributed file system. They give an overview of HBase and the corresponding infrastructure. Further, they propose comparison elements to contrast relational databases with distributed databases like HBase. Jatana et al. [17] examine essential characteristics of relational and non-relational databases. They give a basic overview of both database types and conclude with a comparison of both database types by means of ten characteristics. In summary, all related work focuses either on Cloud-specific or on database-specific criteria. None of them provides a comprehensive criteria list for DBaaS offers. Our work comprises essential elements from both worlds to take the specific characteristics of Cloud-based database offers into account.

## 5 Summary and Outlook

Small and Medium Enterprises (SMEs) in the manufacturing domain act in a highly competitive environment, which is hallmarked by short product life cycles, a high level of customization, and a cheap production in low-cost countries. To handle these challenges efficient new collaboration forms like Virtual Manufacturing Enterprises (VMEs) are required. A major enabler for such agile organizations is Information and Communication Technology (ICT). Traditionally, the deployment of new ICT causes high up-front investments which could be a hurdle for SMEs. To overcome this obstacle we propose the utilization of Cloud Computing (CC). By doing so, the ICT infrastructure can dynamically grow or shrink according the business needs. Besides a wide range of advantages, CC causes challenges regarding the selection of appropriate services. In this paper, we present a catalog of criteria to assess, compare, and select *Database as a Service (DBaaS)* offerings regarding the business needs. Further, we conduct a qualitative and quantitative analysis of DBaaS offers from Microsoft, Amazon, and Google. Our results show that for different load levels different offers are more or less appropriate. In our future work, we plan to implement a Cloud Storage solution as a part of a complete architecture for VMEs and thus to enhance our calculation with results from real world deployments.

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## References

1. Amazon (2013) Amazon DynamoDB developer guide. http://docs.amazonwebservices.com/amazondynamodb/latest/. Developer guide, 2012. Accessed 19 Jan 2013
2. Armbrust M, Fox A, Griffith R, Joseph A, Katz R, Konwinski A, Lee G, Patterson D, Rabkin A, Stoica I, Zaharia M (2010) A view of cloud computing. Commun ACM 53(4):50–58
3. Ayyagari M, Beck T, Demirguc-Kunt A (2007) Small and medium enterprises across the globe. Small Bus Econ 29(4):415–434
4. Buyya R, Yeo C, Venugopal S (2008) Market oriented cloud computing: vision, hype and reality for delivering IT services as computing utilities. In: Proceedings of 10th IEEE international conference on high performance computing and communications, 2008
5. Chen Y, Sion R (2011) To cloud or not to cloud? Musings on costs and viability. In: Proceedings of 2nd ACM symposium on cloud computing, 2011
6. Choi Y, Kang D, Chae H, Kim K (2008) An enterprise architecture framework for collaboration of virtual enterprise chains. Int J Adv Manuf Technol 35(11):1065–1078
7. Corvello V, Migliarese P (2007) Virtual forms for the organization of production: a comparative analysis. Int J Prod Econ 110(1–2):5–15
8. Cryans J, April A, Abran A (2008) Criteria to compare cloud computing with current database technology. In: Proceedings of the international conferences on software process and product measurement, 2008
9. Dowlatshahi S, Cao Q (2006) The relationships among virtual enterprise, information technology, and business performance in agile manufacturing: an industry perspective. Eur J Oper Res 174:835–860
10. Edlich S, Friedland A, Hampe J, Brauer B, Braeckner M (2011) NoSQL: Einstieg in die Welt nichtrelationaler Web-2.0-Datenbanken. Hanser, München
11. Faisst W (1997) Information technology as an enabler of virtual enterprises: a life-cycle-oriented description. In: Proceedings of the European conference on virtual enterprises and networked solutions, 1997
12. Giardino J, Haridas J, Calder B (2010) How to get most out of windows azure tables. http://blogs.msdn.com/b/windowsazurestorage/archive/2010/11/06/how-to-get-most-out-of-windows-azure-tables.aspx. Accessed 20 Jan 2013)
13. Hayes B (2008) Cloud computing. Commun ACM 51(7):9–11
14. Hetzenecker J, Kammerer S, Amberg M, Zeiler V (2012) Anforderungen an cloud computing Anbieter. In: Tagungsband der Multikonferenz Wirtschaftsinformatik, 2012
15. Hill Z, Li J, Mao M, Ruiz-Alvarez A, Humphrey M (2010) Early observations on the performance of windows azure. In: Proceedings of 19th ACM international symposium on high performance distributed computing, 2010

16. Jain S (1995) Virtual factory framework: a key enabler for agile manufacturing. In: Proceedings of symposium on emerging technologies and factory automation, 1995
17. Jatana N, Puri S, Ahuja M, Kathuria I, Gosain D (2012) A survey and comparison of relational and non-relational database. Int J Eng Res Technol 1(6):1–5
18. Kossmann D, Kraska T, Loesing S (2010) An evaluation of alternative architectures for transaction processing in the cloud. In: Proceedings of ACM SIGMOD international conference on management of data, 2010
19. Linthicum D (2009) Cloud computing and SOA convergence in your enterprise: a step-by-step guide. Addison-Wesley, Reading
20. Martinez M, Fouletier P, Park K, Favre J (2001) Virtual enterprise—organization, evolution and control. Int J Prod Econ 74(1–3):225–238
21. Microsoft (2012) Developer center. http://www.windowsazure.com/en-us/develop/overview/. Accessed 20 Jan 2013
22. Microsoft (2013) Windows Azure support: service level agreement. http://www.windowsazure.com/en-us/support/legal/sla/. Accessed 20 Jan 2013
23. Microsoft (2012) Pricing details. http://www.windowsazure.com/de-de/pricing/details/. Accessed 21 Jan 2013
24. Microsoft (2012) Table service REST API. http://msdn.microsoft.com/en-us/library/dd179423.aspx. Accessed 20 Jan 2013
25. Microsoft (2012) Windows Azure trust center. https://www.windowsazure.com/en-us/support/trust-center/. Accessed 20 Jan 2013
26. Park K, Favrel J (1999) Virtual enterprise—information system and networking solution. Comput Ind Eng 37(1–2):441–444
27. Repschlaeger J, Wind S, Zarnekow R (2011) Klassifikationsrahmen für die Anbieterauswahl in der Cloud. In: 41. Jahrestagung der Gesellschaft für Informatik, 2011
28. Strauch C (2011) Nosql databases. http://www.christof-strauch.de/nosqldbs.pdf. Accessed 20 Jan 2013
29. Transaction Processing Performance Council (2012) TPC benchmarks. http://www.tpc.org/information/benchmarks.asp. Accessed 20 Jan 2013
30. World Bank Group (2004) World Bank review of small business activities
31. Youseff L, Butrico M, Silva D (2008) Toward a unified ontology of cloud computing. Grid computing environments workshop, 2008
32. Yusuf Y, Sarhadi M, Gunasekaran A (1999) Agile manufacturing: the drivers, concepts and attributes. Int J Prod Econ 62(1–2):33–43

# An Infrastructure to Construct an Individualized Manufacturing Information System for Small and Medium Manufacturing Enterprises

**Joseph Oh, Bo-Hyun Kim and Jae-Yong Baek**

**Abstract** Small and medium manufacturing enterprises (SMMEs) face many difficulties when introducing their manufacturing information systems because of realistic limitations such as the large initial investment needed to buy the system, the burden of maintaining staff to operate it, and continuous payment of maintenance costs, etc. However, most systems are not used properly due to the characteristic difference between SMMEs' shop-floors and their functions, the lack of understanding concerning their many complex functions, and so on. To overcome the situation, we propose an infrastructure to support the construction of the individualized manufacturing information systems for SMMEs. The infrastructure consists of a Manufacturing Application (MfgApp), Plug-and-Play (PnP) Platform, and a Manufacturing Application Store (MfgAppStore) such as Apple's business model. The MfgApp is a small-sized application software to treat specific manufacturing tasks and is performed only on a PnP Platform. The PnP Platform includes a PnP Developer which provides developers of MfgApps with a development toolkit containing a common database, user interface, and so on, and a PnP Browser which manages and executes MfgApps. The MfgAppStore is the online marketplace on the Internet to register new MfgApps that have passed the peer review process and are made available to purchase by users of SMMEs. Each SMME is able to construct its own manufacturing information system using a PnP Browser with MfgApps selectively downloaded from the MfgAppStore. We are applying the prototype infrastructure to some SMMEs of the mold industry to validate the proposed concept.

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## 1 Introduction

Small and medium manufacturing enterprises (SMMEs) in Korea, which include most domestic manufacturing enterprises, are supporting the substructure of value chains. Therefore, the growth of SMMEs should be accompanied for the sustainable growth of the manufacturing industry. However, until now, the manufacturing business in Korea has been developed centered mainly on large manufacturing enterprises. Due to that, SMMEs are relatively weak in technological power and productivity compared to larger manufacturing enterprises. Recently, in Korea, with employment and shared growth becoming the leading topic of conversation, universities, research institutes, and governments are attempting to improve the productivity and technological competitiveness of SMMEs. One of these attempts is to support SMMEs utilizing Korea's outstanding information technology (IT) [1].

Since utilization of the IT is closely related to national economic development, major countries of the world are promoting industrial innovation as a core policy task. That is, OECD countries are emphasizing the utilization of IT as one of four main propelling engines to improve the productivity of manufacturing enterprises, and the United States Department of Commerce recognizes the IT industry as a prime mover of the new economy (High Growth, Low Unemployment, and Low Price). As such, despite efforts for the reinforcement of IT related infrastructure at the national level, most SMMEs are still utilizing IT at an elementary level such as documentation or simple tasks, and most CEOs are still skeptical concerning the productivity improvements by utilizing IT. This is because when SMMEs introduce IT, they should consider various burdensome factors that inevitably follow, such as securing fully responsible personnel, the cost of continuous maintenance, and the adaptation to new IT systems. In particular, even though SMMEs introduce a high-priced and package-typed IT solution, they restrictively utilize only a part of the functions of the introduced system [2, 3].

As a method to overcome such realistic limits, this study proposes an information infrastructure with which SMMEs are able to establish an individualized information system (IIS) by selectively combining desired IT functions. With the infrastructure, SMMEs are able to establish the IIS by purchasing the functions required to perform actual work without purchasing a high-priced and package-typed IT solution.

This paper is composed as follows: Section 2 presents the definition and configuration elements of the infrastructure for constructing the individualized customized information system (ICIIS), and the model to be applied to SMMEs, which are dealt with in this study. Sections 3 and 4 describe the *Plug-and-Play* (*PnP*) *Platform and Manufacturing Application* (*MfgApp*), which are configuration elements of the ICIIS for SMMEs. Lastly, Sect. 5 presents the significance and effects of the result of this study.

## 2 Infrastructure for Constructing Individualized Information System

### *2.1 Components of ICCIS*

The *Infrastructure for Constructing Individualized Information System* (*ICIIS*) proposed by this study signifies a hardware and software base required for individuals or enterprises to realize an IIS shown in Fig. 1. That is, the information infrastructure consists of: (1) IT devices, (2) application software as IT content; (3) operation platform which manages and operates the application software, (4) development tool of application software for developers, and (5) a business model as an intermediary connecting the user and the developer.

The IT device signifies the hardware in which the application software is installed and utilized, and the application software refers to a small scaled software function used by individuals or users in various enterprises. The operation platform is a supporting tool which comprehensively operates and manages the installation, modification history, interconnection, etc., of the application software. The development tool refers to the software development kit (SDK) which allows the application software to be operated at the operation platform consistently in the aspects of forms and functions. Lastly, the business model is an online market where the application software is able to be purchased and sold, where users are able to buy the necessary application software, and where developers are able to sell application software as a product.

### *2.2 ICIIS for SMMEs*

The *ICIIS for SMMES* proposed in this study has been constructed based on the infrastructure shown in Fig. 1. The category and name of each configuration

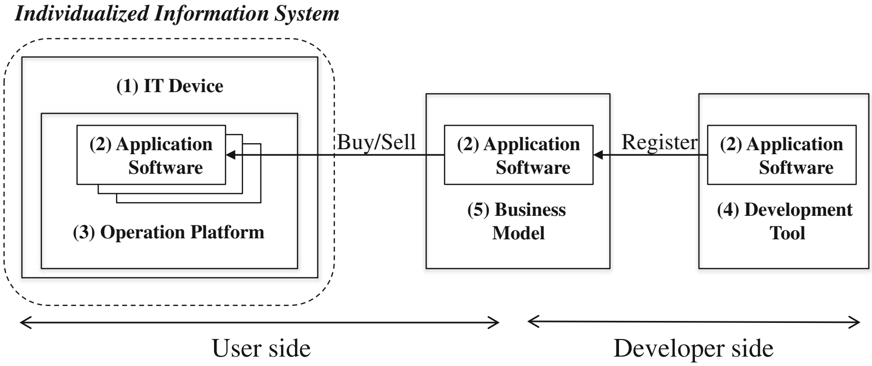


**Fig. 1** The infrastructure for constructing individualized information system (ICIIS)

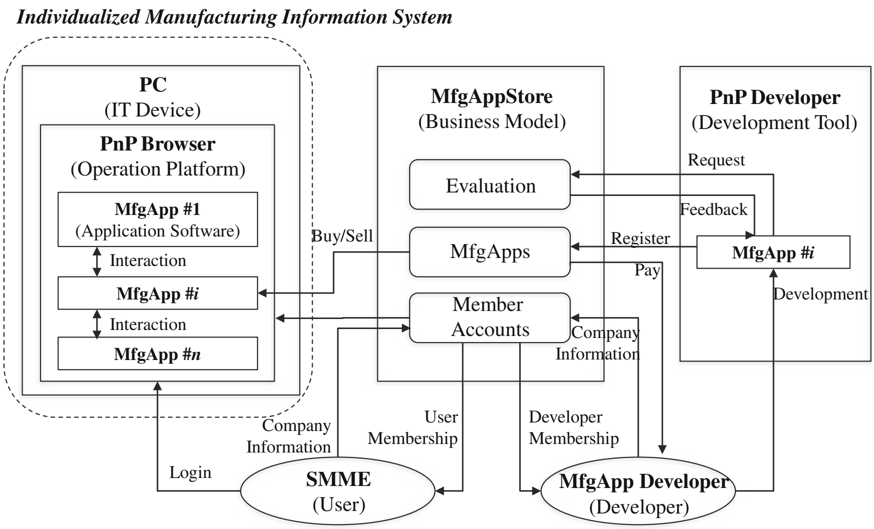


**Fig. 2** The infrastructure for constructing individualized information system (ICIIS) for small and medium manufacturing enterprises (SMMEs)

element are as follows. The IT device is a general PC owned by most SMMEs. The Application Software is referred to as the *Manufacturing Application* (*MfgApp*) taking into account the characteristics of the manufacturing enterprise which serves as a customer. The range of the MfgApp is the collection of functions necessary for executing specific tasks inside an enterprise. As such, SMMEs are able to select only those MfgApps that are necessary according to the task execution range and utilize them as customized functions. The *Plug-and-Play* (*PnP*) *Browser* performing the role of the operation platform stores their history such as installation and upgrade, operates them in a consistent environment, and manages data related to them. The *Plug-and-Play* (*PnP*) *Developer*, a development tool for developers, allows the MfgApp to be developed easily and consistently. The aforementioned PnP Browser and PnP Developer are commonly called the *PnP Platform*, which will be described in greater detail separately in Sect. 3 since it is an important item in this study. The last element, the Business Model, is referred to as the *Manufacturing Application Store* (*MfgAppStore*), which is an online open market where the MfgApp is able to be purchased and sold. The MfgAppStore helps developers verify and register the MfgApp, and provides the functions by which SMMEs are able to easily search or purchase an MfgApp [4, 5].

As shown in Fig. 2, the basic flow of the ICIIS for SMMEs is as follows: A developer registers the MfgApp developed using a tool called PnP Developer to the MfgAppStore, and SMMEs run the MfgApp purchased from the MfgAppStore on the PnP Browser. In addition, the developer signs up to be a member of the MfgAppStore. Then, the feasibility and effectiveness of the MfgApp developed by the developer are evaluated. If the MfgApp passes evaluation, it is registered to the

MfgAppStore. On the other hand, SMMEs sign up to be the member of the MfgAppStore and use the MfgAppStore and PnP Browser with the account provided from the MfgAppStore. SMMEs perform login to the MfgAppStore to buy the desired MfgApps and login to the PnP Brower to utilize the purchased MfgApps freely.

## 2.3 *Difference of Information Infrastructures Between the Individual and the Enterprise*

In the case of the information infrastructure described in the previous section, the details of the configuration elements differ depending on the object, even though the overall concepts are the same. The representative infrastructure for individuals is a mobile-based platform, which corresponds to Apple's App Store and Google's Android Market model. The common point of the two cases is that an infrastructure is constructed which allows an individual to buy and download the desired application software from an online market.

Table 1 shows the comparison and description of the aforementioned information system construction environment for individual users and SMMEs in the aspects of five configuration elements. As shown in Table 1, the two infrastructures exhibit difference in three aspects. Firstly, the configuration and characteristics of the application software vary due to the fact that the users to be applied are different. That is, in the case of the application software for an individual, its contents are configured according to the preference and personality of a target individual customer, while in the case of the application software for an enterprise, its contents are configured taking into account the tasks and production site characteristics of a manufacturing enterprise. Secondly, the IT devices used by users are different. The information infrastructure for an individual is constructed based on the mobile device owned by an individual while the application software for an enterprise is constructed based on a PC used most commonly by SMMEs.

**Table 1** Difference in configuration elements for the customized informatization

| | Customized informatization for individual users | | Customized informatization for SMMEs |
|---|---|---|---|
| | Apple | Google | |
| (1) IT device | Smart device (iPhone, iPAD) | Smart device (Android Phone, Tab) | PC |
| (2) Application software | Application | Application | Manufacturing applications |
| (3) Operation platform | iOS | Android | Plug-and-play browser |
| (4) Development tool | iPhone SDK | Android SDK | Plug-and-play developer |
| (5) Business model | AppStore | Google Play | Manufacturing application store |

Thirdly, there is a problem with information links between application software. In the case of the information infrastructure for an individual, since there are not many links between application software in the mobile device, most application software is independent, while in the application software for an enterprise, the link between applications should be considered importantly due to the close relation between the internal tasks of individual enterprises [6, 7].

## 3 PnP Platform

As mentioned in the previous section, the PnP Platform is divided into the PnP Developer, which is a platform for MfgApp developers, and the PnP Browser, which is a platform for MfgApp users and SMMEs. Figure 3 shows the image screens of the PnP Developer and PnP Browser implemented as an example by this study. This section provides a rough description of the PnP Developer and PnP Browser.

### *3.1 PnP Developer*

The PnP Developer is a development tool kit providing a development library and function to allow the MfgApp to be developed consistently. Table 2 shows four major modules provided by the PnP Developer. The UI development module is used when designing the user interface (UI) of the MfgApp. Through that module, the source code of the program is automatically created according to the basic screen design. In other words, if a developer defines the major information of the MfgApp and designs the UI, the UI development module automatically creates the source code by binding the major defined information and UI information. In addition, since it is possible to process database input/output using that module, a developer is able to easily implement the initial screen of the target MfgApp. The

(a) (b)

**Fig. 3** PnP platform: **a** PnP developer, **b** PnP browser

**Table 2** Major functions of the PnP developer

| Major module | Detail function |
|---|---|
| UI development module | Creates internal screen information of the MfgApp |
| | Screen UI design |
| | UI information binding |
| | Creates the program source code automatically |
| Common API module | MS Excel interlocking method |
| | Data format processing method |
| Screen template management module | Provides the basic screen template |
| | Connects the UI development module |
| Integrated development management module | Manages development environment |
| | Manages terminology for work |
| | Manages database objects |

common Application Programming Interface (API) module provides a set of the functions of the MfgApps frequently used or complicated to improve the software development efficiency. The PnP Developer provides approximately 100 common APIs including MS Excel interlocking method, data format method, etc. The Screen Template Management Module is a function which provides MfgApp screens by patternizing some of them. It improves the development standardization and productivity, and provides a consistent program user environment. Lastly, the Integrated Management Module inputs the MfgApp development process of 'Analysis → Design → Development → Distribution → Post Management' in a database for its systematic management. It is usefully utilized for the development and post management of the MfgApp.

## 3.2 *PnP Browser*

The PnP Browser is a tool which performs integrated operation and management of the selected MfgApps. All MfgApps are run by the PnP Browser. The PnP Browser has three major functions: (1) MfgApp Operation Management, (2) MfgApp Version Management, and (3) Basic MfgApp Management. The MfgApp Operation Management Function allows all MfgApps purchased from the MfgAppStore to be used under the same environment. If the MfgApp purchased by a customer is updated, the MfgApp Version Management Function automatically connects the MfgApp to the MfgAppStore to update it to the latest version. Therefore, it is not necessary for a user to check version information one by one in order to update the MfgApp purchased. Lastly, the PnP Browser provides embedded MfgApps necessary for SMMEs to perform basic work. Currently, it provides 10 types of basic MfgApps. Those basic MfgApps were developed to prevent duplication of a basic function and to perform integrated management of master data for common use. Table 3 shows the list of basic MfgApps supported by the PnP Browser.

**Table 3** List of basic MfgApps

| No. | Name | Description |
|---|---|---|
| 1 | Application management | Performs integrated management of MfgApps purchased from the MfgAppStore |
| 2 | User management | Manages the information of logged in users who utilize the PnP Browser |
| 3 | Common code management | Performs integrated management of the common code information used by the MfgApp |
| 4 | Corporation/ workplace management | Manages information on corporations and reported workplaces |
| 5 | Department information management | Manages department information including department name, department manager, etc |
| 6 | Employee management | Manages basic information including the name, address, position, etc., of officers and staff |
| 7 | Customer information management | Manages the basic information including the company name, contact point, address, etc. of customers |
| 8 | Item information management | Manages item information including the item name, model, unit, size, etc |
| 9 | Project management | Manages basic information including the project name, period, PM, etc |
| 10 | Warehouse management | Manages warehouse information including warehouse name, as well as information as to whether it is used or not |

# 4 Interaction Between MfgApps

## *4.1 MfgApp and Database*

Since various works performed inside an enterprise interact with each other according to a specific process, the information interaction between MfgApps is very important to construct a customized information system for SMMEs. That is, MfgApps need the process to share and reprocess some pieces of information in order to perform work inside an enterprise. The interaction between material procurement management and stock management works is an example of the information interaction between MfgApps. In general, after purchasing materials, the person in charge of procurement management hands over the information including the name, purchase quantity, purchase date, warehoused date, etc. The person in charge of Stock Management checks for the storage, release, and return of the materials with the information, and performs inquiry about materials in shortage.

To achieve information interaction between MfgApps, it is necessary to share information at the database level. To do so, the database should be first established. However, it is significantly burdensome for SMMEs to establish a database independently. For these SMMEs, this study proposes a cloud service structure that can provide such a database server online. As a matter of fact, it may be required for enterprises to maintain an independent server for reasons of security.

**Table 4** Database type

| Database name | Name of internal table |
|---|---|
| Core database | MfgApp information, customers, user accounts, etc |
| Basic database | Departments, employees, customers, items, etc |
| Extended database | (Added and named by a user as necessary) |

Therefore, this study designs a cloud service so that a database server is able to be separately installed inside an enterprise. Table 4 shows the types of databases designed under such a structure. The databases including MfgApp information are divided into three types: The *Core Database* stores information necessary for classifying the MfgApp purchased by specific users among MfgApps. Therefore, user account and MfgApp table purchased by the user, etc., are located in the database. Here, in order for the MfgApp to be run on the PnP Browser, these tables should be referred to. The *Basic Database* includes master data which is able to be used in duplication in multiple MfgApps, where tables of departments, employees, items, etc., are located. Lastly, the *Extended Database* stores characteristic information needed by the MfgApp in addition to the master data included in the Basic Database. Accordingly, in the *Extended Database*, when a new MfgApp is registered, a new table is created additionally, or some of existing tables are updated. The newly created table is named by the developer according to the Naming Rule guideline.

Table 5 shows the way the internal table of each database type is referred to the MfgApp. The types of the MfgApps shown in Table 5 are divided into two: Firstly, the *Basic MfgApp* is, as described in Sect. 3.2, the MfgApp built in the PnP Brower, which does not need to be purchased from the MfgAppStore. On the contrary, the *Selective MfgApp* is the MfgApp purchased from the MfgAppStore by SMMEs. Those two types of MfgApps refer to all tables of the Core Database in order to identify specific MfgApps. In the case of the Basic Database, the two types of MfgApps refer only to some of the tables needed to run them. The *Selective MfgApp* refers only to the tables of the Extended Database created together when it is developed. The MfgApp has more than two tables which are able to be managed directly. In the case of such tables which are able to be directly managed, a user is able to read and write data in the corresponding tables through specific MfgApps. In addition, even in the case of tables which are not to be managed directly by the MfgApp, it is possible to read the corresponding data

**Table 5** Tables referred to for each MfgApp

| | Basic MfgApp | Selective MfgApp |
|---|---|---|
| Internal table of core database | Refer to all tables (possible to read data) | Refer to all tables (possible to read data) |
| Internal table of basic database | Refer to some tables (possible to read and write data) | Refer to some tables (possible to read data) |
| Internal table of extended database | | Refer to some tables (possible to read and write data) |

through the API opened within the allowable range so that the aforementioned information interlocking between MfgApps is able to be achieved. The Basic and Selective MfgApps directly manage the designated tables in the Core and Extended Databases, respectively.

## 4.2 Plan for Interaction Between MfgApps

As shown in Fig. 4, the interaction between MfgApps is divided into two. The $\alpha$ and $\tau$ in Fig. 4 show the tables of the MfgApp and Database, respectively. In the case of the plan for *the Type 1 Interaction*, the Selective MfgApp refers to the tables of the Basic Database managed by the Basic MfgApp. That is, if the basic information on departments, employees, customers, items, etc., is stored in the corresponding tables through the Basic MfgApp, the Selective MfgApp refers to the information. Developers refer to the desired basic information through the open APIs of the PnP Developer. In the case of the plan for *the Type 2 Interaction*, one of the two Selective MfgApps developed by the same company refers to the other MfgApp. This means that a developer internally uses the APIs through which the information of a specific table can be referred to, without opening it externally. That is, a developer can sell several MfgApps together by emphasizing that

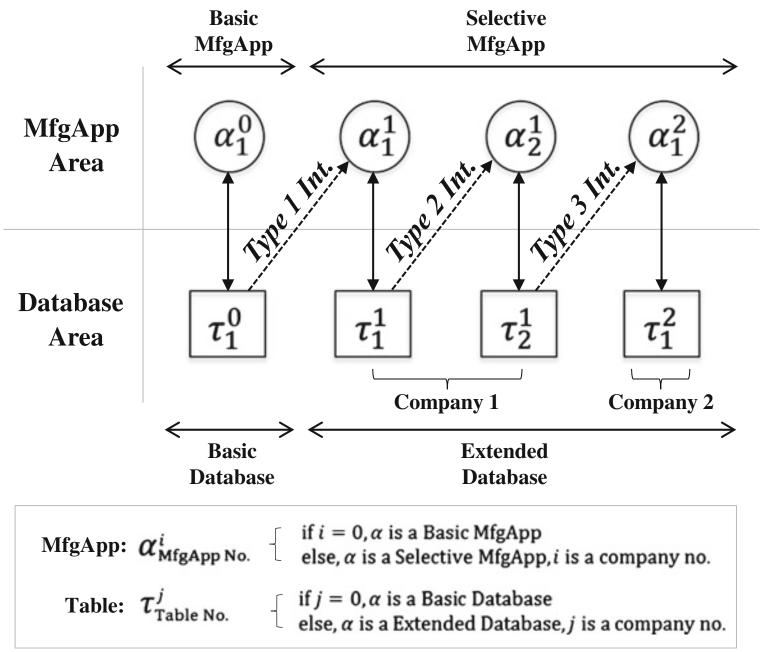


**Fig. 4** Three plans for information interaction between MfgApps

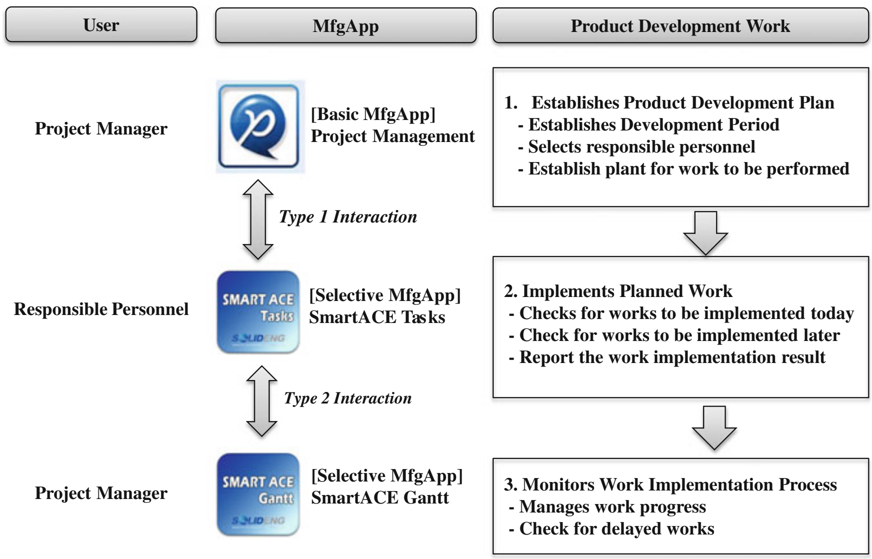


**Fig. 5** MfgApp utilization scenario at the time of product development

multiple MfgApps it developed can be interlocked. In the case of the plan for *the Type 3 Interaction*, a specific Selective MfgApps refers to an MfgApp developed by other companies. Since the plan has problems of security and disclosure of development know-how, it requires effort to solve these problems as well as the strategic tie-up between developers. These three plans for the interaction between these MfgApps have many problems to be solved technically and strategically as the interaction plan moves from Type 1 to Type 3.

## 4.3 Scenario Using MfgApps

Figure 5 shows a virtual scenario where a manufacturing enterprise utilizes the MfgApp for product development. In the virtual scenario, the product development work is divided into: (1) Establishment of Product Development Plan; (2) Execution of Planned Work; and (3) Work Execution Process Monitoring. The project manager (PM) and responsible personnel can utilize the MfgApps for each of their tasks divided into three types. First, the project manager establishes a product development plan including establishment of development period, selection of responsible personnel, a plan for work to be implemented, etc., with the Project Management, a Basic MfgApp. If the project manager establishes a product development plan, detail tasks are implemented according to the established plan. At that time, the person responsible for each task checks the tasks to be performed today and later with *SmartACE Tasks*, a Selective MfgApp and inputs the task implementation results to report it to the project manager. The project manager checks the task implementation process of each responsible person and its result with *SmartACE Gantt,* a Selective MfgApp. With that, the project manager checks the progress and delay of tasks and performs project management so that product development work can be implemented smoothly. As such, the information interlocking between MfgApps is necessary in order for work at the time of product development to be implemented successively. The Type 1 Interaction was made between the MfgApps, Project Management, and SmartACE Tasks and the Type 2 Interaction was made between the SmartACE Tasks and SmartACE Gantt.

## 5 Conclusions

This paper proposed an ICIIS as a method to improve the productivity of SMMEs. The proposed infrastructure consists of five elements: General PC, MfgApp, PnP Browser, PnP Developer, and MfgAppStore. In addition, unlike the information infrastructure based on existing mobile systems, in the case of the proposed infrastructure, information interlocking between MfgApps was dealt with as an important issue. As such, this study presented the structure and three information interlocking plans by which work data between the MfgApps is able to be shared at the database level.

Since SMMEs are able to construct an IIS by selecting only the necessary IT functions through these infrastructures, the investment cost is relatively low and little time is required compared to existing package based IT solutions. The result of this study will have a direct influence on SMMEs and a positive influence on the IT industry due to the expansion of the pool of designers and developers who develop MfgApps. As a result, this study has a great significance in that both SMMEs using MfgApps and developers developing MfgApps are able to create a new form of informatization ecosystem to be profitable.

## References

1. Black SE, Lynch LM (2001) How to compete: the impact of workplace practices and information technology on productivity. Rev Econ Stat 83(3):434–445
2. Reuther D, Chattopadhyay G (2004) Critical factors for enterprise resources planning system selection and implementation projects within small to medium enterprises. Engineering management conference 2004, proceedings of 2004 IEEE international, 2, 2004
3. Markets and Markets, Industrial Controls (SCADA, PLC, DCS) & Factory Automation (Field Devices, MES, ERP) Market: Global Forecast and Analysis Till 2016, 2012
4. http://mfg-app.co.kr. Accessed 20 July 2012
5. http://mfg-app.co.kr:8088/index.htm. Accessed 20 July 2012
6. https://developer.apple.com/devcenter/ios/index.action. Accessed 20 July 2012
7. http://source.android.com. Accessed 20 July 2012

# Business Process Monitoring and Management in Virtual Enterprise Through Interactive User Interface Layer

**Ahm Shamsuzzoha, Filipe Ferreira, Américo Azevedo, José Faria and Petri Helo**

**Abstract** This research provides mechanisms that facilitate to monitor and manage of Virtual Enterprise (VE) collaborative business processes in an efficient and effective way. First, it shows a self-contained process monitoring tool specification that contains the following main functionalities: events capturing from a workflow engine, business activity monitoring, process analytics and monitoring rules definition and evaluation. An interactive user interface layer in the form of dashboard is then highlighted within the scope of this research with the objective to monitor the VE operational processes. The dashboard will be the integration platform for a set of components that allow the establishment and operation of VE successfully. This platform enables a seamless integration of business processes and provides an end-to-end ICT solution among the VE member organizations. The work presented in this paper is developed within the scope of the European Commission NMP priority of the Seventh RTD Framework Programme for the ADVENTURE (ADaptive Virtual ENterprise ManufacTURing Environment) project.

## 1 Introduction

Nowadays, the global financial crisis together with the low-cost manufacturing countries, have stressed the need of European SMEs, to re-invent the concept of enterprise joining forces by collaborating with outside partners, in order to

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continue competitive. Collaborative networks, especially in the form of virtual enterprises are a good way to achieve business goals, enter in new market segments, and answer quickly to business opportunities with special and innovative requirements.

Currently, European SMEs operate in an open, global market, facing strong competition from large companies, and from non-European companies, where, among other things, low labor costs, and more flexible labor legislations represent a strong competitive advantage. Factors like price and quality are no longer a competitive advantage. This reality, together with the global economic crisis, turns innovation, product customization, and quick time to market into key success factors [1]. Therefore, manufacturing has to improve its innovation activities and come up with new ideas to transform old products and processes to new cost effective and efficient ones. However, many of the manufacturing companies are SMEs with only a few of them having capacity to implement innovative manufacturing technologies. SMEs have not benefited the most from the advantages that modern business strategies and sophisticated technologies can offer. These advantages have mostly been limited to major companies so far. The use of manufacturing execution systems among SMEs is rare. Currently, SMEs are mostly component suppliers for leading companies and the complexity of operational processes is limited and in most cases is still paper based. The economic recession has fragmented the market place and the number of SMEs that have lost the links to the OEM's has continued to grow. This has left many SME's in a position where they need to find new customers and also reduce their base costs to compete in an open market.

Providing SMEs with tools and methods to build, optimize, monitor, and maintain virtual factories by establishing collaborative manufacturing processes will help them to provide new, highly-developed products, as well as to re-factoring existing manufacturing processes [2]. Manufacturing processes need to be monitored with the objective to successfully control them. In order to control a process, it is necessary to update the real-time process information as are coming from different sources. By integrating information from sensors and other sources commonly known as "Internet of Things", it is possible to generate a realistic estimation of the current "status of manufacturing" across companies (SMEs) just as within one company as it is today. This information needs to be provided through an open infrastructure which is nevertheless able to constrain data access and handling based on privacy and other concerns. Using Key Performance Indicators (KPIs), processes can be monitored and governed; here, it is necessary to recognize very early if certain constraints cannot be met and initiate adequate countermeasures. In particular, environmental sustainability is becoming a more and more important aspect of manufacturing tasks. The ability to have an overall view of the processes within an organization and have clear information regarding delivery times and dates is a clear advantage for any business. It provides the competitive edge for reducing costs of delivery, reduced stock levels, and eliminating waste [3, 4].

The essential issue tackled in this paper and underlying research question refer to the virtual enterprises manufacturing processes monitoring. In this research, it is of interest to face the following four research questions: (a) what are the requirements for virtual enterprises manufacturing processes monitoring?, (b) what are the functionalities needed to process monitoring?, (c) how to design a loosely coupled process monitoring module, and finally (d) how to integrate it in a virtual enterprise interactive user interface management platform?

This paper is organized as follows. Section 2 reviews the literature about virtual enterprises characteristics, business activity monitoring, and process analytics concepts in order to build a theoretical background and to support the business process monitoring for virtual enterprises specification. Section 3 presents the research methodology. Section 4 contains the main contribution presenting the results of this research with the requirements, functionalities, and design of a loosely coupled collaborative manufacturing process monitoring tool. Section 5 presents the interactive user interface layer to monitor and manage those manufacturing processes. Finally, Sect. 6 concludes the paper.

## 2 Foundations and Research Topics

### *2.1 Business Activity Monitoring*

Business Activity Monitoring describes the processes and technologies that provide real-time situation awareness, as well as access to and analysis of key performance indicators, based on event-driven sources of data. Business Activity Monitoring (BAM) is used to improve the speed and effectiveness of business operations by keeping track of what is happening now and raising awareness of issues as soon as they can be detected. BAM applications can emit alerts about a business opportunity or problem, drive a dashboard with metrics or status, make use of predictive and historical information, display an event log and offer drill-down features. BAM also “drives the innovation by detecting events, filtering them, and triggering business process management (BPM) solutions”. BAM may enable new ways of performing vertical applications that will result in significantly increased revenue or cost savings for an enterprise [5].

Although the purpose of BAM technology is to provide business users with real-time access to, and analysis about, key performance indicators, the level of complexity in the solution can widely vary. BAM functionality is based on a relatively simple architecture. Alerts and frequently updated displays are driven by a processing and analytic engine that is supplied with a stream of events that is received or collected from a variety of sources working in real time. BAM must address the general requirements and each the basic features of four architectural categories: Event collection, filtering and transformation, Delivery and display, analysis and processing, and Operational databases.

The current challenge is to bring BAM functionalities to the Manufacturing SMEs field, through a web based platform. Thus, SMEs can manage their collaborative processes without the need of large ICT investments as in many cases they are not capable to do such type of investments [6, 7].

## 2.2 Complex Events Processing in Distributed Systems

Complex event processing (CEP) is an emerging network technology that creates actionable, situational knowledge from distributed message-based systems, databases, and applications in real time or near real time. CEP can provide an organization with the capability to define, manage, and predict events, situations, exceptional conditions, opportunities and threats in complex, heterogeneous networks. Many have said that advancements in CEP will help advance the state-of-the-art in end-to-end visibility for operational situational awareness in many business scenarios. These scenarios range from network management to business optimization, resulting in enhanced situational knowledge, increased business agility, and the ability to more accurately (and rapidly) sense, detect and respond to business events and situations. CEP can be applied to a broad spectrum of information system challenges, including business process automation, schedule and control processes, network monitoring and performance prediction, and intrusion detection. The publish/subscribe mechanisms allow loosely coupled exchange of asynchronous notifications, facilitating extensibility, and flexibility. The channel model has evolved to a more flexible subscription mechanism, known as subject-based addressing, where a subject is attached to each notification [6]. Subject-based addressing features a set of rules that defines a uniform name space for messages and their destinations. This approach is inflexible if changes to the subject organization are required, implying fixes in all participating applications.

## 2.3 Virtual Enterprise

In recent years, a diversity of new organizations based on collaboration have emerged (the so-called collaborative networks). These coalitions between firms were created to face market challenges and overcome the limitations by joining abilities. Thus, companies with specific knowledge and competencies, seek to align with other companies to meet requirements and thus exploit and quickly answer to emerging business opportunities, forming a Collaborative Network in the form of Virtual Enterprise [1, 5, 8].

The definition of Virtual Enterprise (VE) used in this paper is based on the definition proposed by Camarinha-Matos et al. “A Virtual Enterprise represents a temporary alliance of organizations that come together to share skills or core competencies and resources, in order to answer to a specific business opportunity” [1].

The establishment of a VE is triggered by a new business opportunity. Consequently, partners with the skills needed for product development and manufacturing are selected. After the negotiation of contracts for signature, the virtual enterprise is ready to start its operation [2, 4]. Normally there is an entity which performs the processes of partner search and selection, and configures suitable infrastructures for VE formations and commitment. This entity is normally the one that identifies the business opportunity as is known as the VE Broker [2, 5, 9].

Temporality is an important characteristic of virtual enterprises because it seeks to operate in the short run, and aims to achieve business opportunities in the short and medium term. Virtual enterprises are expected to overcome geographic and temporal barriers, bringing together dispersed firms. The prevailing feature of the virtual enterprise is the complementarity of skills between partners, i.e., each network partner dominates a sub-process or has a specific knowledge about a process or product. All partners have to contribute directly or indirectly in creating value. Thus, the combination of skills provides synergy and greater flexibility to meet customer requirements.

## 3 Research Methodology

This study followed 4 steps. Firstly, we reviewed the existing literature in areas such as virtual enterprise, business activity monitoring, and complex events processing. Secondly, we analyzed a set of open source and commercial Business Process Management Suites (BPMS), which contain process monitoring functionalities. Thirdly, we carried out a requirement elicitation process, which includes semi-structured interviews to 3 different business enterprises: a machinery manufacturing SME located in north of Portugal (Engineer-to-Order business model), an electronic and automation SME located in United Kingdom (Engineer-to-Order) and a big Assembly-to-Order company located in Finland. The results of these 3 steps conducted the process monitoring requirements list, which answers our first research question and functional specification, answering second research question. The fourth step carried out in a set of discussions with the platform development team to understand the integration and technical requirements. This fourth step answers to the third and last research questions. In next section, we introduce the process monitoring specification for virtual enterprises as well as its integration with a complete VE management platform.

## 4 Process Monitoring for Virtual Enterprises Approach

The Process Monitoring (PM) Component will be an independent component that relies on events as provided by a process execution engine. This way, the PM component can be directly applied to every process engine. This component

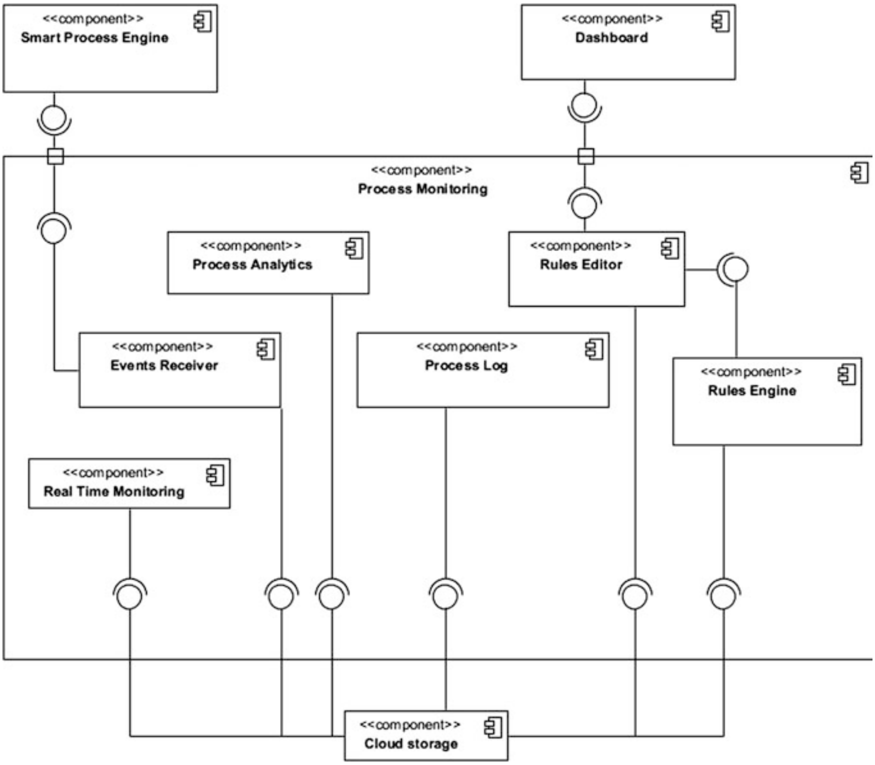


**Fig. 1** Virtual enterprise monitoring components diagram

should provide real time, log ,and performance data relating to the collaborative manufacturing processes. As depicted in Fig. 1, it contains 5 main sub-components: Events Receiver; Real-time Monitoring; Process Analytics; Process Log, and Rules Engine.

## *4.1 Events Receiver*

The Events Receiver captures the events produced by the Process Execution Engine and stores the relevant event data within the Cloud Storage. The different events may be outlined as follows: Events from the Dashboard and Process Designer will include all activities conducted by brokers regarding the process modeling and optimization. Events from the Process Execution component will include all process execution related aspects. Processes describe the flow of invocation of all other components, including those responsible for gather the raw data related with the manufacturing activities from all partners information systems (e.g., Enterprise resource planning, Manufacturing Execution systems, smart sensors installed on the equipment's/products which are capable to send information directly to a cloud based data storage).

## 4.2 Real Time Process Monitoring

The Real-time Monitoring sub-component provides a live view of the ongoing processes, using the same interface as Process Editor Component, so that Virtual Factories brokers may decide to undertake flow adjustments and efficient decisions, in order to improve the performance of the manufacturing processes. Thus, the interface of the Process Model Editor must be extensible, in order to include on click events, change graphic elements properties (e.g., changes the color of a given task depending on its status). In order to provide a graphical representation of the process models, the Process Designer will save the graphical representation of the model into format. In this way the Real-time Monitoring will be able to manipulate and enrich the graphical representation of the model, adding the necessary information to show all the real-time monitoring information as captured by the SPE. The Process Editor will also expose read only behavior mode, and calling interfaces, so that Monitoring can use the SVG option to represent information on top of a specific technology for visualization. Thus, monitoring can show the current execution status of a process model instance.

## 4.3 Process Analytics

The Process Analytics sub-component provides key performance indicators related to the manufacturing processes and VE partners. Most process analyses are based on the aggregation, correlation, and evaluation of events that occur during the execution of a process. These events represent state changes of objects within the context of a business process. These objects may be activities, actors, data elements, information systems, or entire processes, among others. For example, activities can begin and end, actors can log on and off, the values of data elements may change, and many other events can occur over the typical lifespan of a process instance. The scope of events considered for analysis determines the context envelope of the analysis. In other words, a narrowly scoped process analysis might focus on a single activity, by examining just those events that originated from this activity, its performers, and the resources that are input in and output from the activity. In contrast, a more widely scoped process analysis might include events from multiple instances of a process; involve data sources outside the organization, and events from non-process-centric information systems.

### 4.4 Process Log

The Process Analytics sub-component allows users to search for finished process instances and visualize historical data in a graphical interface. Serving the needs of both business and IT domain experts to monitor and understand business activities within SOA (Service Oriented Architecture) and Cloud deployments, PM is not only designed to monitor SOA metrics, but can also be configured to monitor KPIs through the Process Analytics sub-component.

### 4.5 Rules Engine

The embedded Rules Engine may trigger automated actions such as automatic notification of decision makers or automatic reprioritization of work. This configuration allows the automation of certain exception handling mechanisms, and results in the implementation of a simple sense-and-respond environment. Businesses need to measure and evaluate the success of their activities. The user interface allows users to manipulate data and create KPIs, which can be used for performance measurement. First, businesses must define specific tasks, since this allows them to manipulate data and carry out custom data operations. Analyzer tasks are used to organize the flow of functions, It is possible to build KPIs such that they become an inherent part of Process Monitoring. By building KPIs, you build business intelligence." Once KPIs have been built, this data has to be extracted out of the database.

Rules Engine and Rules Editor sub-components allow the definition of rules based on process execution delays that are evaluated by the Rules Engine. This component throws alerts to the Dashboard, as well as performs actions upon the Process Execution Engine. This Rule engine deals with creating notifications, alerts, and messages that may: Trigger the creation of new process instances, e.g., to write a message that updates an ERP system. Trigger the adaptation of a process, e.g., the automatic selection of a new VE partner/service, to improve delivery time or stop a process and require action from a VE broker.

## 5 Virtual Enterprise Management Platform Integration

In order to present a visual interface to the VE partners, it is essential to design and develop a user interface component known as 'Dashboard'. This Dashboard component can be used as the integration platform for monitoring and managing the VE manufacturing processes. This component is supported by other components, such as Data Provisioning and Discovery, Process Designer, and Process Monitoring. All the functionalities are visualized by the Dashboard in four functional groups: Process Design, Process Management, Partner Management, and Application Configuration. The Dashboard serves as a graphical user interface (GUI) to all VE functionalities. By using the Dashboard the user can create process templates and share the best practices with other business partners to improve the Virtual Factory Management process. The Dashboard provides convenience to users through a Web browser based interface, thus enabling users' access on any device that supports HTML and JavaScript. This component is configurable for VE partners with different roles allowing different views of the VE components.

## 5.1 Dashboard Overview

The Dashboard will act as a "cockpit" for VE users to see important system information in one single place, right after logging in. After logging in into the Dashboard user interface, the VE users will see a welcome page with an overview of all their manufacturing processes and their status information. Figure 2 presents an 'Overview of Dashboard Home Page', where the user can observe the overall high level status information of each of the processes that allows monitoring and controlling the collaborative activities, as needed to run a virtual enterprise successfully. Clicking on the tabs on menu bar will lead to a more detailed view of current processes of a VE user.

After logging in into the Dashboard user interface, the VE users will see a welcome page with an overview of all their manufacturing processes and their status information.

According to functional perspective, the Dashboard component can be classified into four functional groups such as Virtual Factory Process Design; Virtual Factory Process Management; Virtual Factory Partner Management and Application Configuration and Setup.

Each group includes different functionalities to realize Virtual Factory Management. For instance, Virtual Factory Process Design contains necessary supportive information related to design a virtual factory. It also provides template suggestions to VE brokers, in order to improve the process design action. This group includes functionalities such as Process Model Management (PMM), Process Model Editor (PME), Process Simulation, and Process Optimization.

The Virtual Factory Process Management deals with the activity that supports the execution, monitoring, and assessment of the business processes. This functionality group includes Real-time Monitoring, Process Log, Process Analytics, and Process Adaptation. When there is any potential risk during the Process Execution, an alert message or notification presents the detailed information to brokers. This alert message includes forecasting of delay or content related information such as "low stock level". If any process fails, process adaptation should be readily available to overcome it.

The Virtual Factory Partner Management provides basic functionality to maintain the profiles of the Virtual Factory Partners. This profile is populated with


**Fig. 2** Overview of the VE dashboard homepage

both the description of the attributes of the partners related to a specific business service such as capacity and capabilities, production lead-time, price level, KPIs, performance level, etc., and the level of process interoperability that allows them to join in a Virtual Factory successfully. The functionality of this group includes the useful information according to the user needs such as Profile Editor, Partner Finding, and Partner Analytics. The Application Configuration and setup group provides the ability to customize the application, which includes Configurable User Interface, Gateways Configuration, Alarms Configuration, Message Transformation, and Routing Configuration. This allows brokers to customize the process visualization according to their own needs.

## *5.2 Dashboard Component Structure*

The user interface component, ‘Dashboard’ if developed from scratch should include three sub-components such as: content presentation, user navigation, and data manipulation. All these three sub-components can be explained as follows with their corresponding specifications:

- Content presentation: Developers need to consider the presentation layer of the Dashboard, for instance appropriate chart types, table format, and the content presentation. The display’s parameters such as captions, type of chart or graph, minimum/maximum values, data source, color codes, and others should be defined properly.

- User navigation: The way the user navigates to other pages and how the pages are linked to each other should be considered. The user navigation affects the usability of Dashboard.
- Data manipulation: The Dashboard is used to update the Dashboard's internal database. It is important to ensure the content of Dashboard is up to date, hence the queries must run regularly to deliver information and refresh the data on Dashboard.

The purpose of the Dashboard is to visualize all the functionalities, so it is good to spend the core of implementation time on other design aspects. The Dashboard Component Structure (Fig. 3) gives a basic illustration of the Dashboard architecture. From Fig. 3 it is seen that the core of the Dashboard is the application server. Other sub-components of the Dashboard component can be detailed as in the following paragraphs.

a. *Web Browser*: The Client-Side Engine of Vaadin manages the rendering in the Web browser using Google Web Toolkit (GWT). It communicates user interaction and UI changes with the server-side using the User Interface Definition Language (UIDL), a JSON-based language. The communications are made using asynchronous HTTP or HTTPS requests.
b. *VE Portlet*: The VE Portlets are reusable and pluggable UI modules that are managed and displayed in the VE Dashboard. Portlets provide access to other VE Components. A portal page is displayed as a collection of non-overlapping Portlet windows, where each window displays a Portlet. Hence a Portlet (or collection of Portlets) resembles a Web-based application that is hosted in a portal. Some examples of Portlet applications in VE are Order Summary, Stock Levels, Notification, Process Status, etc. The Portlet can be collapsed, removed, and edited. The Portlet can be placed in different position by using drag and drop technique.

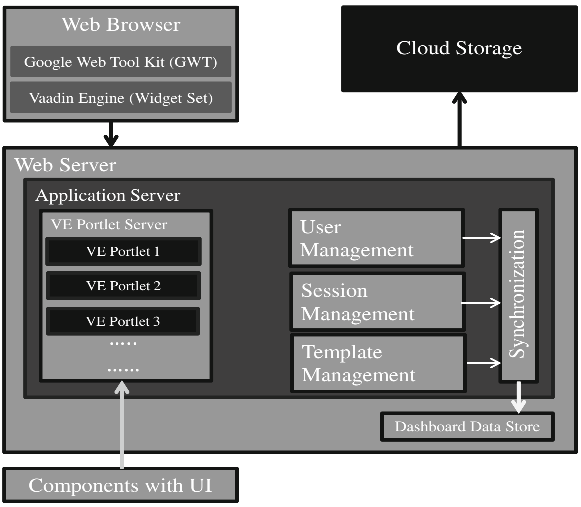


**Fig. 3** Dashboard component structure

c. *VE Portlet Container*: The VE Portlet Container is responsible for aggregating a set of Portlets that are to appear on any particular page. That means, a page can contain multiple Portlets and when the user interacts with one Portlet, it may need the other Portlets to react to the change immediately. The VE Portlet Container executes Portlets and manages their life cycle. It is the runtime environment for Portlets using the JSR 168/286 or WSRP specifications, in which Portlets are instantiated, used, and finally destroyed. The VE Portlet Container is responsible for aggregating the set of Portlets that are to appear on any particular page.
d. *Component with UI*: Several components within the VE need a UI. For instance, Process Designer, Process Monitoring, Process Optimization, Process Forecasting and Simulation, Process Execution, and Process Adaption. For each such component the UI can be designed and decomposed into several Portlets. Although these Portlets are responsible for different functionalities, they cooperate with each other. Therefore, a portal page contains a collection of non-overlapping Portlets.
e. *User Management*: User accounts within the VE platform will be managed. This Dashboard provides a UI to create, edit, and delete users. Roles with different privileges are created to manage the users.
f. *Session Management*: User sessions within the VE platform will be managed. User login information, user actions, and running Portlets will be tracked. Once the client requests are sent to the Web server, they are interpreted into user events for a particular session. Sessions are tracked using cookies.
g. *Template Management*: The configurable VE Dashboard will have a flexible UI to support the needs of different users, which means a portal page may display different Portlets to different users. Therefore, Template Management will allow users to create a role-or user-based view on the VE integration platform.
h. *Synchronization*: The User Management, Session Management, and Template Management need to be synchronized and managed together. The data will be directly loaded from and saved into Dashboard Data store, which could be integrated with Cloud Storage.
i. *Dashboard Data store:* The Dashboard Data store will be used to store all the related data to running a VE. For instance user information, login information, and application setting information, etc.

All the VE functionalities are presented through the Dashboard.

## 6 Conclusion and Further Research

This paper presents a complete loosely coupled tool capable of supporting Virtual Enterprise brokers in monitoring and controlling their collaborative manufacturing processes by using a holistic monitoring dashboard which uses a set of advanced technologies in order to gather, aggregate and thus, show real time information about their business at the operational level. This Monitoring tool is part of a broader platform developed in the scope of a European project. We propose a loosely coupled solution for the monitoring based on complex events processing and key performance indicators definition based on the overall stakeholder's point of view. Adopting this solution, VE's Brokers become capable to have real time information in a flexible way so that it can be used as pillar for decision makers.

Five modules compose this tool: Events Receiver; Real-time Monitoring; Process Analytics; Process Log; and Rules Engine. Events Receiver will be responsible for receiving the events published by the process execution engine and storing them in the Cloud Storage, so that all data will be available for future aggregation and analysis. The Real Time Monitoring will show the actual status of process instances using a holistic collaborative process live model. This way, it will be easy for the user to identify and track the process instances. Process Analytics will be an independent service that just queries finished process instances and show them to the user. The Business Activity Monitoring will be an independent service that will rely on the data stored by the Events Receiver in the Cloud Storage. The purpose is to allow the user to configure KPIs related to the manufacturing processes and then provide a graphical display in the Dashboard in order to track the KPIs. The Rules Engine will allow the user to define rules and associated actions. For that purpose, a graphical rules editor should be developed.

As next steps, we intend to implement this approach as part of a complete collaborative manufacturing environment management platform being developed in the scope of a European project. This platform will then be applied in the case studies identified before.

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## References

1. Camarinha-Matos LM, Afsarmanesh H, Galeano N, Molina A (2008) Collaborative networked organizations—concepts and practice in manufacturing enterprise. Comput Ind Eng
2. Carneiro Luis et al (2010) An innovative framework supporting SME networks for complex product manufacturing. Collaborative Netw Sustain World 336:204–211
3. ADVENTURE: D3.1 Global architecture. Deliverable D.3.1 of adventure project—adaptive virtual enterprise manufacturing environment FoF-ICT-2011.7.3 - 285220 (2011)
4. ADVENTURE: D3.2 Functional specification. Deliverable D.3.2 of adventure project—adaptive virtual enterprise manufacturing environment FoF-ICT-2011.7.3 - 285220 (2011)
5. Molina A, Velandia M, Galeano N (2007) Virtual enterprise brokerage: a structure-driven strategy to achieve build to order supply chains. Int J Prod Res 45(17):3853–3880
6. Buchmann AP, Bornhövd C, Cilia M (2005) Event handling for the universal enterprise. Inf Technol Manage 6, 123–148

7. Azevedo A, Almeida A (2011) Factory templates for digital factories framework. Robot Comput-Integr Manuf 27:755–771
8. da Piedade FR, Azevedo A, Almeida A (2012) Alignment prediction in collaborative networks. J Manufact Technol Manage 23(8):1038–1056
9. Azevedo A, Francisco RD (2007) Dynamic performance management in business networks environment. In: Cunha FP, Maropoulos PG (eds) Digital enterprise technology—perspectives and future challenges. Springer, New York, pp 401–408

# Part II
# Manufacturing Technologies and Intelligent Systems

# Conceptual Development of Modular Machine Tools for Reconfigurable Manufacturing Systems

**Nokucinga Majija, Khumbulani Mpofu and D. Modungwa**

**Abstract** Manufacturing industry is extremely broad and plays a key role in the global economy. However, there are rapid and continued technology changes due to rapid response required by the market challenges and customer demands, therefore the manufacturing industry needs to keep up with market demands at all the times. Reconfigurable manufacturing systems will enable manufacturers to produce a variety of goods within a short time and improve sales. Reconfigurable Machine tools (RMTs) together with Reconfigurable Manufacturing Systems (RMSs) are the new invention introduced in 1999 at the Engineering Research Center for Reconfigurable Manufacturing Systems (ERC/RMS). This paper presents the conceptual development of modular machine tools, by selecting and compiling a list of modules available commercially off the shelf. The machine tool is developed in such a way that it can be configured accumulatively in terms of degrees of freedom, to accommodate different reconfigurations of machine structures. As the modules can be assembled in different ways to create different types of tools capable of performing a variety of functions using the same hardware and software, depending on demand, one should be able to increase or decrease the number of degrees of freedom.

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## 1 Introduction

The rapid change of technology requires equipment which can manage to machine complex products within a short period of time. The newly invented machines possess customized flexibility to accommodate sudden changes in production and the concept formulation of the RMS was based on the development of machines which will combine the advantages of traditional manufacturing systems for manufacturing processes. Traditional manufacturing systems, which include dedicated line machines and flexible manufacturing systems, have been on the market since the inception of the 20th century, but lack the responsiveness which is required in the new market place. According to Koren et al. [1] responsiveness is an attribute enabling manufacturing systems to quickly launch new products on existing systems and to react rapidly and cost-effectively to market changes.

Today competition is driven by the development time, cost of the product and flexibility of machines to produce complex and varying products when needed. Reconfigurable manufacturing systems are a possible viable intervention to improve economic effectiveness in the light of global competition at the moment. These conditions require a responsive new manufacturing approach that enables [2]:

- The introduction of new product models to be undertaken very quickly and rapid adjustment of the manufacturing system capacity to meet market demands or changes.
- Quick adjustment of the new functions and process technologies into existing systems, and
- Easy adaptation to variable quantities of products for niche marketing.

Market changes include [2]:

- Changes in product demand
- Changes in current product
- Introduction of new product
- Changes in government regulations (safety and environment)

It is envisaged that the implementation of these machines will change the future of the manufacturing industry into a profitable business, especially for small and medium enterprise players. Theoretically a lot of investigation has been done on reconfigurable manufacturing systems at various universities, though the systems have not been extensively deployed into the market as yet, for example, the University of Michigan has built an arch-type Reconfigurable Machine tool (RMT) and other machines to demonstrate the basic concepts of the RMT design [3, 4].

The second section of this paper covers the literature review of the existing manufacturing systems and the newly invented machines-RMTS in the RMS paradigm. The development approach of the design will be covered in the third section, followed by the presentation of the two machine concepts which have been developed at Tshwane University of Technology (TUT) for further development purposes.

## 2 Literature Review of Current Manufacturing Systems

The review will give an overview of the Dedicated Manufacturing Line (DML), Flexible Manufacturing Systems (FMS), Reconfigurable Manufacturing systems (RMS), and manufacturing tools.

### 2.1 *Dedicated Manufacturing Lines and Flexible Manufacturing Systems Review*

The evolution and introduction of technological innovation in engineering is becoming prominent by the day; hence a need for constant improvement in manufacturing engineering to meet market demands. Many years ago before the invention of dedicated manufacturing systems, metal was worked manually using the basic hand tools such as hammers, files, scrapers, saws, chisels, and other equipment. This was not a challenge for small parts but for large and complex parts it was costly and time consuming. As the technology advanced dedicated manufacturing machines and flexible manufacturing machines were introduced to increase productivity and meet the mass production economies and flexibility respectively which was required by the market. However, the FMS are expensive since they possess general flexibility as a result, according to the survey conducted by Koren et al. [1] they have not been widely adopted by many manufacturers. In addition, flexible manufacturing systems consist of Computer Numerical Controls (CNC) and programmable automation these are the some of the functions or causes which add cost to price of the CNC machines. For example Scamp flexible manufacturing systems have many functions which are not needed by the small manufacturing companies, although it is a good system for bigger industries.

The definition of flexible manufacturing systems is as follows:

> A flexible manufacturing system (FMS) is a system which has an amount of flexibility that allows the system to react in the case of changes, whether predicted, or unpredicted. FMS is called flexible due to the fact that it is capable of processing a variety of different parts simultaneously at the workstations, and that quantities of production can be adjusted in response to changing demand patterns [5, 6].

The Scamp flexible manufacturing system is a well-known system which was designed, installed, and commissioned on its present site in Colchester between 1979 and 1982 [7]. The total cost of the system was approximately $4.5 million [7]. This is a reasonable price if the customers are planning to use all the functions of the systems, but unfortunately most manufacturers cannot afford to buy these machines at this high price. Highly costing machines will force manufactures to increase the price of their product and they can end up losing business. All that manufacturers need is a simple adaptable machine which can meet their customer's needs at a reasonable cost exactly when needed. One of the main purposes of investing in FMS machines was to bring the economies of scale of high

**Table 1** Comparison between DML and FMS [1]

| Systems | Limitations | Advantages |
|---|---|---|
| DML | Not flexible | Multi-tool operation |
| | Fixed capacity | Low cost |
| | Not scalable | |
| | For Single part | |
| FMS | Machine focus | Scalable |
| | Expensive | Flexible |
| | Single–tool machines | |
| | Low throughput | |

production to small batch production. The product rate of a FMS is very small as compared to DML machines because they are controlled by computers. Flexible manufacturing systems are not designed for quick change and they are not responsive to variation in market demands.

Table 1 shows the advantages and limitations of DML and FMS. As indicated on the table FMS are scalable whereas the DML are not.

Dedicated manufacturing systems are based on fixed automation, and therefore are reserved for the company's main product. Core products are central to the company's performance and make high returns which usually sustain the business. Each dedicated line is typically designed to produce a single part at a high production rate. Dedicated manufacturing lines are cost effective as compared to flexible manufacturing systems, but with increasing pressure from global competition, there are many situations in which dedicated lines do not operate at full capacity, and thereby create a loss [2]. As much as the production rate of the DML is very high as compared to FMS machines, but the challenges cannot be solved with the DML which are not flexible or scalable to adapt to market changes.

## *2.2 Reconfigurable Manufacturing Systems*

Reconfigurable Manufacturing System (RMS) and Reconfigurable Machine Tool (RMT) were invented in 1999 in the Engineering Research Center for Reconfigurable Manufacturing Systems (ERC/RMS) at the University of Michigan College of Engineering [8]. Reconfiguration manufacturing systems (RMSs) are machines which can be configured to meet new requirements or sudden changes in the market. The flexibility of the RMS machines allows manufactures to change the functionality and kinematics of the machine to meet new requirements and amendments at any time. In a reconfigurable manufacturing system, many components are typically modular (e.g., machines, axes of motion, controls, and tooling) [8].

According to Koren et al. [1] Reconfigurable manufacturing systems are defined as:

> A manufacturing system which is designed at the outset for rapid change in its structure, as well as its hardware and software components, in order to quickly adjust its production capacity and functionality within a part family in response to sudden market changes or intrinsic system change [1, 9].

The formulation of the RMS paradigm is based on modularity of the structure, software, and hardware which make it easy to adjust to market demands. Reconfigurable manufacturing systems possess six core characteristics: modularity, integrability, customized flexibility, scalability, convertibility, and diagnosability. If the RMS possesses these characteristics, it increases the speed of responsiveness which is required by the market. The RMS machines must integrate with the existing components or modules and be able to adapt to the new changes which can be made in future on the structure, controllers, and software. Reconfigurable systems are designed around part family, and provide the flexibility around the families, and therefore reduce cost unlike the flexible manufacturing systems which are flexible on variety of part. Reconfigurable manufacturing systems operate according to a set of basic principles formulated by Professor Yoram Koren and are called Koren's RMS principles [10]. The more of these principles are applicable to a given manufacturing system, the more reconfigurable is that system. Therefore, the RMS principles below are as formulated by Professor Yoram Koren [1, 10]:

1. The RMS is designed for adjustable production resources to respond to imminent needs. The RMS capacity is rapidly scalable in small, optimal increments. The RMS functionality is rapidly adaptable to the production of new products.
2. To enhance the speed of responsiveness of a manufacturing system, core RMS characteristics should be embedded in the whole system as well as in its components such as mechanical, communications, and controls.
3. The RMS is designed around a part family, with just enough customized flexibility needed to produce all parts in that family.
4. The RMS contains an economic equipment mix of flexible and reconfigurable machines with customized flexibility, such as reconfigurable machine tools, reconfigurable inspection machines, and reconfigurable assembly machines.
5. The RMS possesses hardware and software capabilities to cost-effectively respond to unpredictable events both external (market changes) and intrinsic events (machine failure).

### *2.3 Current RMS Development*

The Engineering Research Center for Reconfigurable Manufacturing Systems, has already designed and successfully built a few different RMTS prototypes, such as 3 Axis RMT, a reconfigurable inspection machine, and an arch-type RMT [11]. Though several studies have been conducted on reconfigurable manufacturing systems and tools, the systems have not been deployed extensively into the market as yet. Once all the modules are available on the market, it should be easy to design and build RMS. The side mounted arch—type RMT design is based on the characteristics of customized flexibility which makes the design procedures more involved than the design of a dedicated machine tool [12]. The spindle housing of an arch type RMT is attached to an arch plate that moves in a curved shape, which allows it to machine complex parts on an inclined surface. The milled part or surfaces are at different angles with respect to the horizontal, 30° and 45° [11].

In response to the market changes and the proposed new RMS machines, the University of KwaZulu-Natal has developed a Modular Reconfigurable Machine (MRM) tool. The modularity and flexibility of the machine is achieved by adding and removing the modules, which are selected from precompiled modules that are concatenated by means of a series of standardized mechanical interfaces, which permit a variety of combinations in which modules could be joined [4, 13].

## 3 Mechanical Machine Design Approach

The concept formulation of a modular machine tool for reconfigurable manufacturing systems will adopt Basic Morphology Method and Decision-Matrix Method. In this paper only the Morphology Method will be presented. According to Ullman [14, 15] morphology assists design engineers to formulate as many alternative concepts as they can then refine them for a better system. There are two steps to morphology technique:

- The goal of the first step is to find as many concepts as possible that can provide each function identified in the decomposition
- The second is to combine these individual concepts into overall concepts that meet all the functional requirements

In the early development stages of the product it is important to research and select the methods which will be followed as there are quite a number of methods that can be used. A modular development approach enhances the modularity and flexibility of the machine as mentioned in Sect. 2 and will also be adopted in the design task at hand.

### *3.1 Modular Tool Design for RMS*

The modularity in the structure, software, and hardware components allows manufacturers to quickly adjust the capacity and functionality of the machine to meet sudden changes; therefore modular systems are systems with loose components which can be mixed and matched to function as desired by the market. Mpofu et al. [16] define modular architecture as physical product sub structures that have a one to one correspondence with a subset of a products function.

Modules are easier to maintain, shorten the development time, reduce the cost of the system, and can be added or reduced to meet customer's requirement. According to Mpofu et al. [16] modular machines have been available; however, they have not been designed to be reconfigurable.

### 3.2 Morphology Method

This section describes the main functions of the system and it then gives a range of possible concepts for each particular function. The idea is to have as many alternative concepts as one can and select three which will be evaluated with the decision-matrix method also known as Pugh's concept selection, using certain criteria which will be formulated based on the specification and the main objectives of the system. The one with the highest score will be selected. The main functions and possible concepts for the spindle head assembly and structure of the system are represented on Table 2.

## 4 Conceptual Design

The aim of this research study is to develop modular machine tools, by selecting and compiling a list of modules and standard components available commercially off the shelf. To reduce the development cost and time most of the components which are used to build the modules of the Modular Machine Tool (MMT) are standard component. MMT is design in such a way that it should be integrated with other machines and modules as required by market changes. The use of standard component on MMT gives the machines the flexibility and customization which is required in the market to produce part family when needed. The machine tool is developed in such a way that it can be configured accumulatively in terms

**Table 2** Morphology for spindle head assembly and structure

| Functions | Concept 1 | Concept 2 | Concept 3 |
|---|---|---|---|
| Transmit power to the spindle head | Pneumatics | Hydraulics | Motors/and manual |
| Type of drivers | Direct with gears | Drive belt | Direct drive with the key |
| Control the movement of the spindle | Pneumatics | Hydraulics | Motors |
| Guide the spindle head assembly | Linear shaft slide | Ball screws | Lead screws |
| Transmit force to workpiece | Cantilever | Actuators | Vertical slide |
| Lock the spindle head | Screws | Lever lock | Lock |
| Drive the base table of the structure | Pneumatics | Hydraulics | Motors/and manual |
| Drive the spindle head | Motor | Manual | Hydraulics |
| Guide the base table | Linear shaft | Ball screws | Lead screws |
| Rotate about z/x axis | Arm mechanism | Rotary slide | Lead screw unit |


**Fig. 1** Standard component and MMT modules

of degrees of freedom, to accommodate different configurations of machines structures. The modules are assembled in different ways to create different types of tools capable of performing a variety of functions using the same hardware and software, depending on the demand and a manufacturer should be able to increase the number of degrees of freedom or should be able to reduce them with a minimum ramp-up. Figure 1 presents some of the standard components and modules which were selected for construction of the MMT concept.

Machine modules are treated as a separate entity, and therefore need to be tested and validated separately, which makes the machine more flexible and reduces time for production and repairs. The MMT spindle head unit which is mounted on a spindle carriage unit moves along the x and y-axis, and it can also rotate about the z-axis, when the rotary module is added. Most of these modules consist of linear actuators and the prototype power is transmitted by stepper-motors. Linear actuators translate rotational motion to linear motion with little friction. Since high precision is the concern of the machine, ball screws are used on the z-axis slide module, spindle head unit, and spindle carriage to maintain the accuracy of the machine. To support and reduce friction on the z-axis slide which move along the z-axis, SNS linear slides are mounted on the sides. More than four possible concepts were formulated and evaluated for this design and two concepts which are presented below received the highest score.

## *4.1 Concept 1*

Concept 1 has adopted one of the systems designs rule, keep it simple and the fewer components the better, this concept has few components as compared to

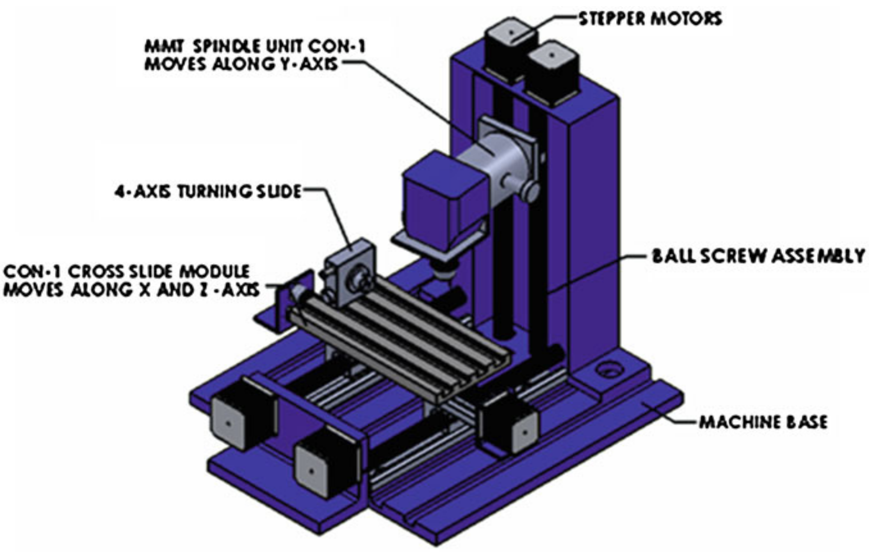


**Fig. 2** 4-Axis concept

concept 2, which shortens the development time and reduces the cost of the system. Both machines are developed for common machining operations such as milling, drilling, and turning. There are four minimum possible degrees of freedom, which can be achieved, with one configuration.

When the turning slide module is added, a maximum of 5° of freedom can be achieved. The workspace and motion orientation is limited, as the spindle head can only go in the y- axis direction and be rotated for the inclined part, and only the worktable can move in the x and z direction. In Fig. 2 which present concept 1 the possible configurations and degrees of freedom per module are as follows:

- **Spindle head assembly modul**e: moves in the y-axis direction and can rotate to cut part at an inclined position.
- **Cross slide module**: which is used as a work-table, two degrees of freedom can be achieved as worktable moves in the x and z-axis.
- **4th-Axis turning slide**: rotate around z axis

### *4.2 Concept 2*

In concept 2 as illustrated in Fig. 3a, a minimum of two and maximum of five configurations is anticipated to be possible when adding and removing modules as per customer requirements. Modules can be added or removed without changes in the structure and possible degrees of freedom are presented clearly in Fig. 3b. In one configuration a maximum of five degrees of freedom can be accomplished, if

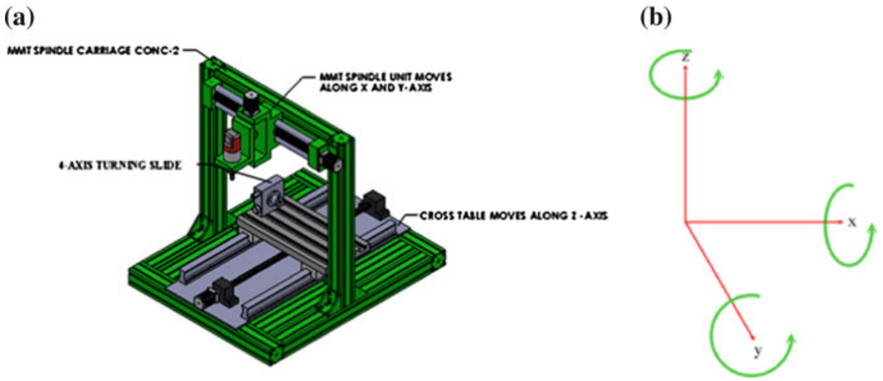


**Fig. 3** Concept 2. **a** 5-axis concept 2, **b** 6-degrees of freedom

the turning slide module is utilized as a work-piece holder. With just a single change of a tool all three basic operations can be performed in set. Possible configurations and degrees of freedom per module are as follows:

- **Spindle head assembly module**: moves in the y, x—axis direction and can rotate to cut part at an inclined position.
- **Cross slide module**: moves along z-axis and more degrees of freedom can be achieved when other modules are added.
- **4th-Axis turning slide**: can also be used as a work-piece holder with rotational axis facing up. With this orientation, module has a freedom to move in four directions in one configuration. Three basic operations can be performed with a change of tool in this configuration. When the turning slide is in a normal position as it is at the moment on the diagram in Fig. 3, the machine can only be configured for turning functions.

## 5 Conclusions

Reconfiguration manufacturing systems together with RMTs were proposed in the late 1990s by the researchers at the University of Michigan and developed from precompiled library modules [13]. The machines are anticipated to be systems which in future will have a great impact on the manufacturing industry. According to Padayachee [13], the Modular Reconfigurable Machine (MRM) which is part of the RMS has been developed to display variations of the degree of freedom and processing functions on a single platform. The use of standard components on the development can reduce costs and development time of systems. Flexibility and responsiveness of the RMS is achieved through addition and deletion of modules, which are selected from modules available commercial off the shelf. During the evaluation concept two received the highest points than concept one, although it consists of many components.

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## References

1. Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, Van Brussel H (1999) Reconfigurable manufacturing systems. Ann CIRP 48:527–540
2. Mehrabi MG, Ulsoy AG, Korea Y (2000) Reconfigurable manufacturing systems: key to future manufacturing. J Intell Manuf 11(1):403–419
3. Mpofu K, Tlale NS (2011) Multi-level decision making in reconfigurable machining systems using fuzzy logic. J Manuf Syst 31:103–112
4. Padayachee J, Bright G (2011) Modular machine tools: design and barriers to industrial implementation. J Manuf Syst 20:30
5. ElMaragh HA (2006) Flexible and reconfigurable manufacturing systems. Intell Manuf Syst (IMS) 17:261–276
6. Shivanand HK, Benal MM, Koti V (2006) Flexible manufacturing system. New Age International (P) Limited, pp 1–23##
7. Greenwood NR (1988) Implementing flexible manufacturing systems. MacMillan Education LTD, Hong Kong, pp 24–34
8. Michigan Engineering | About our ERC (2012)##
9. Abdi MR, Labib AW (2004) Grouping and selecting products: the key of reconfigurable manufacturing systems (RMSs). Int J Prod Res 42(3):521–546
10. Koren Y, Ulsoy G (2002) Vision, principles and impact of reconfigurable manufacturing systems. Powertrain Int 5(3):14–21
11. Dhupia J, Powalka B, Katz R, Ulsoy AG (2007) Dynamics of the arch-type reconfigurable machine tool. Int J Mach Tools Manuf 47:325–334
12. Son H, Choi H, Park H (2010) Design and Dynamic analysis of an arch-type desktop reconfigurable machine. Int J Mach Tools Manuf 50:575–584
13. Padayachee J, Bright G, Butler LJ (2009) The development of a mechatronic control system for modular reconfiguration machine tools. In: Australasian conference on robotics and automation (ACRA), Sydney, Australia, 2–4 Dec 2009
14. Ullman DG (1987) Mechanical design methodology: implications on future developments of computer-aided design and knowledge-based systems. Eng Comput 2:21–29
15. Ullman DG (2003) The mechanical design process, 3rd edn. McGraw-Hill, New York, pp 142–182
16. Mpofu K, Kumile CM, Tlale NS (2008) Adaptation of commercial off the shelf modules for reconfigurable machine tool design. In: 15th international conference on mechatronics and machines vision in practice (M2VIP08), Auckland, New-Zealand, pp 144–150

# Global Green Production by Integration of Automated Decision Layers

**Reza Hosseini and Petri Helo**

**Abstract** Process industries are highly automated and energy intensive. They produce considerable share of greenhouse gas (GHG) emissions. In these industries, automation and related controls of operations in different layers of production from process level instrumentation to distribution level scheduling and planning have been implemented in separated layers with few respects to sustainability. It is clear that without consideration of sustainable factors in Enterprise Wide Operations holistically; predefined targets of Green Production for industrial operations are unachievable. Substantial requirements for Green Operations rely on the establishment of suitable platforms, tailored to achieve Enterprise Wide Sustainability. This paper tries to model and conceptualize an integrated automation platform for green operations of process industries, including production and scheduling.

## 1 Introduction

Process industries are businesses that add value to materials by chemo-physical operations as mixing, separating, forming, or chemical reactions [1]. Consequently industries such as iron and steel, nonferrous metals, pulp and paper, oil and gas, petrochemicals, food, glass and glass products, cement and lime, ceramic, tile and brick, and many others are included in process industries. Sustainable global development and related production policies evolve into new sustainable concepts of production managements. Moreover new regulations impose all spectrums of industries to bring new challenges into their sustainable considerations. Challenges include perusing renewable energy sources and implementations of new

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technologies to pave the ways of implementation of cutting-edge processes, green operations management and reduction in global greenhouse gas (GHG) emissions. Statistics show that the process industries are amongst the most energy-intensive, energy consuming industries therefore they are the most GHG emitters of the environment [2]. Even without taking consumption of power plants into the accounts industries, they consume more than one-third (37 %) of global primary energy and contribute about 25 % of global greenhouse gas (GHG) emissions [3]. Analysis of the kilograms of carbon dioxide as Fig. 1 in different types of industries in three countries of Canada, United States, and China shows that the process industries are the biggest GHG industrial emitters. Mentioned data highlights that each optimization method, real time computation of sustainable indexes, or innovation enabling process industries to implement sustainable responsive policies play key role in reduction of global greenhouse gas (GHG) emissions.

The structure of this paper is as following: In the beginning and in Sect. 1 we will present basic definitions of the required concepts in the paper and highlight process industries role in the emissions. We will provide relevant article review about the sustainable operations and productions management, strategies, and methods in coming Sect. 2. In Sect. 3 introduction of a framework for Global Green Production will be presented. In the end and in Sect. 4 we will conclude the paper with investigations of opportunities and barriers in implementation of proposed framework.

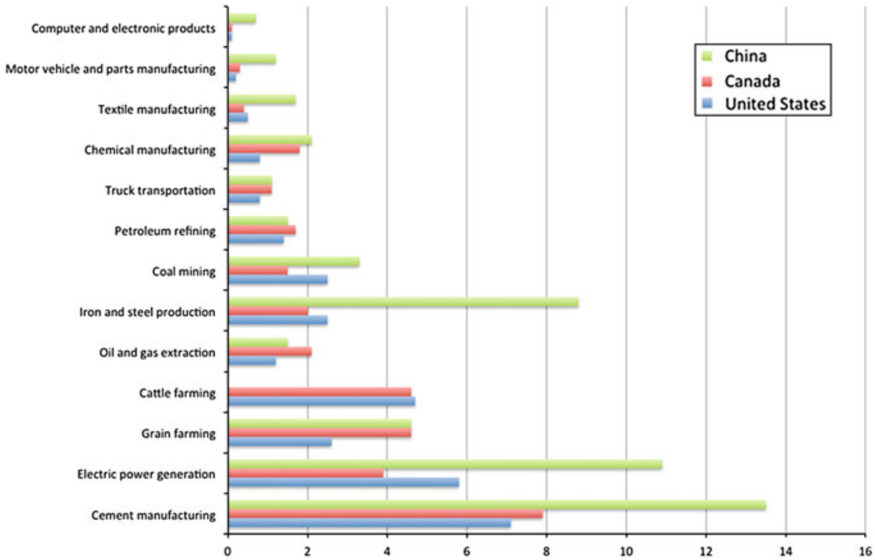


**Fig. 1** Kilograms of carbon dioxide equivalent per Canadian dollar of production, Includes direct and indirect emissions in Canada, the United States, and China, Year 2011, *Source* (Statistics Canada)[2]

## 2 Green Operations and Production Managements in Literature

Even though supply chain sustainable models and operations have been extensively discussed in recent literatures [4, 5], modeling of appropriate frameworks for green, sustainable holistic operations management of industries have been noticed in few literatures. Recent trends show the number of publications in this area is growing considerably [6–8]. Bunse et al. [9] reviewed gap analysis of sustainable modeling requirements in which they have compared literatures and industrial motivations. The paper has concluded that to have effective energy management and related emission controls in-process energy measurements and enhancement of Information and Communication Technologies (ICTs) of different decision layers are substantial.

### *2.1 Strategic, Inter Organizational Sustainable Considerations*

Having roots in global green strategies, the concepts of sustainability, and energy efficiency create new concepts in strategic levels of decision-making of process industries as well. From one side they enforce restrictions for existing productions, operations, and business procedures and narrow down the options of previous profitable operations areas. On the other hand, this creates fertile land for harvesting innovations, breakthroughs, and new economic opportunities. Unification of information and decision-making process with consideration of sustainable regulations and policies, establishment of dynamism in operation management of inter-organizational data flows need to keep close eye on the strategic level of organizations. Based on the fact that data and information flows are foundations of sustainable strategic policymaking, few coherent integrated policymaking frameworks have been modeled [10]. The proposed structure in strategic planning level of the industries might be a proper approach to explain how a dynamic and sustainable conceptual framework needs to be conceptualized. New products and processes [11] and interchangeability in products process [12] (having different production procedure for the same product) play a principal role in consideration of efficient long-term sustainable investment policies. Ren [12] mentioned few of the main drivers and barriers to activities, aiming in improvement of existing processes and development of new sustainable processes in petrochemical industries. Although sustainable holistic views are being considered in the strategic planning layers of industries, it is obvious that in strategic layer still more fundamental qualitative, quantitative, and longitudinal studies are required [13].

## 2.2 Supply Chain, Production, and Process Data Flow

Few literatures with focus on sustainable supply chains propose new platforms of production and supply chains [14, 15]. However, in the system green supply chain responsibilities, existing data structures somehow neglects sustainable responsive platforms. To solve the problem and to design a green production and supply data framework, integration in data flow as establishment of integrative databases and historians of enterprise planning with financial data has been proposed [16]. Additionally in process industries, advantageous synergic effects of integrated production and related collaborative efficiencies are modeled, surveyed, and studied [17]. But industrial operability of such integrated production plants relies on the successful programming, logic planning, and application of suitable integrated control. Previous economic studies in implementation of advanced control systems demonstrate that utilization of control systems could reduce the process energy consumptions up to 45–65 % [18]. Nevertheless recent reviews indicate that sustainable productions just engineered for sustainability in the design phases of the projects and in the operation phase adequate controls for sustainable efficiencies are absent [19]. In the other words, in the process facilities, utilities are adjusted to achieve production goals and supplementary controls for sustainable factors as waste streams and energy efficiencies are still rare. Obtaining better products qualities while considering sustainable efficiency and production dynamism are intertwined parameters; accordingly, optimizations of processes are multi objective phenomena with consequent robust computations [19, 20]. In spite of practical demanding for modelings of sustainable mathematics and their applications in sustainable process controls, researches with focus on real time sustainable process optimizations are still lacking in the literatures.

## 2.3 Legislations and Industrial Standardizations

Stringent governmental restrictions and legislative bodies' commitment to reduce green house gasses emissions especially in EU area initiate many industrial energy performance-increasing applications particularly in process industries. In compliance with realization of new sustainable societies and standardizations, International Electrotechnical Commission's (IEC) IEC-TC 65 attempts to standardize framework of "Low Carbon Society" and "Digital Factory" by 2015 [21]. IEC has introduced IEC 61850 standard for electrical substations automation communication protocol amongst Intelligent Electronic Devices (IEDs), sensors, and actuators as well. Besides pioneers of industrial process productions such as BASF and Bayer strive to implement sophisticated sustainable procedures for their routine productions. For example, Drumm et al. [22] published their framework of STRUCTese® which modeled a systematic approach in reduction of energy consumption. This method uses the detailed measurement and tracking of energy efficiency in all levels of the organization in contrast to measuring traditional lump energy consumption. BASF also has its sustainable framework with indications of carbon footprint and emissions published by Uhlman and Sabry [23]. In this way, control system providers attempt to introduce sustainable enabling control platforms. Concerns for sustainable automation is strong enough to grab the attention of suppliers of automation technology such as Siemens and ABB. Grounded on IEC 61850 standard, ABB's architecture of Electrical Integration (unification of process and power automation) is one of the greatest industrial strides that have been taken lately [24]. Recently in supervision of electric power in discrete-part manufacturing industries, specific energy efficient protocol of Profienergy® has been developed to manage the power consumption of robot assembly cells in auto manufacturing industries (Siemens, website). To position field instruments in current control structures; Fig. 2 shows the ANSI/ISA 95 Enterprise-Control System Integration framework. Generally current integrated automated systems in process industries utilize most of the required control devices in level 1 and 2 of its integrated system.

In a sustainable responsive system, filed instruments are the basic hardware for creation of automation managing sustainability throughout the process. International Electrotechnical Commission's TC 65 committee in industrial process measurement, control, and automation is one of the standardization bodies that initiated the policy in standardization of new generation of filed instruments with capability to measure and implement new energy efficient sustainable strategies. Even if filed instruments and related automation system account for very small portion of electrical energy consumption; IEC/TC65/JWG14 in cooperation with other organizations such as Energy Efficiency in Industrial Automation (EEIA), ISO TC184/SC5 and Information Communication Technology for Energy Efficiency (ICT4EE) are trying to develop standards for energy efficient automation system [25].

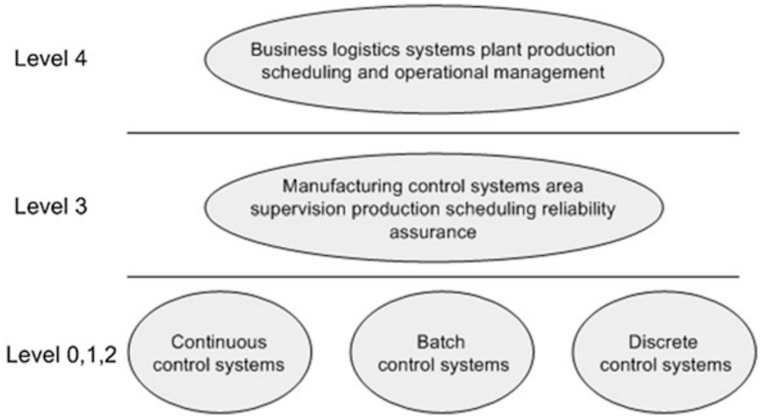


**Fig. 2** ANSI/ISA95 enterprise-control system integration

## 3 Conceptual Framework for Global Green Production

To have sustainable operations in current automation systems Siirola and Edgar [19] raise the questions of whether it is not the time to consume some of our degrees of freedom in sustainability efficiency of our routine control logics. Why in energy intensive processes direct energy control or real time optimization of energy is not being implemented? Or what we need to have the abilities to implement sustainable systems. Seborg et al. [26] defines the data interaction between control layers of the process plant control as Fig. 3.

To have optimized real time answers, the solver algorithms of this stochastic planning have to be in a centralized computation. To guess the best initial input of iterative-shared algorithm various methods could be used in different layers as considered in recent literatures [27, 28]. Holistic sustainable optimization of multi objective systems with consideration of sporadic sustainability in separated current platforms of controls and operations is impossible. Integration of scheduling and control layers paves the way of sustainable considerations in the networks of operations. This could be started from consideration and prediction-estimation of sustainable factors in strategic planning layer and conclude in the demand forecast with known probabilistic distribution and calculated the decision variables that we consider as process variables with normal process constrains. By integrating historians and data availability for "data-dependent" sustainable optimizations one of the greatest strides of integrated sustainable operations management will be taken. Financial expenses arising from instruments investment compare than to the positive effects of new generations of hardware and sensors with ability to record sustainable data sufficiently is negligible. For instance, in electrical energy side, electrical integration [24] helps recording all electrical data and in process side. Therefore in-process measurements would be recorded energy oriented. In the other words, in an integrated energy-recording platform, accesses to energy data and varieties for online solvers are guaranteed.

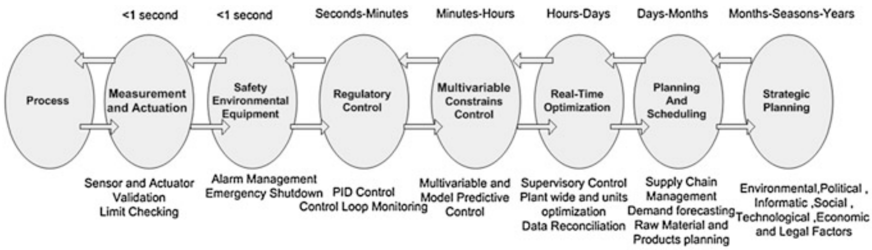


**Fig. 3** Data interaction in different layers of automations with time horizon; strategic planning is included

## 4 Conceptual Framework

By relying on characteristics of process industries, Fig. 4 shows the conceptualized framework. The main idea behind this framework is to acquire, monitor, and control operations variables based on the need of a responsive sustainable operations management. Commonly most of the hardware of control, monitoring, and related computational services including control rooms in process plants, related financial and inventories optimizations tools in scheduling layer located remotely in few to few hundred meters away from the servers. On the other side remote accessibilities with utilization of fiber optic broadband, satellite driven wireless control infrastructures are reliable technologies and have been under rapid developments. If the servers could be located few hundred meters away from Human Machine Interfaces (HMIs), why not considering, establishment of facilities of industrial unified computations 1,000 km away with integrative abilities in achievement of sustainable operations?

It establishes sustainable unique ICT and responsive operations system for process industries. This platform is required for supervision of green operations and in-process measurements and recording of sustainable variables, which are the fundamentals in calculations and supervisions of sustainability. Currently unified computational tools such as cloud computing empower the capabilities to adhere global optimal decisions for all of the parameters in Enterprise Wide Optimization with data flow diagram as Fig. 5. As Chu and You [28] suggested generations and

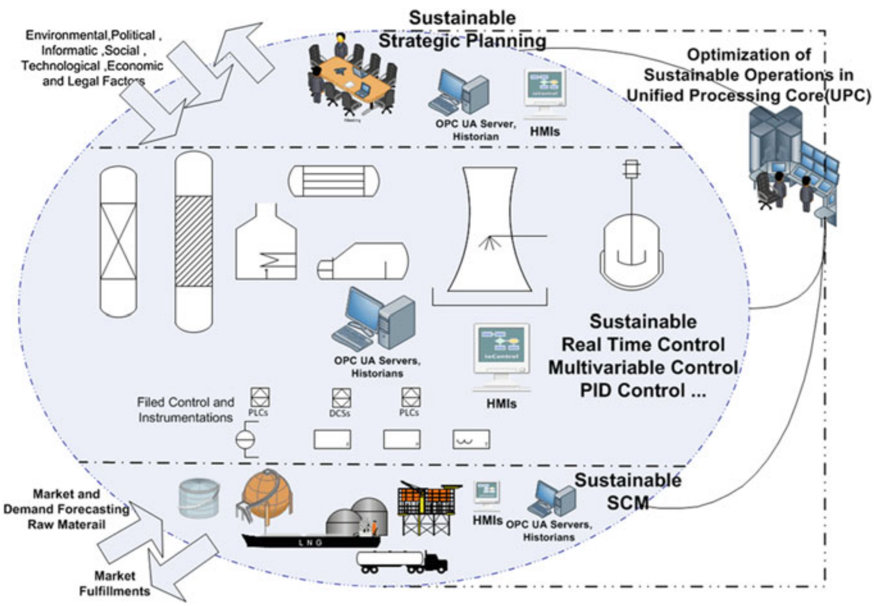


**Fig. 4** Conceptual integrated framework for global green production

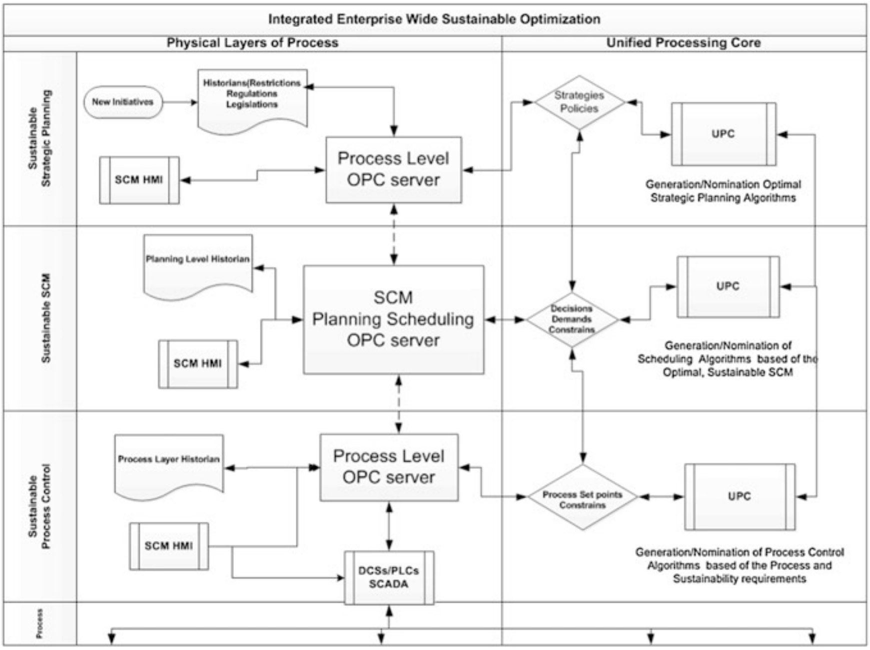


**Fig. 5** Data flow diagram in integrated enterprise wide sustainable optimization

nominations of algorithms and related data flows necessitate reverse direction of data and logics upwardly from control layers in the filed instrument level to strategic planning level as illustrated in data flow diagram of Fig. 5. The interaction of data from top to bottom and nominations-generations of algorithms and creation of scenarios from bottom to up counter currently make the required integrated systems in general view for optimized green operations.

## 5 Summary and Research Challenges

Although process industries contributes significantly in the world's waste streams, carbon emissions and energy consumptions, sustainability, and Triple Bottom Line (3BL) considerations are still not being considered in process plants adequately. As sustainable operations cannot be separately optimized in different layers of industrial operations, to integrate the separated islands of optimizations and overcome mathematic robustness of stochastic behaviors of Enterprise Wide Optimization; centralized computation is necessary to have sustainable efficient operations. This paper defined a conceptual model to show how a centralized and unified processing center could be implemented to handle the sustainability concerns of the production processes.

### 5.1 Barriers in Industrial Applications

- As operation and establishment of integrated systems should be implemented in multidisciplinary atmosphere with process and control knowledge, the operators capable of working with HMIs should be highly trained and familiarized with the logic behind of processes.
- There is still no strong intention of sustainable management consideration and integration neither among the hardware of control system providers (controllers, instrumentations) nor in software providers of MES, ERP etc. Furthermore, economic benefits of the providers have enormous advantages when they are routinely selling the products with overlaps and different domains of applications in current industrial marketplace.

### 5.2 Challenges

Although implementation of operable and integrated sustainable platforms of enterprise operations requires real size industrial case studies, most of the previous researches are single operational units optimization. Thereby, involvements of industrial research partners with strong desire for application of sustainable operations are key factors. The realizations should include suppliers providing tailored hardware and software, which are the domains for future research. On the other side, integration of strategic planning layers and possible decisions requires it unique endeavors. This also need much closer policies and index definitions with numerical outlets.

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## References

1. Wallace T (1984) APICS dictionary, 5th edn. American Production and Inventory Control Society, Falls Church
2. Statistics Canada, Environment Accounts and Statistics Division special tabulation CANSIM (database) (2011)
3. Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (2007) Contribution of working group III to the fourth assessment report of the inter-governmental panel on climate change, 2007, mitigation of climate change, Section 7. Cambridge University Press, Cambridge, United Kingdom and New York, USA
4. Carter CR, Rogers DS (2008) A framework of sustainable supply chain management: moving toward new theory. Int J Phys Distrib Logistics Manag 38(5):360–387
5. Ageron B, Gunasekaran A, Spalanzani A (2012) Sustainable supply management: an empirical study. Int J Prod Econ 140:168–182

6. Kleindorfer PR, Singhal K, Van Wassenhove LN (2005) Production and operations management, vol 14. pp 482–492
7. Wong CWY, Lai KH, Shang KC, Lu CH, Leung TKP (2012) Green operations and the moderating role of environmental management capability of suppliers on manufacturing firm performance. Int J Prod Econ 140:283–294
8. Tang CS, Zhou S (2012) Research advances in environmentally and socially sustainable operations. CEJOR 223:585–594
9. Bunse K, Vodicka M, Schoensleben P, Bruelhart M, Ernst OF (2011) Integrating energy efficiency performance in production management—gap analysis between industrial needs and scientific literature. J Cleaner Prod 19:667–679
10. Kua HW (2007) Information flow and its significance in coherently integrated policymaking for promoting energy efficiency. Environ Sci Technol 41(9):3047–3054
11. Ren T, Danieelsb B, Patela MK, Bloka K (2009) Petrochemicals from oil, natural gas, coal and biomass: production costs in 2030–2050. Resour Conserv Recycl 53:653–663
12. Ren T (2009) Barriers and drivers for process innovation in the petrochemical industry: a case study. J Eng Tech Manage 26:285–304
13. Schoensleben P, Vodicka M, Bunse K, Ernst FO (2010) The changing concept of sustainability and economic opportunities for energy-intensive industries. CIRP Ann Manuf Technol 59:477–480
14. Fabbe-Costes N, Roussat C, Colin J (2011) Future sustainable supply chains: what should companies scan? Int J Phys Distrib Logistics Manag 41(3):228–252
15. Mollenkopf D, Stolze H, Tate WL, Ueltschy M (2010) Green, lean, and global supply chains. Int J Phys Distrib Logistics Manag 40(1):14–41
16. Fakoya MB, Van der Poll BHM (2013) Integrating ERP and MFCA systems for improved waste-reduction decisions in a brewery in South Africa. J Cleaner Prod 40:136–140
17. Munir SM, Manan ZA, Wan Alwi SR (2012) Holistic carbon planning for industrial parks: a waste-to-resources process integration approach. J Cleaner Prod 33:74–85
18. Bauer M, Craig IK (2008) Economic assessment of advanced process control: a survey and framework. J Process Control 18:2–18
19. Siirola JJ, Edgar TF (2012) Process energy systems: control, economic, and sustainability objectives. Comput Chem Eng 47:134–144
20. Afshar P, Brown M, Maciejowski J, Wang H (2011) Data-based robust multiobjective optimization of interconnected processes: energy efficiency case study in papermaking. IEEE Trans Neurual Netw 22:2324–2338
21. Shin S, Sasajima H (2012) SICE international standardization activities for future low-carbon + smart society. In: SICE annual conference 2012, pp 670–674
22. Drumm C, Buschb J, Dietricha W, Eickmans J, Jupke A (2012) STRUCTese®—energy efficiency management for the process industry. Chem Eng and Process. http://dx.doi.org/10.1016/j.cep.2012.09.009
23. Uhlman BW, Sabry P (2010) Measuring and communicating sustainability through eco-efficiency analysis. Chem Eng Prog 106(12):17–26
24. Vasel J (2012) One plant, one system: benefits of integrating process and power automation. In: 65th annual conference for protective relay engineers, article no. 6201235, pp 215–250
25. Ishikuma T (2011) International standardization for low-carbon society—status of energy efficiency and environmental guidelines. In: SICE annual conference 2011, pp 2057–2058
26. Seborg DE, Edgar TF, Mellichamp DA, Doyle FJ (2010) Process dynamics and control, 3rd edn. Wiley, New York
27. Hosseini R, Helo P (2012) Integration in process industries via unified processing core (upc) in operational and logistic planning levels. Comput Aided Chem Eng 30:427–431
28. Chu Y, You F (2012) Integration of scheduling and control with online closed-loop implementation: fast computational strategy and large-scale global optimization algorithm. Comput Chem Eng 47:248–268

# Flexible SOA Based Platform for Research on Start-Up Procedures for Reconfigurable Production Machines

**M. Abel and P. Klemm**

**Abstract** Starting-up production machines is a complicated task and takes a substantial part of time and expenses. Especially, in the field of reconfigurable machining systems (RMS), where changes in the machines occur regularly, a short start-up phase is essential. Many activities, which are necessary during the start-up can be automated. Among them are the configuration of control- and field-bus systems, user interfaces, and industrial automation devices, as well as the extensive testing of functions. In reconfigurable manufacturing the concept of mechatronic modularization leads to new system boundaries. As a result, RMS are composed of diverse mechatronic modules (MM) which contain mechanical and electrical components as well information technology. This paper presents an approach to automate the start-up of a RMS by applying a machine-internal service-oriented architecture. Moreover, a reference platform is presented, which can be used for research on the automatic generation of start-up procedures for RMS systems. Modules contain not only a range of mechatronic functions, but also additional software and Web-Services, which support the automatic start-up of a machine. Internal Web-Service communication is handled by a Service-Bus whose communication is tunneled through an automation-bus system. Thus, deterministic real-time communication can be combined with flexible Web-Service communication for the configuration and set-up of MM. Moreover, every MM is equipped with a real-time simulation model for mechanical and electrical parts and a database to store module specific data like CAD models, module descriptions, and software components. The functionality for configuring MMs and the start-up sequence generation for the machining system is provided by an internal configuration system based on Web-Services. Finally, a RMS system can be automatically put into operation by means of the configuration system which derives and executes an automatically generated start-up sequence.

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## 1 Introduction

In the field of production engineering flexible manufacturing systems play an increasingly important role. In order to be able to adapt production to the constantly changing needs of the market, flexible machines are indispensable. Possible solutions are reconfigurable machining systems (RMS), which can be adapted to new manufacturing tasks rapidly. Reconfiguration means modification of the structure, production-capacity, or technology [1–3]. Modifications must be done with minimal loss of time to be able to compete with conventional machines. Consequently, in the last years a lot of research has been done on this type of machines. Thus, various machine concepts for the mechanical and structural design have been brought to practice. Projects investigated in the areas machine modularization techniques [4], flexible control systems [5–7], mechanical module interfaces [8], and device configuration [9].

The key concept for designing RMS is modularization. A consequent application of modularization concepts leads to new logical module boundaries within machines. A concept to subdivide machine functionality into modules is based on intelligent mechatronic modules (MM) which can be used as basic building blocks to build RMS. MMs contain functionality from the disciplines mechanical and electrical engineering as well as from information technology. MMs are characterized by their internal functionality and the interfaces they provide on their boundaries. New machine structures can be created or modified by interchanging or adding MMs, which also enables an easy maintenance of modules [10] and forms a basis for re-use.

After building or modifying, a production machine has to be started up, which is still a time-intensive challenge. As the start-up is the last procedure before a machine can start production, it is a very complicated task. Even engineers with a lot of knowledge and experience are no guarantee for a rapid start-up. Thus, start-up still requires a significant part of time and expenses. In reconfigurable production, a RMS has to be started-up after a reconfiguration. Therefore, every change in the RMS increases the overall life-cycle cost. Starting-up a RMS for the first time is very similar to the procedure which has to be carried out, when a RMS was modified and has to be brought to operation again. Hence, an automated start-up sequence is a must if RMS are modified regularly. However, there is no method yet available for the automatic start-up of production machines which are built of mechatronic modules from different manufacturers.

In the field of research on distributed systems for manufacturing systems a lot of methods and technologies are available. Methods to handle distributed manufacturing systems are, for example, holistic and agent-based [11] systems or systems based on a service-oriented architecture (SOA) [12]. SOA is an architectural pattern for the design of distributed systems [13]. Moreover, service-orientation is a paradigm of designing business applications by using services which are self-contained, platform-independent, and discoverable. SOA concepts can be used to handle large and complex distributed systems. Furthermore, orchestration is an important concept [14] which describes the ability to automatically execute tasks within a SOA system from a central instance which is often called orchestration engine. Although, agents may be equipped with the ability for self-organization, many tasks in a production environment have to be done in a deterministic manner. Therefore, systems based on services are more suited for a production environment as execution can be controlled centrally. Services need a Service-Bus system as communication platform. Very often, so called Web-Services are used which use SOAP [15] as communication protocol. A Web-Service can be described as function (e.g., program) provided at a certain network address that is always available. Furthermore, there is already research available on SOA systems based on Web-Services which are applied to general industrial automation and manufacturing systems [16]. Especially, the Device Profiles for Web Services (DPWS) standard [17] is a convenient technology for embedded high-level device networking [18].

## 2 Vision for the Future of RMS Systems: Service-Orientation

In the future, RMS will perform their own start-up sequence since they will be equipped with capabilities for self-configuration. This enables RMS to bring themselves to operation after a reconfiguration. By analyzing their complete internal structure as well as internal machine documentation, machines will gain enough knowledge for an automatic start-up. On this way, the concept of MMs forms an enabler technology for reconfigurable production.

Figure 1 shows an RMS which consists of MMs with additional interchangeable modules from different manufacturers. After a reconfiguration the machine is able to analyze the changes and to perform an automatic start-up. Modern production machines already contain a high amount of control systems, embedded controllers, and computers. According to computer science, such a system forms a distributed computer system. Consequently, by changing the point of view from engineering to computer science, a machine can be seen as distributed system.

Moreover, functionality for an automatic self-start-up cannot just added to an existing machine system. Indeed, a completely new system approach is necessary to solve this issue. Therefore, this research project aims to create and implement a concept for the automatic start-up of RMS. As this concept combines methods derived from Universal Plug and Play (UPnP) with Plug and Play methods for production it is also called Universal Plug and Produce [19, 20]. In this approach, concepts found in the field of service orientation are transferred to the field of manufacturing to enable automation of the start-up of a RMS. An automatic start-up of a RMS can be carried out by describing the start-up process in a machine-executable workflow, which can be executed by an orchestration engine. Thus, by automating the start-up process a lot of time and effort can be saved.

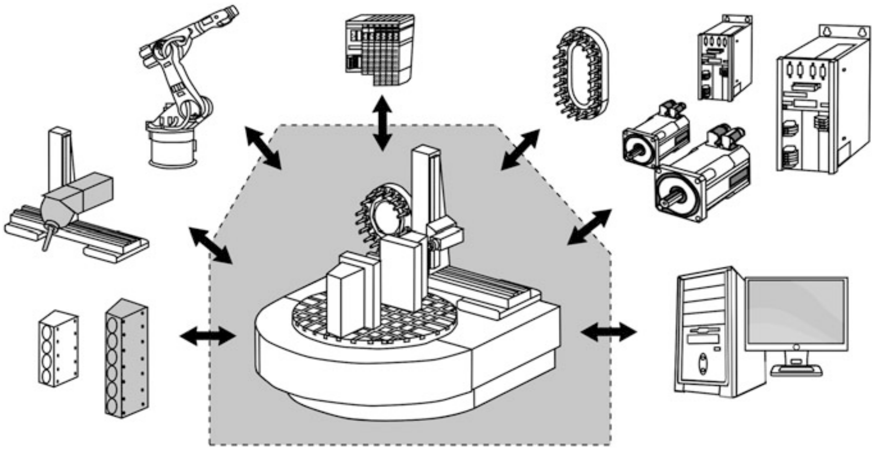

**Fig. 1** RMS built of intelligent mechatronic modules (MMs)

Reconfigurable machining systems will probably not find their way into practice as long as there is no mature support for commissioning. On the other hand, commissioning a machine is not possible until such a machine was realized. To solve this dilemma, a standard reference architecture is designed, which can be used for research on automatic start-up sequence generation for reconfigurable machines, generation of parameter configurations for mechatronic modules and other purposes. The platform is aimed toward research purposes, but is also suited for the integration into industrial automation devices, since it is based on widely used standards and software designed for embedded devices.

## 3 General Approach

In this chapter, a system-architecture is proposed, which provides features for an automatic start-up of a production machine. This is accomplished by applying a service-oriented concept to an RMS. Figure 2 gives an overview of such an exemplary system structure. A production machine is composed of several MMs. In addition, an open control system, which is also modeled as MM, is utilized. Every MM, which is incorporated into the production process, is connected to a field-bus system or deterministic real-time communication. MMs are also connected to a Service-Bus to enable flexible service communication. Moreover, a configuration system (CS) that contains general services and start-up functionality is integrated as a part of the machine. The Service-Bus can be used as a flexible communication medium during the start-up of the machine. However, no additional cabling efforts are necessary as Web-Service communication is tunneled

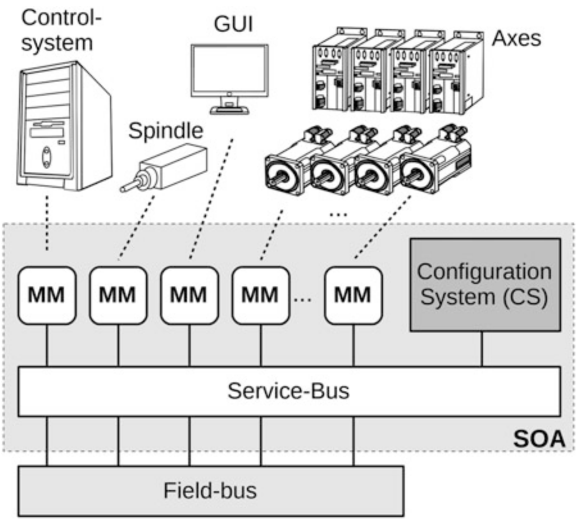


**Fig. 2** Overall system structure

through the field-bus system. Afterward, when the machine is operational, the Service-Bus can be used for alternative purposes like low priority communication, production analysis, and optimization.

## 4 Intelligent Mechatronic Modules

Intelligent mechatronic modules (MM) are used as basic building blocks for RMS, they contain mechanical and electrical functionality as well as information technology in the form of software components. In order to communicate with other modules they must also contain computational capabilities in terms of a processing unit. Additionally, a communication interface for a network or a field-bus system and data storage is essential. MMs can represent functionality of complex machine parts, field-bus devices or may also be software modules like graphical user interfaces (GUI) or the control system [20]. Consequently, the concept of MMs allows a more abstract view on the functionality provided by production machines. Moreover, the production capabilities of a RMS can be adopted by exchanging MMs with differing functionality.

A module needs to contain information about its internal functionality, interfaces, and start-up procedure. This information can be stored in documents, which can be accessed via services hosted in the modules. Figure 3 gives a more detailed overview of the internal structure of an MM.

Traditional mechatronic functionality of field-bus devices is located on the left side. Here, mechanical and electrical functions as well as the device firmware can be accessed via the field-bus interface. On the right side, services, and module descriptions, which are hosted inside the module, are shown. Module descriptions

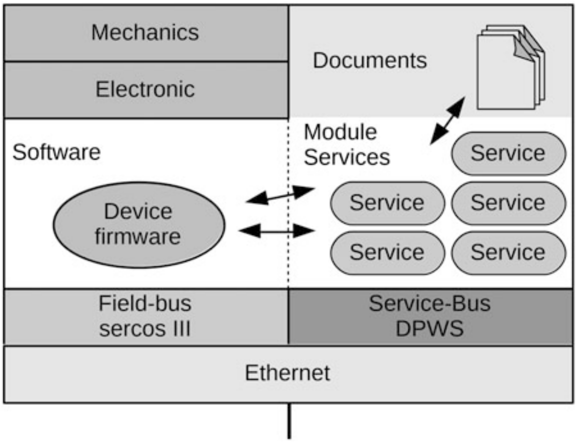


**Fig. 3** Overview of a mechatronic module

are organized in multiple documents which describe the functionality of the module. Services located inside the module can also interact with the device firmware to exchange data.

## 5 Automation of the Start-Up Process

Configuration steps during the start-up sequence of the machine are performed by means of the CS. Here, services in the CS are negotiating with services contained inside MMs to determine a manner in which the machine can be brought into an operational state. The task of the CS is to generate a step by step start-up sequence and to find a valid configuration for all MMs.

To start-up the machine, it is necessary to put each MM to operation as well. In order to achieve this, a sequence for the start-up has to be derived by the CS. Figure 4 shows an exemplary sequence of a start-up workflow composed of several activities which are mandatory during commissioning. In the beginning, information has to be gathered from all MMs in the machine. Based upon the gathered information, a step by step start-up sequence has to be generated. In the following steps machine internal facilities are configured and started. In the end, functional tests need to be executed to test every desired functionality in the intended production case. MMs need to provide a description of their own start-up workflow in a machine readable format to support the CS. Services located in the CS have to retrieve and evaluate these descriptions (see Fig. 5). An orchestration engine located in the CS is able to perform the configuration of MMs and put the production machine to operation. In order to be able to use orchestration, the start-up process has to be formulated in a process/workflow execution language.

During start-up, workflows have to be collected and ordered into an executable sequence. Figure 5 shows an exemplary overview of the CS and how exemplary

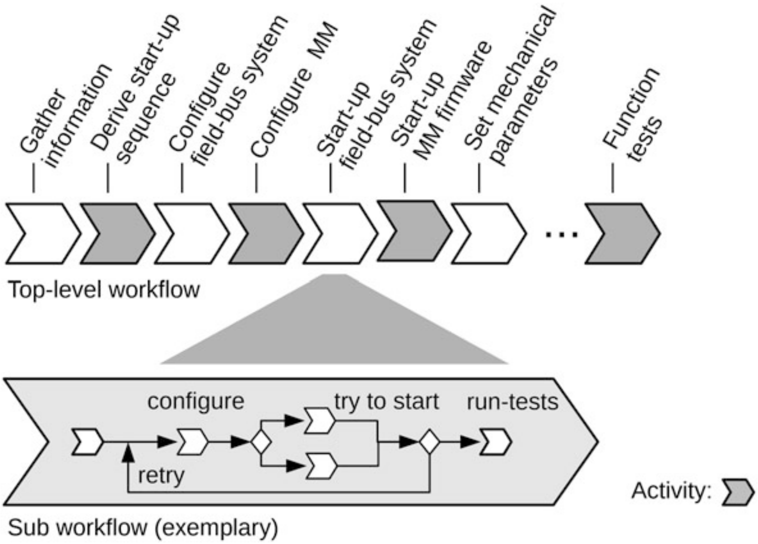


**Fig. 4** Example start-up workflow

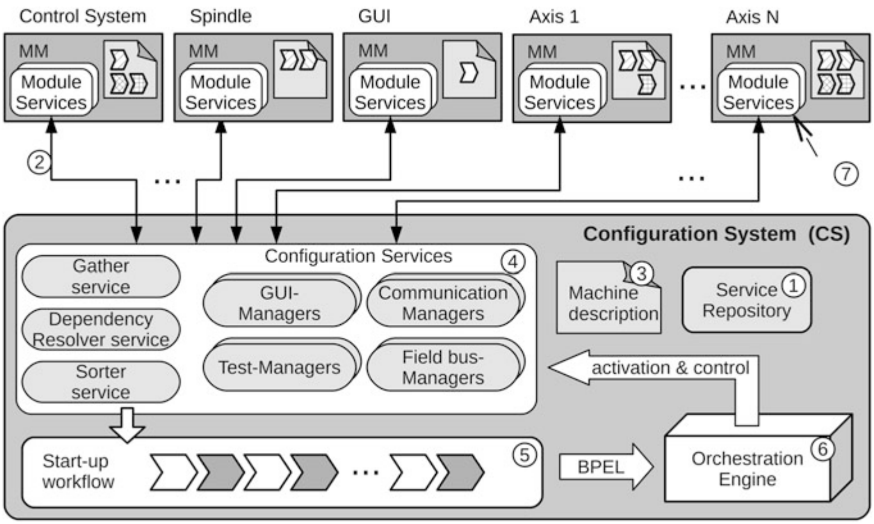


**Fig. 5** Workflow automation in the configuration system (CS)

services can collect, sort, and execute workflows retrieved from MMs, which are combined to a production machine. Commissioning begins after a reconfiguration at the first activation of the machine. In the beginning, every service located in the machine is registered at the service repository (1) to make it discoverable. The next step done by the CS is gathering available MM descriptions from the modules to get information about the available mechatronic functionality (2). Afterward, a formalized machine description (3) is evaluated to get knowledge about the intended manufacturing task and the purpose of the machine. Hence, available functionality is matched against required functionality for a specific manufacturing process. Services (4) in the CS can now derive a start-up workflow and compute necessary parameter configuration, e.g., motor torque, machine dimensions, communication parameters, GUI construction, etc. To perform these tasks, the CS contains a set of services which can be extended by additional services if further functionality is necessary. The automatically derived start-up sequence (5) is then executed by the orchestration engine (6). During execution, the engine utilizes module services (7) to configure the internal settings and functionality of MM's. In the end, every module is brought to operation including configuration of the field-bus system, adoption of the GUI, and configuration of channels for real-time communication. In cases where no automatic decision could be derived, a menu driven guide is presented to the commissioning engineer. In order to gain information about the manner in which the machine should be brought to operation. After that, test sequences are performed together with the start-up engineer to test all relevant functionality. Finally, commissioning is accomplished and the machine is left in an operational state and is ready for production.

## 6 Relization of a Reference Architecture for a Mechatronic Module

In this chapter, a novel reference platform for the design of mechatronic modules is presented. Modules which are built according to this reference platform can be utilized for research on automatic start-up sequence generation for RMS. Web-Services as well as field-bus communication utilize the same communication infrastructure. Web-Services usually apply the Internet Protocol (IP). This IP communication can be transmitted within a separate non-real-time (NRT) communication channel of a modern field-bus system. As a result, it is possible to use both communication systems at the same time without interference. The automation-bus sercos III is a reliable and Ethernet-based field-bus for the automation industry [21]. It provides high flexibility and deterministic real-time communication. Since sercos III also provides a NRT-IP channel, it is applied in this project. However, other field-busses may be used in addition or alternatively as long as they provide IP communication in every communication state. Moreover, DPWS services are deployed as they are more suited for changing distributed environments in manufacturing than standard Web-Services. To specify mechatronic functionality and communication interfaces of MMs, several description languages are necessary, such as function and interface descriptions in the Sercos Device Description Language (SDDML) [22] and the Web Service Description Language (WSDL) [23]. Moreover, other descriptions for integration of GUIs, configuration parameters as well as drivers and software components can be used. As basis to structure information, the format AutomationML might serve as basis since it is extensive and already contains formats to describe geometry, topology, and behavior [24]. In order to be able to use orchestration, the start-up process has to be formulated in a process/workflow execution language, e.g., the Business Process Execution Language (BPEL) [25] can be used to describe such processes. Not only the overall start-up process can be described in BPEL, but also start-up descriptions stored in MM which represent fragments of the overall process.

Figure 6 shows an overview of the platform which serves as a reference architecture for the design of MMs. An MM is represented by a personal computer which is equipped with a sercos III master or a sercos III slave networking card (NIC). A Linux system with a real-time extension is used as operating system. Furthermore, services which are contained in the module can be executed. Services may communicate with other services in the machine by utilizing the Service-Bus system. Examples for services inside MMs may be providers for documents and descriptions, managers for the internal firmware, services that handle internal module states or interfaces to (real-time) software modules. Besides, other software modules with real-time software can be executed within an MM. This is important for the execution of integrated simulation software, which can be used to emulate real machine behavior during manufacturing. Mechanical and electrical parts of MMs can be emulated for example with the real-time simulation environment Virtuos [26]. In order to support integration of IP traffic, which is necessary for service communication, a virtual networking card (VNIC) is integrated. For programs like services, this device behaves like standard networking hardware. However, functionality differs as incoming packets from applications are forwarded to the sercos communication stack and are sent in the NRT channel of the sercos network. Incoming NRT packets on the sercos bus are forwarded to the virtual networking card and can be processed in an application. IP Communication is therefore possible in every sercos communication phase from the power-on to the operational phase. A Personal Computer is necessary in the current setup to execute the internal simulation models. Final requirements for MMs will be much lower. Since, besides traditional functionality, only IP communication, execution of an embedded Web-Service stack, and a small data storage unit is necessary.

Module services also enable access to the device firmware for modifying and adapting settings in the device database. For this special purpose the sercos communication stack was extended by a DPWS service with read and write access to the device database. Thus, it is possible to configure and modify the device firmware via module services, which is important regarding automating the start-up sequence. Consequently, it is possible to configure field-bus communication during the start-up sequence, before starting the field-bus system. This feature is important, since some parameters have to be configured before the field-bus can be started which enables advanced management of module properties. With this reference architecture, complete machine structures with real networking and simulated mechatronic behavior can be created. Finally, these structures serve as

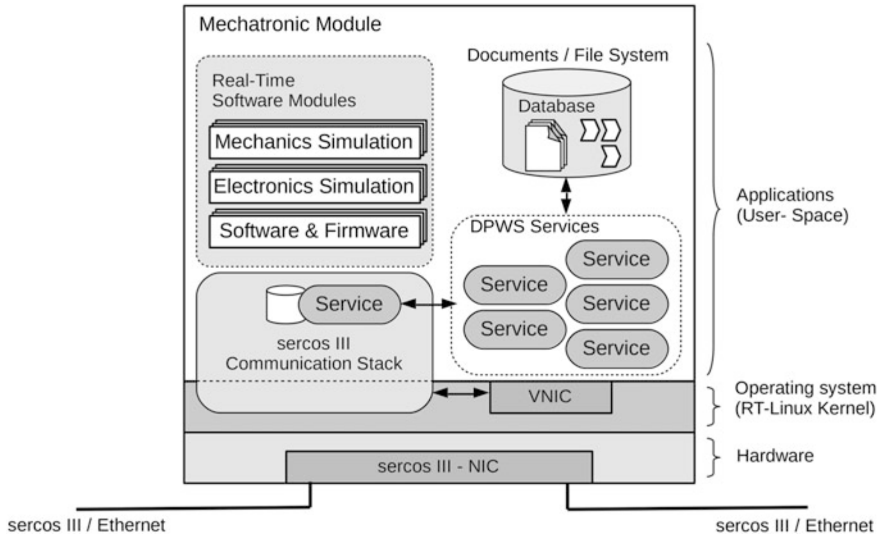


**Fig. 6** Reference architecture for the design of MM

testbed for the evaluation of high level concepts like orchestration of automated start-up sequences in reconfigurable production scenarios.

## 7 Experimental Results

To validate the proposed concept, a set-up of three MMs (MM A, MM B, and MM C) has been chosen, which are solely connected via the sercos automation-bus. All of them are build according to the reference architecture proposed in the previous chapter. MM A is equipped with sercos slave hardware and contains the CS. Furthermore, MM B is equipped with slave hardware whereas MM C contains hardware for a sercos bus master. The bus is configured to run with a moderate cycle-time of 2 milliseconds. All measurements have been executed in three different Communication Phases (CP): CP NRT: Bus in non real-time (NRT) mode; CP 2: Bus in configuration mode; and CP 4: Bus in real-time mode. The execution time of requests done by the gather service in the CS was chosen as exemplary use case. This service collects XML description documents from module services in the MMs and transfers them to the CS for further processing. Figure 7 shows the resulting average transfer time.

Measurements have been executed with a Maximum Transfer Unit (MTU) of 1,500 Bytes. The XML document has a size of 43 KB which does not fit into a single Ethernet packet and therefore is split and transmitted in several fragments. It can be observed from the figure that requests that do not cross computer

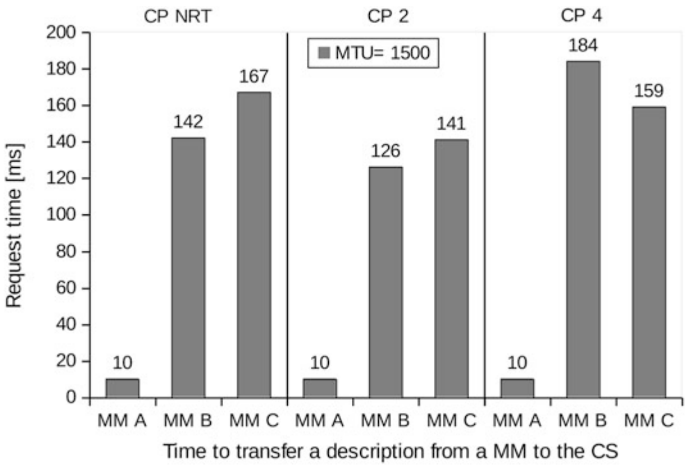


**Fig. 7** Time to transfer an XML description from an MM to the CS

boundaries are handled in 10 ms, other requests can mostly be handled within 120 and 200 ms.

## 8 Conclusions

In this article, a concept for the automatic start-up of reconfigurable production machines is proposed. For this purpose, the information and communication technology in a production machine is designed to match the paradigms of service-orientation. An automatic start-up can be achieved by flexible services which are used to execute commissioning tasks in the machine. Orchestration can be used to automate the creation and execution of the start-up process as workflow. Machines are composed of intelligent mechatronic modules which are used as basic building blocks. Each of them is equipped with a field-bus interface for real-time communication as well as a Service-Bus interface for flexible service communication. Both communication systems share the same physical Ethernet interface. In addition, intelligent mechatronic modules contain various documents which can be accessed for automating of the start-up sequence. This sequence is derived by means of a configuration system, which gathers and executes start-up descriptions. These descriptions are scattered in the machine and can be executed by an orchestration engine. Moreover, a standard reference architecture for research purposes is presented. This architecture can be used for the realization of software structures within mechatronic modules. Furthermore, the automation-bus sercos III is used as communication medium for real-time communication between mechatronic modules. Besides, services, based on the DPWS specification, are used to implement flexible functionality. Realization of the concepts described above will help to gain more knowledge of automatic start-up procedures in reconfigurable production. Finally, in the future a production machine can be automatically put to operation and therefore a lot of time and expenses can be saved.

## 9 Outlook

The approach presented in this paper focuses on the creation of a new method to start-up reconfigurable machines. Current work on this project covers technological aspects like service integration as well as workflow generation. However, to achieve a complete functioning system, more effort is necessary. Further research topics need to cover: standardization of mechatronic functionality, mechatronic description languages, integration, and processing of mechatronic descriptions, interpretation of machine and module information, transfer and distribution of drivers and software modules between MMs, automatic generation of start-up workflows, and extensive testing and evaluation of the implemented functionality. In addition, further realizations of mechatronic modules need to consider more aspects not only from information technology but also from mechanics and electronics. Moreover, to be ready for production the concepts need to be integrated into real automation systems.

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## References

1. Wurst K-H, Kircher C, Seyfarth M (2005) Conception of reconfigurable machining systems—design of components and controllers. In: Advances in integrated design and manufacturing in mechanical engineering, Springer, Berlin
2. Bi ZM (2008) Reconfigurable manufacturing systems: the state of the art. IJPR 46(4):967–992
3. ElMaraghy H (2005) Flexible and reconfigurable manufacturing systems paradigms. Int J Flex Manuf Syst 17(4):261–276
4. Heisel U, Meitzner M (2003) Progress in reconfigurable manufacturing systems. In: CIRP 2nd international conference on reconfigurable manufacturing, NSF ERC for RMS, Ann Arbor
5. Pritschow G et al (2003) Requirements for controllers in reconfigurable machining systems. In: CIRP 2nd international conference on reconfigurable manufacturing, Ann Arbor
6. Kircher C et al (2005) Self-adapting control systems for RMS. In: CIRP 3rd international conference on reconfigurable manufacturing, Ann Arbor
7. Mendes M et al (2008) Service-oriented control architecture for reconfigurable production systems. In: 6th IEEE international conference on industrial information, Daejeon

8. Abele E et al (2007) Mechanical module interfaces for reconfigurable machine tools. J Prod Eng Res Dev 1(4):421–428
9. Weck M, Neuhaus J (2001) Mechatronic modules for quick configuration of flexible manufacturing cells using Plug and Play. In: Annals of the German academic society for production engineering, vol 8(1). Berlin
10. Lechler A et al (2007) Flexible reconfiguration and maintenance through mechatronic modules in manufacturing systems. In: IFPR, 19th international conference in production research, Valparaiso
11. Gruver W, Kotak D, Van Leeuwen E (2004) Holonic manufacturing systems: phase II Holonic and multi-agent systems for manufacturing. In: Lecture notes in computer science, Springer, Berlin
12. Jammes F, Smit H (2005) Service oriented paradigms in industrial automation. IEEE Trans Ind Inform 1(1)
13. Erl T (2004) Service-oriented architecture. concepts, technology, and design. Prentice Hall PTR, Upper Saddle River
14. Jammes F et al (2005) Orchestration of service-oriented manufacturing processes. In: 10th IEEE conference on emerging technologies and factory automation
15. World Wide Web Consortium (W3C), SOAP Version 1.2 (2007)
16. Souza L, Spiess P, Guinard D (2008) SOCRADES: a web service based shop floor integration infrastructure. In: Lecture notes in computer science, Springer, Berlin
17. Organization for the Advancement of Structured Information (OASIS) (2009) Devices profile for web services version 1.1
18. Jammes F (2005) Service-oriented device communications using the devices profile for web services. In: Proceedings of the 3rd international workshop on middleware for pervasive and ad-hoc computing
19. Abel M et al (2011) Service-orientierte Architektur für die Konfiguration und Inbetriebnahme von Produktionsmaschinen—Universal Plug and Produce. 8. AALE Fachkonferenz, Oldenburg Industrie Verlag, München
20. Abel M et al (2011) Start-up of reconfigurable production machines with a service-oriented architecture. In: 21st international conference on production research, Stuttgart, Germany, 31 Jul–4 Aug
21. sercos International e.V. (2011) Serial real time communication interface (SERCOS), Süssen
22. sercos International e.V. (2007) sercos device description markup language, Süssen
23. World Wide Web Consortium (W3C) (2001) Web services description language (WSDL) 1.1
24. Automation ML Consortium (2010) AutomationML architecture specification v2.0. www.automationml.org
25. Organization for the Advancement of Structured Information Standards (OASIS) (2007) Web services business process execution language (WS-BPEL) version 2.0
26. http://www.isg-stuttgart.de, ISG Industrielle Steuerungstechnik GmbH, ISG-Virtuos. Accessed Jan 2012

# Application of Modularity Principles in the Press Tool Enterprise: Reconfigurability

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**Abstract** This paper aims to explore the literature related to modularity in an enterprise in order to apply the idea of modularity into the business services context. The paper design follows an adductive logic beginning with the construction of a theoretical pre-understanding. Streams of literature that are applied are service marketing and operations and modularity research. Special attention is paid to some of the modularity dimensions such as in services, organizations, and customer interaction to build business competitiveness. To stay competitive, enterprises must apply systems or use principles that not only produce their goods with high productivity, but also allow for rapid response to market changes and consumer needs. A new business capability that allows for quick production launch of new products, with production quantities that might unexpectedly vary, becomes a necessity. Reviewing literature of modularisation of manufacturing products and semi- structured face to face interviews with some of the South African press tool enterprises provided rich data for setting up background for further research. The paper shows how businesses can use modularisation to meet customer demands and product mix, cost efficiently, and flexible.

## 1 Introduction

Today's business and manufacturing companies are encountering many challenges to compete effectively and efficiently in a competitive environment. However, challenges are identified and analyzed to determine whether enterprises can eliminate or manage them to meet rapidly changing customer demands and product variations in the manufacturing area. Changes of the business environment

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do not only affect the production but also other departments of the enterprise. Reconfigurable enterprises have shown in the past the ability to be flexible to meet various customer demands and product mix. Furthermore, these reconfigurable enterprises are using modular principles to outperform their competitors. The reconfigurable manufacturing systems are designed for specific range of manufacturing requirements [1]. The reconfigurable manufacturing systems are those systems that are designed for rapid change of structure as well as hardware and software components. In other words, the reconfiguration is the process of changing the current configuration to a new one, which may involve changing the set of processes. Furthermore, press tool manufacturing as an enterprise has more machines and functions, which can accommodate application of modular principles. For the enterprise to manage business complexity and flexible customer demands, the paper argues the potential of a variety of management strategies that have been developed thus far. More importantly, it is shown that these strategies have unequal potentials of complexity reduction. The paper concludes that in order for an enterprise to reduce the complexity of business functions and operations, an enterprise has to ensure that customer requirements and customization responsiveness are both independent from the point at which the customer orders are received. Due to the separateness of functions to handle customer requirements and responsiveness within enterprises, functions can be disjointed and recombined into new function configurations without loss of functionality. Finally, the paper demonstrates that the application of modularity can be regarded as a necessary and can be used to meet various customer demands and product volume mix cost efficiently and flexible.

## 2 Modular Principles in Machine Design

Shinno and Ito [2–4] developed a methodology whereby machine tools may be structurally generated from simple geometric objects. Researchers at the University of Michigan further extrapolated this methodology into the fabrication of a library of precompiled mechanical modules from which machine tools may be assembled [5–7]. Supplementary to the organization of mechanical modules into a library is the methodology of module enumeration developed by Ouyang et al. [8]. Selection of basic modules, and the way they are connected, must allow creation of systems that can be easily integrated, diagnosed, customized, and converted. While modular principles applications are effective in the design of machines, but the press tool enterprise in South African context lacks these principles in the business side. A focus on the relevancy to the SMMEs will be a good value add given the notion of seeking to establish affordable automation, affordable business enterprises.

## 3 Modularity

A general theory of modularity can be defined as the degree to which the components of a system can be separated and recombined to create a variety of configurations without losing functionality [9]. A year earlier, Chun, and Kusiak [10] has defined modularity as a tool to describe the use of common units to create products by aiming the identification of independent, standardized, or interchangeable units to satisfy a variety of functions. Newcomb et al. [11] has explained the term modularity as the separation of a system into independent parts or modules that can be treated as logical units, where a product that is divided into modules has a great effect on life cycle viewpoints such as assembly, disassembly, and service. Modularity is a general set of principles for managing complex systems [12] and is becoming more important as a strategy for organizing systems efficiently [13, 14].

According to these authors, modularity provides a form of system reconfiguration that reduces the level of system complexity, hence reducing the costs of organizing. A significant body of literature has explored the proposition that modular products drive modular organizations [15, 16]. However, enterprises know they need to simplify whenever possible, manage systematic complexity, and promote a mindset of being fast and flexible. In order for the enterprise to do well in their business, much effort should be placed on reconfigurability of their manufacturing components and business process.

### *3.1 Modularity Framework*

Duray et al. [17] and Duray [18] developed a framework separating modularity and customization in order to distinguish different mass customized types of product and service. They differentiate between modularity types varying across the production cycle, and customization levels depending on the customer involvement in production of their product. In contrast, our framework combines the degrees of modularity and customization. Bask et al. [19] uses similar evaluation criteria for the degree of customization related to service production but for modularity, the focus is on the level of modularity and not on the type. To explore more on modular principles, in Fig. 1 the paper highlights the modularity and customization in service offering.

## 4 Reconfigurability

According to Vyankatesh and Rajesh [20], he said that tool system is very important in machining process. He further indicated that a complete tool set contain punch, alignment ring, stripper, and die. If one of these components not conducts wisely it will damage the product or will facing with machine damage. In

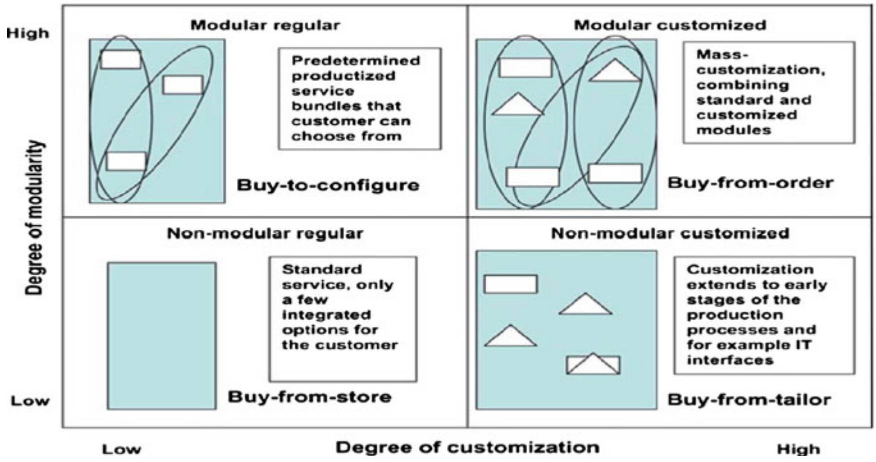


**Fig. 1** Combining modularity and customization in service offerings (*Source* Bask et al. [19])

order for press tool enterprise to save substantial part to the overall cost of manufacturing components, it is essential to keep down this cost by ensuring that the reconfigurability of operational processes work for a long period without interruption. Flexible for the enterprise to be able to adjust its production setup quickly without any major delay to production, an enterprise should reconfigure their manufacturing system and their business environment so as to respond to complexity with operational flexibility.

According to Stefanovic [21] reconfiguration refers to the redesign of certain elements or components of a system. If an organization is perceived as a system, organizational units can be viewed as elements or components of that system. Thus, business unit reconfiguration is the addition of units to the enterprise, deletion of units from the enterprise, and recombination of units within the enterprise such that resources and activities are still retained by the organization [22]. This approach can be seen as the modular architecture of an organization. It is interesting to note that the concept of "patching," which was originally developed by Eisenhardt and Brown [23], corresponds to the idea of modularity. Figure 2 represents crucial components of reconfigurability to be considered when applying modular principles; focus on relevance to the Press tool enterprise will be to gain recognized benefits, including reconfigurability, which will have multiple options for each module that make up process according to its configuration.

## 5 Business Orientation in Uncertain Environment

Business Orientation essentially portrays the pervading culture or style of an organization. There are many types of business orientation, such as marketing orientation, production orientation, or relationship orientation. The dominant presence

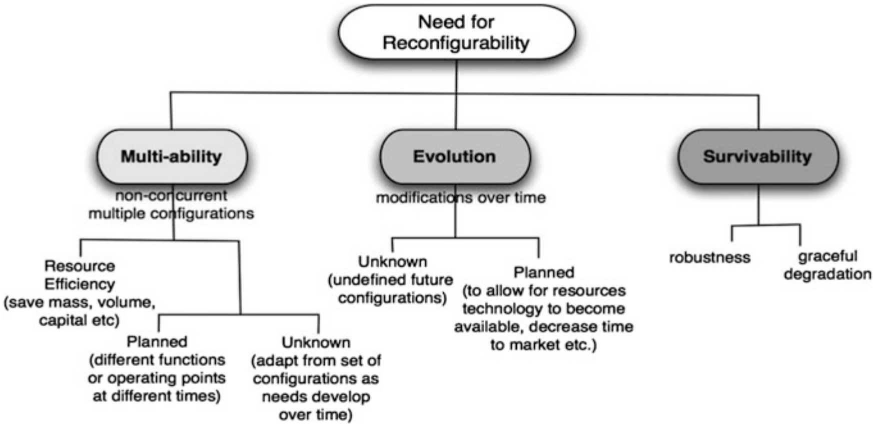


**Fig. 2** Properties enabled by reconfigurability. *Source* Siddigi and De Weck (2008): modeling methods and conceptual design principles for reconfigurable systems

of any of these alternative types of business orientation can have a profound influence on the development and evolution of an organization's strategic outlook. A business orientation essentially represents the way in which the enterprise pursues its mission and sets its objectives. Many authors agree that business orientation is conceptual and advocate that adopting an appropriate business orientation is fundamental to business success [24]. One thought about enterprise design based on modular principles is the flexibility, which helps enterprises to address short and long term objectives. Due to competitiveness and economic turbulence in the nature of today's business it is critical for an enterprise to put much effort on the reconfigurability of its manufacturing and service process.

It can be argued that the role of the business orientation influences "all strategic decisions," acting as the underlying philosophy, which guides the firm internally when responding to changes within the business environment [25].

Indeed, this interdependent relationship between business orientation and corporate strategy is exhibited when firms are forced to change their strategy, as this initially requires changes to the business orientation [26].

It is argued that the alignment between business orientation, the corporate strategy and the business environment can provide a source of competitive advantage [25]. All businesses need to be aware of the likely pressures from the market place or business environment [27]. Examples of such pressures include demand volatility, economic turbulence, and increased competition [28, 29]. These in turn translate into different challenges to the firm. When subjected to pressure from the external environment, senior managers experience a level of uncertainty. This uncertainty presents more of a problem when managers are faced with long-term decision-making to determine the correct way forward for both their businesses per se and invariably their supply chains [30, 31].

# 6 Global Strategies and Local Responsiveness

In a business environment where both forces of local responsiveness and global integration are relatively low, there will hardly be any drivers for a global strategy formation.

The suggested integrated network strategy is comparable to the transnational strategy described by Barlett and Ghoshal [32]. In this strategy, in this context, national operations are not simply independent activities attempting to respond to local market needs; they are also repositories of ideas and technologies the organization might be able to use and apply in its other global operations [33]. When an organization in one country is able to develop a competence in manufacturing activities, it can be used for operations in other countries.

## *6.1 Service Modularity and Customer Value Perception in the Enterprise*

Value creation in business relationships has gained a lot of attention in the marketing literature in the last decade, and of course the notion of value has been described in the literature [34, 35]. Due to this high concentration on service modularity, management of the enterprises tend to pay much attention on customer as service receiver. For both customer and enterprise to experience benefits of modularity, both entities must understand the following:

1. Service modules;
2. Modularity in processes; and
3. Modularity in the organization [36].

To explore the possible influence of service modularity on customer-perceived value, the paper highlights the model illustrated in Fig. 3 (Fig. 4).

## *6.2 Modularity of Enterprise and Supply Chain*

Currently, South African press tool enterprises are importing high number of machines from Asia and other continents. For the press tool enterprises to be efficient and effective, modularity must be applied on both enterprise and its supply chain. Globalization has created a competitive environment in which innovation and flexibility is crucial to survive and to compete with local and global enterprise. Regarding organizations, Schilling, and Steensma [37] argues that organizational systems are becoming increasingly modular. As an enterprise in a given industry begins to “outsource” functions and to use organizational components that lie outside the enterprise, the entire production system becomes

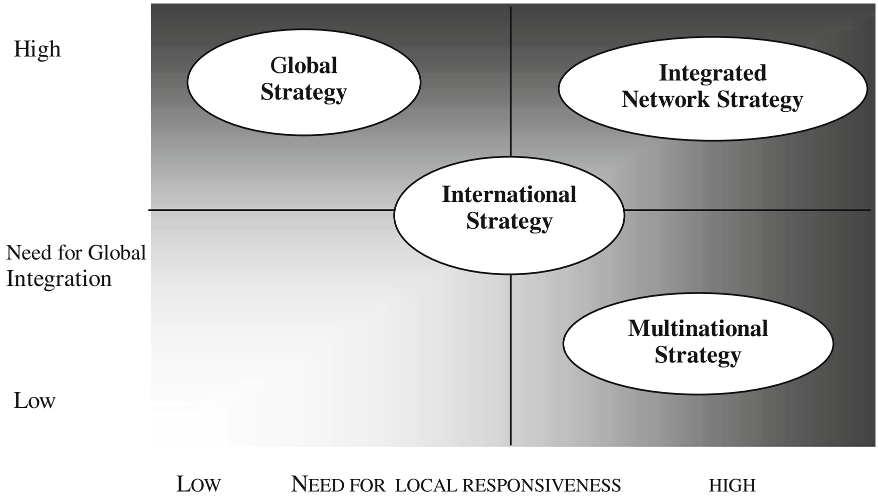


**Fig. 3** Appropriate business strategies. *Source* Barlett and Ghoshal [32]

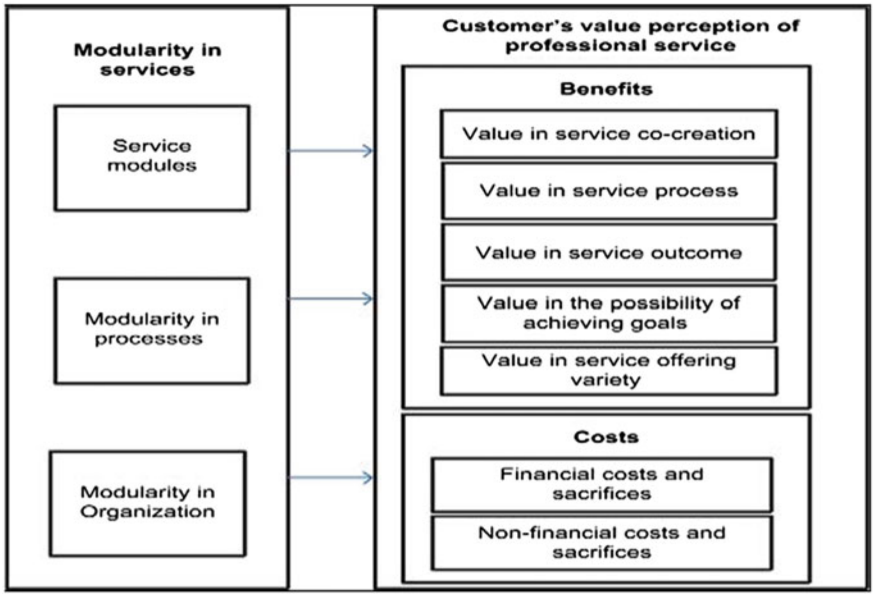


**Fig. 4** Service modularity's possible influence on the customer's perception of value (Pekkarinen and Ulkuniemi [36])

increasingly modular. According to Schilling and Steensma [37], firms use three primary ways of loose coupling, i.e., contract manufacturing, alternative work arrangements, and alliances. This type of organizational modularity is referred to as production systems modularity by Campagnolo and Camuffo [38].

One thought about supply chain is that the effective supply chain network can be the pillar to a successful business, but supply chain alone cannot do much if the entire enterprise supply chain and structures are not modularized. Arnheiter and Harren [39] maintains that it is possible to greatly simplify the supply network by reducing a product containing thousands of individual parts to a handful of subassemblies. They also state that there has been a trend among Western manufacturers to reduce the number of Tier 1 suppliers and establish longer-term contracts with a select group of supplier partners. Also, Tu et al. [40] argues that modularity has significant impacts on a firm's supply chain and the industry structure. The result is a more responsive supply chain that can satisfy individual customer needs without higher production and inventory costs.

In the manufacturing industries, modularity is often presented as a design strategy that stimulates innovation through accelerating division of labor, specialization, and concurrent engineering [41]. On the contrary, Galvin and Morkel [42] suggests that when modularity is adopted in the extreme form of internationally accepted standards, the industry will fragment and firms can and will operate entirely independently.

It is critical when dealing with modularity to avoid what we call the modularity trap before implementing modular principles. Ernst [43] refers to the risk of being caught in a "modularity trap." If an enterprise focuses too much on developing products within given interface standards, this may erode the firm's system integration capabilities. On the contrary, Brusoni and Prencipe [44] argues that in fact, the increased division of labor resulting from modularity requires close cross-company interaction and conscious efforts at coordination on the levels of both knowledge and organization.

In the literature, the modularity of supply chains has been related to "loosely coupled" modular product architecture that allows a division of labor and outsourcing of tasks across enterprises and supply chain variations, even leading to modular structures at the industry level. According to Bask et al. [45] there is no consensus about whether the modular structures themselves encompass the means of "embedded" coordination and facilitate management of complex supply chains and if so, how this takes place.

### *6.3 Benefits of Modularity for Enterprise*

Due to the competitive nature of the global business, greater product variety, and shorten life cycle are factors that gives company competitive edge to competitor. South African Press tool enterprise must move from Dedicated Manufacturing System (DMS) to short run, demand driven mode of manufacturing. Information from observation and surveys express of inappropriateness on DMS business. Real time response to unexpected changes on supply chain, order management, and distribution are major challenge facing Press tool enterprise. Application of modularity principles is the way to go for Press tool enterprise in order to revamp their business to competitive level.

According to Donnelly et al. [46], he/she determined the benefits arising from modularity as being:

- Increased enterprise flexibility-in meeting the wide variety of end customer demands.

According to Sanchez and Mahoney [47], they indicated that one aspect of firm strategy is to increase flexibility, and it has been suggested that modularity permits relatively higher degrees of flexibility. This flexibility includes product adjustments after product launch [48], the option to add complementary products [49], and the ability to adjust faster to radical technological changes through appropriate product derivative generation [50]. This flexibility gained through modularization, however, might require new incentive structures for employees in the product creation process.

- Increased enterprise speed of delivery of products from the conceptual stage to the market.

### *6.4 Future Work*

The next steps will be to determine how modular principles can be applied in the manufacturing operations and product life cycle. The researcher will also explore more on green technology and its impact on automation in Press tool industry.

## 7 Summary

Due to the increasing challenges of product development, there is a challenge for Press tool enterprises to optimize the processes of product development and business. This paper focuses on the application of modular principles in the press tool enterprise and the role of reconfigurability in support of modularity in the enterprise. Based on a literature review, the modularity definitions are presented and modularity approaches are discussed. Extensive literature review on the following: modularity framework, supply chain, customer perception that can be adjusted to benefit the business objectives and mission, and business environment.

Frequent changes in product portfolios and fluctuating demand characteristics place a strain on the Press tool enterprise system.

Modular principles have shown possibilities of being solutions within the reconfigurable business, they will provide a cost effective solution when adapting any modular changes on Press tool enterprise hardware and software.

This research contributes to both the academia and industry by providing insights into modularity in Press tool enterprise. The results of this study could be further used in developing modularity metrics and tools and could provide as a basis for benchmarking.

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## References

1. Rogers GG, Bottaci L (2003) Advances in manufacturing systems: a new manufacturing paradigm. J Intell Manuf 8(2):47–56
2. Shinno H, Ito Y (1981) Structural description of machine tools 1: description method and application. Bull JSME 24(187):251–258
3. Shinno H, Ito Y (1981) Structural description of machine tools 2: evaluation of structural similarity. Bull JSME 24(187):259–265
4. Shinno H, Ito Y (1984) A proposed generating method for the structural configuration of machine tools. In: ASME winter annual meeting, 1984. ASME paper 84-WA/Prod-22
5. Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, van Brussel H (1999) Reconfigurable manufacturing systems. Ann CIRP 48(2):527–540
6. Mehrabi MG, Ulsoy AG, Koren Y (2000) Reconfigurable manufacturing systems and their enabling technologies. Int J Manuf Technol Manage 1(1):113–130
7. Tilbury DM, Kota S (1999) Integrated machine and control design for reconfigurable machine tools. In: Proceedings: advanced intelligent mechatronics, 1999 IEEE/ASME international conference, pp 629–634
8. Ouyang MA, Yi C, Li C, Zhou J (1995) Intelligent layout for modular design of machine tools. SPIE 2620:547–552
9. Schilling MA (2000) Toward a general modular systems theory and its application to interfirm product modularity. Acad Manag Rev 25(2):312–334
10. Chun CH, Kusiak A (1998) Modularity in design of product and systems. IEEE Trans Syst MAN Cybernutics-Part A 28(1):66–77
11. Newcomb PJ, Rosen DW, Bras B (2003) Life cycle modularity metrics for product design. In: Proceedings of EcoDesign2003: third international symposium on environmentally conscious design and inverse manufacturing, Tokyo, Japan, pp 251–258, 8–11 Dec 2003
12. Langlois RN (2006) The secret life of mundane transaction costs. Organ Stud 27(9):1389–1410
13. Schilling MA, Steensma HK (2001) The use of modular organizational forms: an industry-level analysis. Acad Manag J 44:1149–1168
14. Baldwin CY, Clark KB (2002) Where do transactions come from? J Econ Lit 6:2–4
15. Sanchez R, Mahoney JT (1996) Modularity, flexibility, and knowledge management in product and organizational design. Strateg Manag J 17:63–76
16. Sanchez R (2002) Designing strategic flexibility into your products and processes: perspectives for managers. IMD 88:1–4
17. Duray R, Ward PT, Milligan GW, Berry WL (2000) Approaches to mass customization: configurations and empirical validation. J Oper Manag 18(6):605–625
18. Duray R (2002) Mass customization origins: mass or custom manufacturing? Int J Oper Prod Manag 22(3):314–328

19. Bask A, Lipponen M, Rajahonka M, Tinnilä M (2011) Framework for modularity and customization: service perspective. J Bus Ind Mark 26(5):306–319
20. Vyankatesh BE, Rajesh RK (2012) Efficient method of producing oval punching holes on sheet metal. J Appl Mech Eng 1:109. doi:10.4172/2168-9873.1000109
21. Stefanovic I (2011) The response to the changing landscape of tomorrow: reconfigurable organizations. Afr J Bus Manage 5(35):13344–13351
22. Karim S (2006) modularity in organizational structure: the reconfiguration of internally developed and acquired business units. Strateg Manage J 27:799–823
23. Eisenhardt KM, Brown SL (1999) Patching: restitching business portfolios in dynamic markets. Harv Bus Rev 77(3):71–82
24. Bennett R, Cooper R (1979) Beyond the marketing concept. Bus Hori 22:233 (Pearson 1993)
25. Miles MP, Russell G (1995) The quality orientation: an emerging business philosophy? Rev Bus 17(1):7–15
26. Miles M, Munilla L (1993) Eco-orientation: an emerging business philosophy? J Mark Theor Pract 1(2):43–51
27. Haperberg A, Rieple A (2001) The role of trust and relationship structure in improving supply chain responsiveness. Ind Mark Manage 31(200):367–382
28. Matanda M, Mavondo F (2001) The effect of market orientation and supply chain efficiency on business performance. In: Paper presented at ANZMAC conference
29. Fugate B, Mentzer J, Flint D (2008) The role of logistics in market orientation. J Bus Logistics 29(2):1–26
30. Christopher M (2005) Logistics and supply chain management: creating value added networks. Prentice Hall, Englewood Cliffs
31. Gilmore G, Lindsay R (2010) Britain exists longest recession on record just. Time-online http://business.timesonline.co.uk/tol/business/economics/article700215.eceE>. Accessed 22 Sep 2010
32. Barlett CA, Ghoshal S (1989) Managing across borders. Harvard Business School Press, Boston
33. Barney J (2001) Gaining and sustaining competitive advantage. Prentice Hall, Englewood-Cliff
34. Eggert A, Ulaga W, Schultz F (2006) Value creation in the relationship life cycle: a quasi-longitudinal analysis. Ind Mark Manage 35(1):20–27
35. Flint DJ, Woodruff RB, Gardial FS (2002) Exploring the phenomenon of customers' desired value change in a business-to-business context. J Mark 66(4):102–117
36. Pekkarinen S, Ulkuniemi P (2008) Modularity in developing business services by platform approach. Int J Logistics Manage 19(1):84–103
37. Schilling MA, Steensma HK (2001) The use of modular organizational forms: an industry-level analysis. Acad Manag J 44(6):1149–1168
38. Campagnolo D, Camuffo A (2009) The concept of modularity in management studies: a literature review. Int J Manage Rev. Retrieved online in advance of print, published online: 26 Mar 2009 6:59AM. www.3.interscience. wiley.com/journal/120125469/issue
39. Arnheiter ED, Harren H (2005) A typology to unleash the potential of modularity. J Manuf Technol Manage 16(7):699–711
40. Tu Q, Vonderembse MA, Ragu-Nathan TS, Ragu-Nathan B (2004) Measuring modularity-based manufacturing practices and their impact on mass customization capability: a customer-driven perspective. Decis Sci 35(2):147–168
41. Jose A, Tollenaere M (2005) Modular and platform methods for product family design: literature analysis. J Intell Manuf 16(3):371–390
42. Galvin P, Morkel A (2001) The effect of product modularity on industry structure: the case of the world bicycle industry. Ind Innov 8(1):31–48
43. Ernst D (2005) Limits to modularity: reflections on recent developments in chip design. Ind Innov 12(3):303–345
44. Brusoni S, Prencipe A (2001) Unpacking the black box of modularity: technologies, products and organizations. Ind Corp Change 10(1):179–205

45. Bask AH, Tinnilä M, Rajahonka M (2010) Matching service strategies, business models and modular business processes. Bus Process Manage J 16(1):153–180
46. Donnelly T, Morris D, Donnelly T (2006) Modularisation and supplier parks in the automotive industry, Caen Innovation Marche Enterprise, Annee 2006-Cahier No 37/2006
47. Sanchez R, Mahoney JT (1996) Modularity, flexibility, and knowledge management in product and organization design. Strateg Manag J 17(Winter Special Issue):63–76
48. Verganti R, Buganza T (2005) Design inertia: designing for life-cycle flexibility in internet-based services. J Prod Innov Manage 22(3):223–237
49. Nambisan S (2002) Complementary product integration by high-technology new ventures: the role of initial technology strategy. Manage Sci 48(3):382–398
50. Jones N (2003) Competing after radical technological change: the significance of product line management strategy. Strateg Manag J 24:1265–1287

# Design of a Multifunctional Cell for Aerospace CFRP Production

**F. Krebs, L. Larsen, G. Braun and W. Dudenhausen**

**Abstract** Due to the rising demand in efficiency and sustainability in commercial aviation, aircraft manufacturers increase the usage of high performance, light-weight materials like carbon fiber reinforced plastics (CFRP). These materials pose new challenges to manufacturing processes concerning cost-effectiveness and quality requirements. To meet these challenges the Institute of Structures and Design within the German Aerospace Center (DLR) designed a flexible robotic manufacturing cell at the Center for Lightweight Production Technology (ZLP) in Augsburg. The multifunctional cell (MFZ) can integrate processes for production and inspection on an industrial scale. Due to large workpieces like fuselage components or wing skins and low production quantities, workshop space, and investment cost are major concerns for effective CFRP production. The large size of the cell (30 × 15 × 7 m) demands a highly reconfigurable space. The platform is composed of five ceiling mounted robots on a gantry like machine frame and may be divided in smaller independent cells. The multifunctional cell will improve the understanding of requirements of future production processes for lightweight components by providing a highly flexible platform on an industrial scale.

## 1 Introduction

In recent years the demand for high grade carbon fiber reinforced plastic (CFRP) components in aerospace applications has risen considerably. Current aviation initiatives like the European Commission's Clean Sky program [1] or ACARE's

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Flightpath 2050 [2] focus on increasing aircraft efficiency facing the challenges of future commercial aviation. Besides other goals, this means a reduction of aircraft emissions. The use of lightweight materials like CFRPs allows a significant reduction of the structural mass. Hence less fuel is consumed during travel and fewer emissions are produced. Unfortunately aerospace quality CFRP components are very expensive to manufacture because current manufacturing technology is largely dominated by manual labor.

In respect to these developments the German Aerospace Center (DLR) founded the Center for Lightweight Production Technology (ZLP). The ZLP is developing automated production technologies which allow cost-effective usage of CFRP components. As production quantities in aerospace are comparatively low and shop floor space is limited, single-use machines cannot satisfy the industrial demands concerning cost efficiency. Because of this the German Aerospace Center's (DLR) Center of Lightweight Production Technology (ZLP) and a major automation systems integrator (KUKA Systems GmbH, Augsburg) have designed a robot-based multifunctional cell (MFZ) for the last three years. Currently the cell is nearing completion which will allow process technology research on an industrial scale.

## 2 Design Considerations

To design a flexible cell the term "flexibility" needs further definition. In terms of the MFZ "flexibility" means the ability to reconfigure the robotic platform in order to perform various CFRP production processes like layup, vacuum-bagging, inspection, or assembly on different aircraft components like fuselage, wings, or empennage parts.

For example to fully perform a resin infusion based on the vacuum assisted resin transfer molding (VARTM) process the following steps must be completed. Individual carbon fiber cut pieces are placed inside a prepared mold. A component like a fuselage section easily requires hundreds of individually shaped cut pieces. After the layup is completed the mold is sealed by a vacuum bag (see Fig. 1). After evacuation, resin is pulled into the composite layup. Then the infused part is cured in an oven. Afterward the vacuum bag is removed and the finished part is demolded. Lastly the part is examined by non-destructive testing methods (e.g., ultrasonic inspection) for possible product anomalies [3].

Furthermore the traditional assembly line paradigm which is prevalent in automotive industries where a component is moved from one station to another by a conveyor belt is only partially applicable because of the large scale of the workpieces. Hence the cell has to be reconfigurable to the effect that sequential processes may be executed with minimal reconfiguration effort.

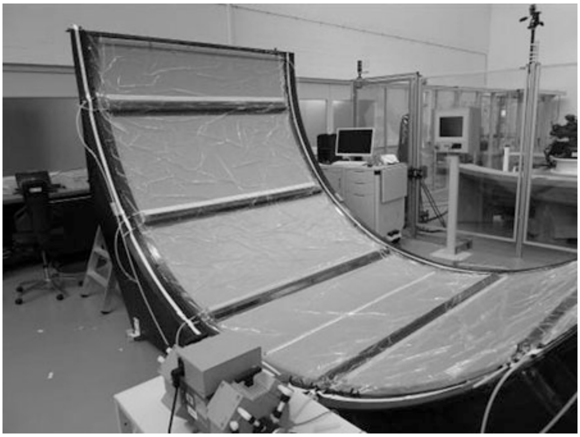

**Fig. 1** Large fuselage component being infused (*Source* DLR)

## 2.1 Use Case Scenarios

To validate design considerations an industrial relevant use case was chosen. The model case consists of the layup of non-crimp fabric (NCF) cut pieces in a fuselage half barrel mold with total length of 16, 5 m in width and approximately 3 m (depending on the mold's underlying support structure) in height. This mold represents two sections of an Airbus A320 fuselage (see Fig. 2).

Other available molds (e.g., pressure bulkhead and cargo door) were also cross checked to reduce the risk of developing a single purpose machine.

## 2.2 Robotic Workcell Layout

Industrial robots are able to perform many different tasks, e.g., welding, painting, and handling. Due to their flexibility they are already commonplace in many industry sectors. In the MFZ traditional six-axis industrial robots and custom

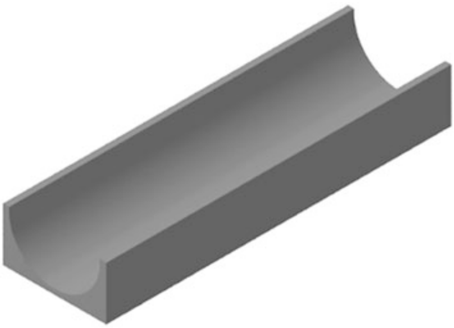

**Fig. 2** Model case mold of a simplified Airbus 320 fuselage

**Fig. 3** Robot types in multifunctional cell (KUKA KR270 R2700, custom 6 DOF-Portal with KR240 arm)

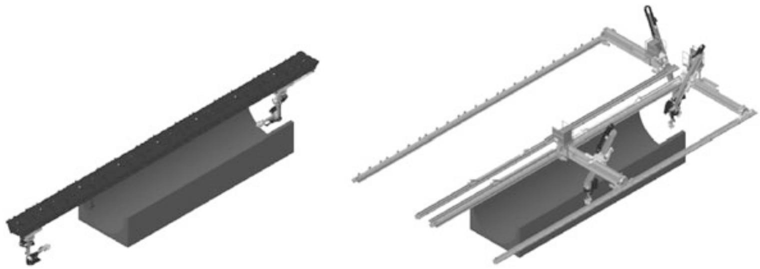

**Fig. 4** Configuration of robots and portals in multifunctional cell

portals fill the role as manipulators. The industrial robots are KUKA KR270 R2700 with a payload of 270 kg and a maximum reach of 2700 mm. The portals are based on a XYZ configuration (A1–A3) with an inclined Z component and a hand of an industrial robot (A3–A6) at the end of the portal structure to achieve six degrees of freedom (see Fig. 3).

To effectively minimize interference contours and maximize the available workspace two industrial robots are mounted on an overhead central linear track. This allows maximum reachability even for concave molds which are often used for resin infiltration processes. To increase possible parallelization three portal robots are also integrated, flanking the central linear track (see Fig. 4). The inclination of the portals' Z-axis toward the linear track enables a maximum overlap of robots' and portals' individual workspaces. Because all participating robots' workspaces overlap, cooperative tasks between robots and portals can be performed in dynamically changing robot teams according to the processing needs at specific point in time.

The central linear track and the portals on each side are integrated into a common machine frame. This gantry like steel structure rests on four concrete columns (see Fig. 5). The dimensions of the whole assembly are approximately 30 m in length and 15 m in width. The height of the lower boundary of the

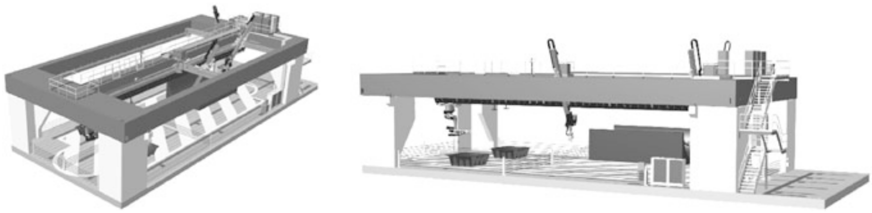

**Fig. 5** The German aerospace center's multifunctional cell (MFZ)

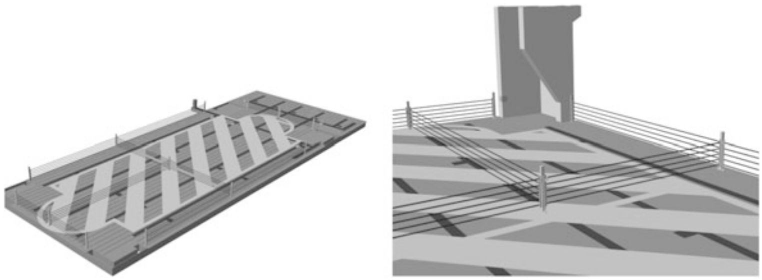

**Fig. 6** Safety light curtains and example virtual cell configuration

machine frame is approximately 7 m. The total height of the multifunctional cell changes with the configuration of the portal robots and peaks at approximately 12 m.

As various processes require different configurations of robots and workpieces do often not occupy the whole available workspace, the whole workspace of the workcell can be used effectively by dividing it in up to four separate virtual cells (see Fig. 6). Each virtual cell is assigned a configuration of robots. Independency concerning safety of other workcells is guaranteed by using a modular light curtain system.

## *2.3 Concerning Robot Accuracy*

Flexibility concerning maximum workspace usage and reconfigurable cell size and robot configurations come with a price. Attaching robots to the ceiling requires a suitable surface. Due to the portals extending and retracting Z axis, concerning the MFZ a closed surface is not suitable. Therefore a machine frame, which withstands the static and dynamic loads of moving robots, had to be developed. Because maximum accessibility from all sides is a requirement for optimal material flow additional support columns could not be used. Therefore the machine frame rests on four corners and spans approximately 30 m without further support.

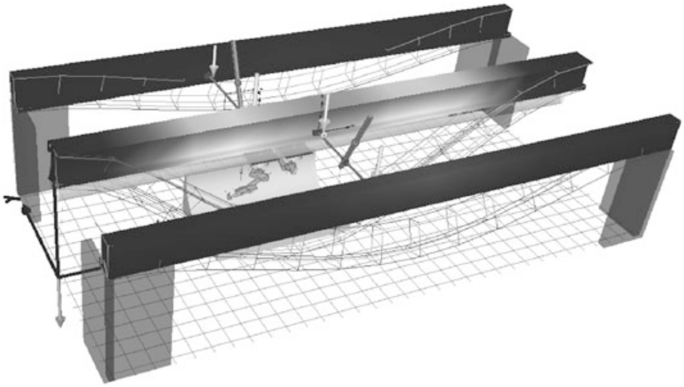

**Fig. 7** Deformations induced by shifting masses [4]

To evaluate the impact of shifting masses due to robot movement a model was developed together with the DLR Institute of System Dynamics and Control [4] (see Fig. 7). As mentioned before the workcell may be divided in up to four separate virtual robotic cells, each running its own program independently. As the programs run independently, they are not supposed to synchronize between each other. Thus the shifts of masses in the common machine frame are unpredictable.

As the robotic system cannot easily determine the deformation of its base structure, it "believes" to be in the correct pose but is effectively in the wrong position.

To mitigate this issue a system has been developed which guides robots along accurate paths and also allows high accuracy positioning. The system consists of a laser tracker (Leica AT901LR including T-CAM), a robot mounted reflector (Leica T-MAC) and a custom developed controller (see Fig. 8).

The laser tracker is set up to measure the T-MAC mounted on the flange of the robot arm and can accurately compute the tool center point's position in the deformed robot cell. As the reflector has integrated infrared LEDs the orientation of the robot's tool center point can also be determined by the additional T-CAM system which is mounted on top of the laser tracker [6].

The controller is able to measure deviations from the nominal trajectories and compensate accordingly in real time. Preliminary experiments show that this system exceeds the default accuracy of an industrial robot. The external guidance system provided an accuracy surpassing ±0.2 mm at a speed of 500 mm/s [5].

## 2.4 Workcell Logistics

As the produced components are very large and require vast amounts of materials, efficient logistics play a major role.

**Fig. 8** External sensor guidance with laser tracker [5]

A main requirement for cost-efficient production is a constant supply of raw material. By allowing material access from multiple sides a maximum of process material flow is guaranteed. Therefore the multifunctional cell maximizes accessibility by using a minimal supporting structure of four concrete pillars.

Furthermore multiple robot tools and additional jigs are required to complete different process steps in the same cell. In the MFZ a clamping field allows easy placement of tools and jigs. The clamping field provides maximum placement flexibility and retains reproducibility by relying on cup-cone systems. Integrated cable conduits supply jigs and tools with power (up to 400 V AC/16 A), Ethernet-based communication (standard TCP/IP and UDP as well as real-time capable ProfiNET and EtherCAT) and other process media (e.g., pressurized air or coolant fluid) (see Fig. 9). Additional specialized process media may be also supplied through the integrated cable conduits.

The robots' interfaces for tools support the same process media as mentioned above. This enables a standardized approach toward robotic tools and makes the integration of automatic tool changers in the process workflow of the MFZ easily possible.

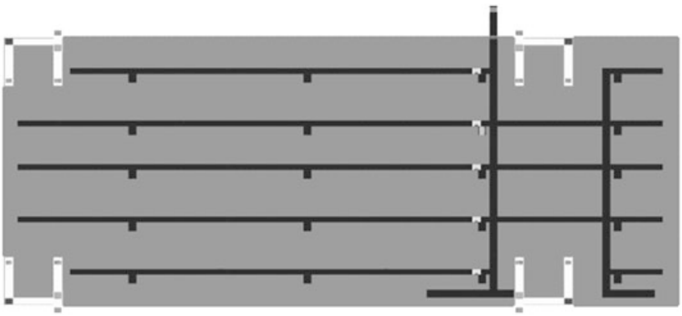

**Fig. 9** MFZ clamping field with integrated cable conduits

## 3 Sample Applications

During the design and construction of the MFZ different sample applications have been developed and tested in a smaller experimental robotic cell at the ZLP. After commissioning of the MFZ, these applications will be transferred to the MFZ to be validated on an industrial scale.

As mentioned before the ZLP is following the promising approach of dry NCF layup and vacuum assisted resin infusion for large CFRP parts. Compared to conventional tape laying machines which use resin pre-impregnated raw materials the layup rate per hour can be much higher and process logistics can be simplified [7].

The first sample is handling of dry NCF textiles. To handle large cut pieces a robotic gripper system called "Streifengreifer" was developed, which is able to handle cut pieces up to 6 m length (see Fig. 10 left). The underlying principle for gripping the material is suction. As the material is strongly air permeable a high flow rate is required to maintain the needed gripping force. Each of two robots' individual grippers picks up a part of the cut piece and then both robots move the whole cut piece cooperatively without warpage damage.

Another example application is an automatic inspection system for NCF layup (see Fig. 10 middle). During the CFRP production process it is essential that cut pieces are placed at the correct position. It is also important that the gap between pieces next to each is less than 0.2 mm in width. Additionally any overlaps between them are completely prohibited. Both requirements are needed to guarantee an optimal structural strength of the final part. To validate correct layup a system has been developed which is able to measure the position, gaps, and overlaps. The measuring system consists of a laser triangulation sensor which is moved along the edge of cut pieces in the mold. To process the raw data of the laser triangulation sensor, a software for analysis has been developed which can compare the CAD nominal position to the actual position of the cut piece. The result is visualized in three dimensions making it easy to assess the result during the production process [8].

A third sample application is the rivetless assembly of a helicopter CRFP structure (see Fig. 10 right). This project was conducted together with Eurocopter. The aim of the project is a fully robot assisted assembly of said structure. First

**Fig. 10** Sample applications for integration in the MFZ (automated layup, quality assurance, and assembly)

single components are put in a tooling station and another part is picked up by the robot. Afterward the other robot applies glue on the parts in the tooling station as well as the part in the gripper. Then the parts are joined and compressed by the robot. To achieve short processing time until the glued parts are suitable for further handling the parts are cured by induction.

## 4 Summary and Outlook

The cell itself is prepared to perform different processes by having a large workspace with multiple manipulators, a high accessibility for material logistics and state of the art communication technology. Additionally a sensor guided system is developed to improve robot accuracy to satisfy the high quality requirements in aerospace industries.

The construction of the cell started in 2011 with the machine foundation and support pillars. In 2012 the upper machine frame and manipulators were installed (see Fig. 11). Currently the cell is being prepared for commissioning in first half of 2013. Sample applications will be transferred from the small experimental cell to the MFZ in the second half of 2013.

The change from manual manufacture to automatic production for CFRP components will not be instantaneous, because new processes need to be validated and many process steps contain many complex manipulation tasks that are very hard to automate. This is why a gradual change is more probable to happen. In this case different tools and jigs need to be easily accessible by humans to perform non-automated tasks. Additionally direct human machine interaction could also play a major role, as the individual advantages of machines and human workers can be used. Humans distinguish themselves in perception and improvisation but lack in strength, speed, and repeatability. In contrast robots excel in these categories but are not able to react to unforeseen changes [9].

Another future extension of the MFZ will decrease the need of a sensor based guiding system. In collaboration with Institute of System Dynamics and Control a

**Fig. 11** State of construction and assembly in October 2012

model based compensation approach is developed which will guarantee a high accuracy and repeatability. Deformations of the cell's structure are calculated in real time and compensated accordingly. When commissioning of the cell is finished experiments will begin to calibrate the developed model [4].

The integration of inter-process logistics between the cutting process of individual cut pieces and layup is another future field of research as it enables an efficient just-in-time logistics chain which is able to react to process anomalies.

Besides the complex hardware solution efficient programming of processes has to be ensured as classical teaching methods fail by the high complexity of CFRP related tasks. Offline programming methods are explored and enhanced to allow the simulation and preliminary validation of future processes before any integration of hardware and enable fast and precise program generation.

Summing up designing a flexible manufacturing environment is one of the key challenges for the broad application of CFRPs in commercial aviation. The multifunctional cell will improve the understanding of requirements of future production processes for lightweight components by providing a highly flexible platform on an industrial scale.

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## References

1. Clean Sky Joint Undertaking (2012) Clean sky at a glance: bringing sustainable air transport closer, Brussels
2. European Commission (2011) Flightpath 2050: Europe's vision for aviation: maintaining global leadership and serving society's needs, Luxembourg
3. Campbell F (2004) Manufacturing processes for advanced composites. Elsevier, Amsterdam
4. Hartweg S, Heckmann A (2012) Modeling of flexible multibody systems excited by moving loads with application to a robotic portal system. In: The 2nd joint international conference on multibody system dynamics. Stuttgart, Germany
5. Gerngross T, Krebs F, Buchheim A (2012) Automated production of large CFRP preforms: challenges and solutions along the process chain. Composite Manufacturing, Frankfurt
6. Leica Geosystems (2010) PCMM system specifications Leica absolute tracker and Leica T-products, Unterentfelden
7. Berchtold G (2007) Innovatives CFK-Fertigungsverfahren unter wirtschaftlichen Gesichtspunkten. DLR-Wissenschaftstag, Braunschweig
8. Larsen L, Dutta S (2011) "Inline Qualitätssicherung in der CFK-Produktion mittels Laserscanner" Produktion 2020: Einsatz, Verarbeitung und Prüfung von Leichtbau- und Faserverbundwerkstoffen, Nördlingen
9. Matthias B (2011) Sichere Mensch-Roboter-Kooperation in industriellen Anwendungen/ Entwicklungsschritte bei ABB Corporate Research, 44. Sitzung des FA 4.13, Steuerung und Regelung von Robotern, Augsburg

# Electrode Wear Estimation and Compensation for EDM Drilling

**Cheol-Soo Lee, Eun-Young Heo, Jong-Min Kim, In-Hugh Choi and Dong-Won Kim**

**Abstract** Electric discharge machining (EDM) is commonly used to machine precise and tiny parts when conventional cutting methods face difficulty in meeting productivity and tolerance requirements. Die-sinking EDM works well to machine micro-parts and perpendicular walls of die and molds, whereas EDM drilling is excellent for machining deep and narrow holes regardless of material hardness and location. However, EDM electrode wear is rapid compared to conventional cutting and makes it difficult to control the electrode feed and machine precisely. This paper presents an efficient method to estimate electrode wear through a hole pass-through experiment while a stochastic method is adopted to compensate the estimation model. To validate the proposed method, a commercial EDM drilling machine was used. The experimental results show that the electrode wear amount can be predicted acceptably.

## 1 Introduction

EDM (Electric Discharge Machining) is widely used in manufacturing mechanical parts, molds, die, and aerospace parts when it is difficult to machine via conventional cutting methods. EDM can be classified according to its electrode; die-

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sinking EDM uses a machine-feature shaped electrode and EDM drilling uses a round, hollow electrode. Due to Computer Numerical Control (CNC) integration into EDM, the electrode motion is controlled precisely and micro-feature machining is possible regardless of material type.

Since productivity and quality depend upon EDM conditions, many studies have been carried out to discover reciprocal relationships. The EDM condition effects and discharge oil on machining quality have been studied experimentally [1, 2]. However, EDM parameter interaction is correlated therefore more complex methods, such as Taguchi method [3] and fuzzy theory [4], are utilized for analysis. Hybrid methods were studied to enhance EDM quality; Jia et al. [5] combined laser and EDM to increase straightness and Kremer et al. [6] studied ultrasonic vibration [6]. Recently, EDM was applied to micro-feature machining [7–10] and EDM drilling is preferred over conventional drilling for machining deep and tiny holes. Many applications are possible, such as air coolant holes in turbine blades, start holes of wired EDM, injection nozzle holes, to name a few. EDM drilling may make micro-hole drilling easier but debris should be removed efficiently for successful EDM. Much research has reported on the relationship between product characteristics and debris elimination methods [11–13].

Together with EDM condition optimization, electrode wear is also a significant consideration in EDM drilling. The electrode of EDM drilling wears out rapidly compared to that of a conventional cutting tool. Mohri et al. [14] analyzed electrode wear against machining time and showed the electrode wear rate (EWR) might reach an equilibrium state. Electrode wear makes it difficult to precisely control electrode motion. EWR can be estimated by a hole pass-through experiment while the wear amount is calculated via hole depth and total machining feed amount. However, EWR depends on the EDM environment. An accurate estimation model might offer basic information for efficient machining in EDM drilling as well as die-sinking EDM. Thus, this paper presents an electrode wear estimation method while the model is adjusted according to EDM conditions. The paper is organized as follows: Sects. 2 and 3 present the EWR estimation model and its compensation methods. Section 4 contains the proposed method which is validated through a discharge experiment. Finally, Sect. 5 presents the conclusion as well as possible future extensions of the proposed method.

## 2 Electrode Wear Estimation

### *2.1 EDM Drilling*

EDM drilling differs from die-sinking EDM in that it machines deep holes via a hollow electrode and spindle rotation in order to remove debris. The negative effects of debris are well known [1]: disturbance of dielectric oil flow, quality deterioration caused by second discharge, electrode wear promotion, etc.

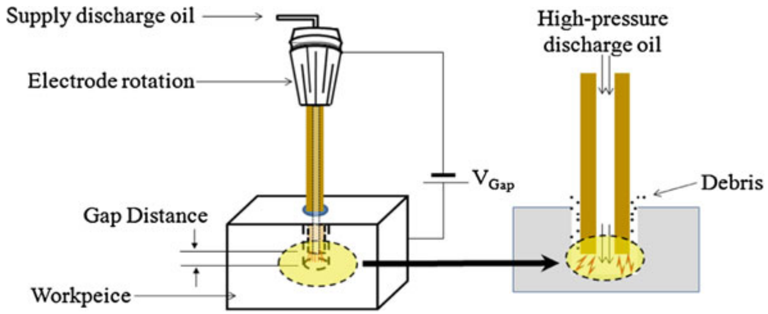



**Fig. 1** EDM drilling illustration

Therefore, effective debris removal in EDM drilling, via high-pressure discharge oil and spindle rotation, determines if machining of deep and tiny holes is successful. An EDM drilling illustration is shown in Fig. 1.

## *2.2 EDM Drilling*

Unlike a general-purpose drill, EDM drilling machines a deep hole via oil discharge from a thin, hollow electrode. The discharging process causes severe electrode wear and the electrode wear amount depends on the EDM conditions and machining time. The initial vertical cross section of the electrode is rectangular and wears down into a round cone-like shape (Fig. 2). The variation in electrode edge shape leads to different electrode wear. The electrode wear rate (EWR) can be evaluated by dividing the wear amount (D-T) by hole depth (T) where D is the distance the electrode passes through the hole (Fig. 3). EWR is

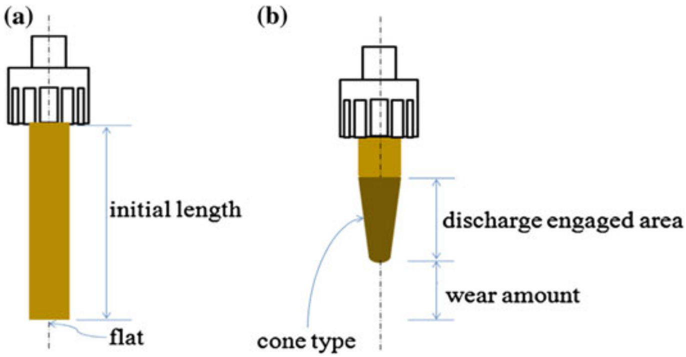
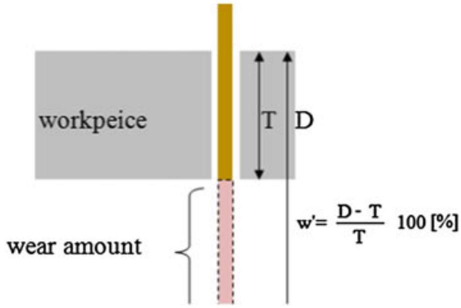



**Fig. 2** Shape of electrode tip according to discharge, **a** initial shape, **b** converged shape

**Fig. 3** Electrode wear calculation




$$\mathit{Electrode\ wear\ rate} = \frac{(D - T)}{T} \times 100\,[\%] \tag{1}$$

However, the electrode wear amount varies according to machining time and hole count though the EDM conditions remain the same. As shown in Fig. 2, the electrode shape changes and therefore affects efficiency. The wear amount increases in proportion to the hole machining and convergence. The convergence speed may differ with the EDM environment but the wear amount pattern is analogous with Fig. 4b. Therefore, the electrode wear model should reflect the wear pattern even when multiple holes are machined. The electrode wear model can be transformed into Eq. (2) and the total wear amount can be calculated with Eq. (3) where $\alpha_n$ and $\lambda_n$ are the coefficients and $n$ equals the hole machining count.

$$w_n(n) = \alpha_n(1 - e^{-\lambda_n n}) \tag{2}$$

$$\left.\begin{aligned} W(n) &= \sum\nolimits_{i=1}^{n} w_n(i) \\ &= \sum\nolimits_{i=1}^{n} \alpha_n(1 - e^{-\lambda_n i}) \end{aligned}\right\} \tag{3}$$

The hole machining count ($n$) can be converted into time by dividing the wear amount with the machining time (Fig. 4b). Thus, Eqs. (2) and (3) may be substituted with Eqs. (4) and (5), respectively.

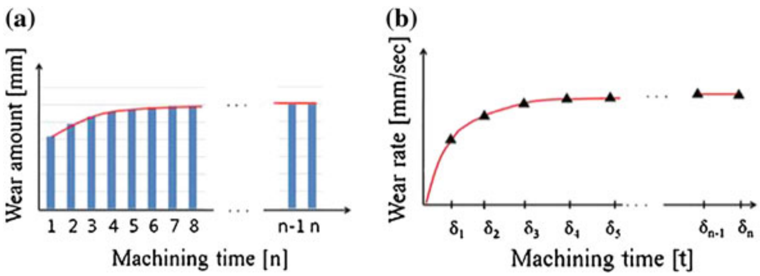



**Fig. 4** Electrode wear amount and wear ratio, **a** electrode wear amount, **b** electrode wear rate

$$w_t(n) = \alpha_t(1 - e^{-\lambda_t n}) \tag{4}$$

$$\left. \begin{aligned} W(n) &= \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} w_t(n)\, dt \\ &\approx \int_0^{t_i} \alpha_n(1 - e^{-\lambda_n i})\, dt + \varepsilon \end{aligned} \right\} \tag{5}$$

To find the electrode wear amount for the $n$th hole machining, $w_t(n)$, subtract the wear amount until the ($n - 1$)th hole machining ($W(n - 1)$) from the wear amount until the $n$th hole machining ($W(n)$). The equation for $w_t(n)$ is

$$\left. \begin{aligned} w_t(n) &= W(n) - W(n-1) \\ &= \int_0^{\delta_n} w_t(n)\, dt - \int_0^{\delta_{n-1}} w_t(n)\, dt \\ &= \int_{\delta_{n-1}}^{\delta_n} w_t(n)\, dt \end{aligned} \right\} \tag{6}$$

## 3 Stochastic Compensation Method

Real time measurement of the electrode wear amount is almost impossible so an estimation model is used instead to predict the machining state. Moreover, the EDM conditions affect the electrode shape causing different machining situations as well as different electrode wear. Consequently, the proposed estimation model in Eqs. (2) and (4) requires adjustment.

Considering that the EWR of the current hole machining is not influenced by the electrode wear history, but only the previous electrode shape, the estimation model can be compensated using the discharge time ($T_s$) until the ($n - 1$)th hole machining and machining time ($t_m$) for the current hole ($n$th). In other words, the EWR of the ($n + 1$)th hole is estimated using Eqs. (7) or (8) and the estimation model is compensated again for the EWR of the ($n + 2$)th hole.

$$\left. \begin{aligned} w_n(n) &= \alpha_n(1 - e^{-\lambda_n n}) \\ \alpha_n^i &= \tfrac{w_n(n)}{(1 - e^{-\lambda_n n})} \end{aligned} \right\} \tag{7}$$

$$\left. \begin{aligned} w_t(T_s + t_m) &= \alpha_t'(1 - e^{-\lambda_t(T_s + t_m)}) \\ \alpha_n^i &= \frac{w_t(T_s + t_m)}{(1 - e^{-\lambda_t(T_s + t_m)})} \end{aligned} \right\} \tag{8}$$

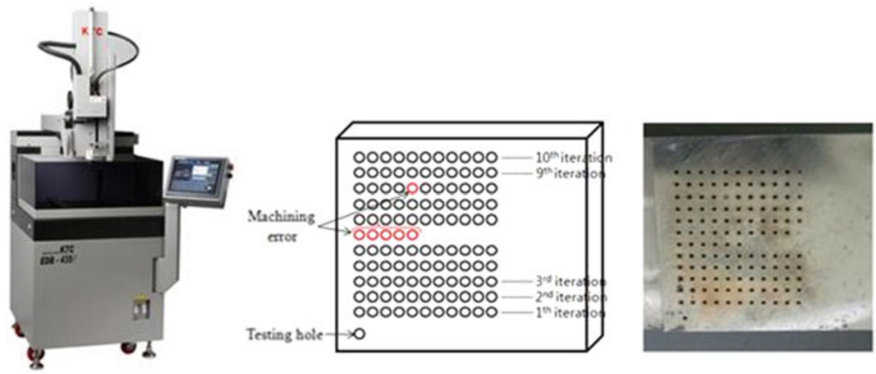



**Fig. 5** EDB-435F EDM machine and estimation experimental results

## 4 Experiment and Results

Experiments were carried out to validate the proposed electrode estimation model using a commercial EDM drill EDB-435F of KTC Co. Ltd (Fig. 5). The electrode is copper and its outer (inner) diameter is Ø0.7 (Ø0.25) mm. The EDM conditions are shown in Table 1. For the electrode wear model, an off-line experiment was carried out to obtain the reference curve of the electrode wear while 10 identical holes were machined with a new electrode 10 times each. 11-hole machining was used for automatic data collection. As shown in Table 2, the electrode wear amount and machining time increases, converging on the constant wear amount and ratio. The electrode wear models using the averages are

$$w_n(n) = 2.497(1 - e^{-1.132n}) \tag{9}$$

$$w_t(n) = 0.238(1 - e^{-0.0989n}) \tag{10}$$

**Table 1** Discharge conditions

| Discharge parameters | | Values |
|---|---|---|
| Electrode diameter (inner) (mm) | | $\phi$ 0.7 ($\phi$ 0.25) |
| Duty ratio | $\tau_{on}$(mSec) | 28 |
| | $\tau_{off}$(mSec) | 10 |
| Current ($A$) | | 12.2 |
| Discharge voltage range | Min ($V$) | 10.5 |
| | Max ($V$) | 20.7 |
| Capacitance (μF) | | 0.18 |
| Spindle speed (RPM) | | 1,450 |
| Feed rate (mm/min) | | 60 |
| Material (thickness) | | SKD-11 (5t) |

**Table 2** The experiment for the electrode wear out

| Iteration | Machining time (electrode wear) | | | | | | | | | | Amount average | Wear ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | |
| 1 | 10.91 | 11.63 | 10.77 | 10.5 | 9.45 | 10.24 | 10.18 | 10.2 | 10.63 | 10.4 | 10.49 | 0.162 |
| | (1.7) | (1.8) | (1.8) | (1.8) | (1.6) | (1.6) | (1.7) | (1.6) | (1.6) | (1.8) | (1.70) | |
| 2 | 11.31 | 11.02 | 10.53 | 10.65 | 10.11 | 10.34 | 10.26 | 12.33 | 14.5 | 10.47 | 11.15 | 0.199 |
| | (2.1) | (2.2) | (2.0) | (2.2) | 2.4) | (2.2) | (2.2) | (2.4) | (2.3) | (2.2) | (2.22) | |
| 3 | 10.63 | 10.77 | 11.8 | 10.89 | 10.33 | 10.56 | 10.31 | 11.15 | 10.44 | 10.72 | 10.76 | 0.230 |
| | (2.3) | (2.4) | (2.6) | (2.5) | (2.5) | (2.5) | (2.4) | (2.4) | (2.5) | (2.6) | (2.47) | |
| 4 | 10.79 | 10.58 | 10.59 | 10.54 | 10.26 | 9.98 | 11.09 | 10.24 | 10.42 | 10.42 | 10.49 | 0.227 |
| | (2.3) | (2.4) | (2.3) | (2.2) | (2.4) | (2.4) | (2.4) | (2.4) | (2.5) | (2.5) | (2.38) | |
| 5 | 10.52 | 10.26 | 10.34 | 10.43 | 10.45 | 10.44 | 10.21 | 10.24 | 10.6 | 10.33 | 10.38 | 0.235 |
| | (2.3) | (2.4) | (2.4) | (2.3) | (2.7) | (2.5) | (2.4) | (2.5) | (2.5) | (2.4) | (2.44) | |
| 6 | 10.57 | 10.46 | 10.37 | 10.26 | 10.24 | 10.21 | 10.58 | 9.99 | 10.43 | 10.17 | 10.33 | 0.237 |
| | (2.4) | (2.5) | (2.3) | (2.4) | (2.6) | (2.5) | (2.4) | (2.2) | (2.6) | (2.6) | (2.45) | |
| 7 | 10.83 | 10.29 | 11.6 | 10.34 | 10.2 | 10.18 | 10.15 | 10.64 | 10.64 | 10.32 | 10.52 | 0.245 |
| | (2.4) | (2.6) | (2.7) | (2.5) | (2.5) | (2.6) | (2.6) | (2.8) | (2.5) | (2.6) | (2.58) | |
| 8 | 10.42 | 10.45 | 10.63 | 10.54 | 10.09 | 10.41 | 10.31 | 10.42 | 11.1 | 10.52 | 10.49 | 0.238 |
| | (2.4) | (2.5) | (2.5) | (2.4) | (2.6) | (2.5) | (2.5) | (2.6) | (2.7) | (2.3) | (2.50) | |
| 9 | 10.41 | 10.24 | 10.26 | 10.45 | 10.28 | 11.0 | 10.45 | 10.22 | 10.39 | 10.91 | 10.46 | 0.242 |
| | (2.5) | (2.6) | (2.3) | (2.5) | (2.5) | (2.5) | (2.6) | (2.5) | (2.5) | (2.8) | (2.53) | |
| 10 | 10.46 | 10.39 | 10.53 | 10.45 | 10.61 | 11.0 | 10.54 | 10.31 | 10.42 | 10.36 | 10.51 | 0.239 |
| | (2.4) | (2.4) | (2.6) | (2.5) | (2.4) | (2.5) | (2.3) | (2.6) | (2.8) | (2.6) | (2.51) | |

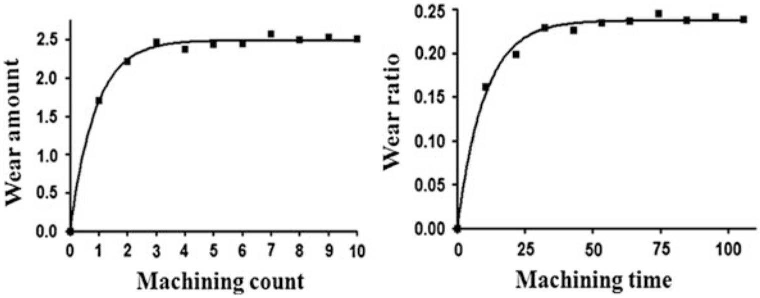



**Fig. 6** The electrode wear estimators: *dots* are the actual wear amounts (ratios) and *solid lines* are fitted curves

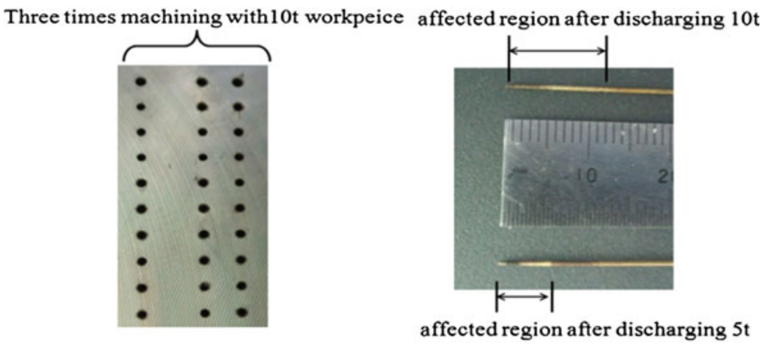



**Fig. 7** Three discharges were carried out to compensate the estimation model and the electrodes are compared after 5t and 10t workpieces are machined

The square sums of the estimation errors are 0.191 and 0.602 respectively, and Fig. 6 shows the fitted curves. An additional experiment was carried out to ensure the wear models share the same EDM conditions while the workpiece thickness was changed to 10t (Fig. 7a). As shown in Table 3, the difference between estimation and actual wear amount is large during the first hole machining, which was caused by the longer engaged discharge area (Fig. 7b). Thus, the changed EDM environment is reflected in the estimation model (reference curve). Comparing the converging speed of the two models, the wear ratio based model [Eq. (4)] is more efficient. Table 3 shows that the estimation error is decreased by Eq. (8), and is less than 3 % after the third compensation.

**Table 3** The estimation model compensation with electrode wear amount (10t thickness workpiece)

| Iterartion | | Cumulated machining time | Electrode wear | | Estimation model and its compensation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Estimator error amount | | | Electrode wear ratio | | |
| | | | Amount | Ratio | Adjusted $\alpha'_n$ | After compensation | Difference | Adjusted $\alpha'_t$ | After compensation | Difference |
| 1 | 1 | 21.24 | 5.4 | 0.254 | 7.9692 | 1.6920 | 3.7080 | 0.2897 | 0.2089 | 0.0453 |
| | 2 | 42.21 | 6.5 | 0.310 | 7.2539 | 7.1409 | 0.6409 | 0.3148 | 0.2852 | 0.0248 |
| | 3 | 63.01 | 6.5 | 0.313 | 6.7253 | 7.0109 | 0.5109 | 0.3131 | 0.3142 | 0.0017 |
| | 4 | 86.56 | 7.1 | 0.301 | 7.1775 | 6.6527 | 0.4473 | 0.3015 | 0.3131 | 0.0116 |
| | 5 | 106.63 | 7.4 | 0.369 | 7.4259 | 7.1525 | 0.2475 | 0.3687 | 0.3015 | 0.0672 |
| | 6 | 126.61 | 7.3 | 0.365 | 7.3082 | 7.4175 | 0.1175 | 0.3654 | 0.3687 | 0.0034 |
| | 7 | 146.50 | 7.3 | 0.367 | 7.3026 | 7.3056 | 0.0056 | 0.3670 | 0.3654 | 0.0017 |
| | 8 | 166.64 | 7.4 | 0.367 | 7.4009 | 7.3018 | 0.0982 | 0.3674 | 0.3670 | 0.0004 |
| | 9 | 186.23 | 7.3 | 0.373 | 7.3003 | 7.4006 | 0.1006 | 0.3726 | 0.3674 | 0.0052 |
| | 10 | 205.97 | 7.3 | 0.370 | 7.3001 | 7.3002 | 0.0002 | 0.3698 | 0.3726 | 0.0028 |
| 2 | 1 | 22.27 | 5.5 | 0.247 | 8.1167 | 1.6920 | 3.8080 | 0.2776 | 0.2117 | 0.0353 |
| | 2 | 48.97 | 6.5 | 0.243 | 7.2539 | 7.2731 | 0.7731 | 0.2454 | 0.2754 | 0.0320 |
| | 3 | 71.55 | 6.9 | 0.306 | 7.1392 | 7.0109 | 0.1109 | 0.3058 | 0.2452 | 0.0604 |
| | 4 | 94.11 | 7.4 | 0.328 | 7.4808 | 7.0621 | 0.3379 | 0.3280 | 0.3058 | 0.0222 |
| | 5 | 116.28 | 7.5 | 0.338 | 7.5262 | 7.4548 | 0.0452 | 0.3383 | 0.3280 | 0.0103 |
| | 6 | 138.69 | 7.4 | 0.330 | 7.4083 | 7.5178 | 0.1178 | 0.3302 | 0.3383 | 0.0081 |
| | 7 | 161.59 | 7.4 | 0.323 | 7.4027 | 7.4056 | 0.0056 | 0.3231 | 0.3302 | 0.0071 |
| | 8 | 184.39 | 7.7 | 0.338 | 7.7009 | 7.4018 | 0.2982 | 0.3377 | 0.3231 | 0.0146 |
| | 9 | 206.31 | 7.2 | 0.328 | 7.2003 | 7.7006 | 0.5006 | 0.3285 | 0.3377 | 0.0093 |
| | 10 | 229.13 | 7.6 | 0.333 | 7.6001 | 7.2002 | 0.3998 | 0.3330 | 0.3285 | 0.0046 |

(continued)

**Table 3** (continued)

| Iterartion | | Cumulated machining time | Electrode wear | | Estimation model and its compensation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Estimator error amount | | | Electrode wear ratio | | |
| | | | Amount | Ratio | Adjusted $\alpha'_n$ | After compensation | Difference | Adjusted $\alpha'_t$ | After compensation | Difference |
| 3 | 1 | 20.84 | 5.4 | 0.259 | 7.9692 | 0.2579 | 5.1421 | 0.2969 | 0.2077 | 0.0514 |
| | 2 | 44.40 | 6.4 | 0.272 | 7.1423 | 7.1409 | 0.7409 | 0.2750 | 0.2932 | 0.0216 |
| | 3 | 65.71 | 6.5 | 0.305 | 6.7253 | 6.9030 | 0.4030 | 0.3055 | 0.2746 | 0.0304 |
| | 4 | 87.17 | 6.8 | 0.317 | 6.8743 | 6.6527 | 0.1473 | 0.3169 | 0.3054 | 0.0114 |
| | 5 | 108.80 | 7.3 | 0.337 | 7.3255 | 6.8503 | 0.4497 | 0.3375 | 0.3169 | 0.0206 |
| | 6 | 130.31 | 7.1 | 0.330 | 7.1080 | 7.3173 | 0.2173 | 0.3301 | 0.3375 | 0.0074 |
| | 7 | 152.81 | 7 | 0.311 | 7.0025 | 7.1054 | 0.1054 | 0.3111 | 0.3301 | 0.0190 |
| | 8 | 174.67 | 7.3 | 0.334 | 7.3009 | 7.0017 | 0.2983 | 0.3339 | 0.3111 | 0.0228 |
| | 9 | 196.35 | 7.1 | 0.327 | 7.1003 | 7.3006 | 0.2006 | 0.3275 | 0.3339 | 0.0065 |
| | 10 | 217.94 | 7.3 | 0.338 | 7.3001 | 7.1002 | 0.1998 | 0.3381 | 0.3275 | 0.0106 |

## 5 Conclusion

Electric discharge machining is widely used to manufacture precise parts. Compared to conventional cutting, the EDM electrodes wear out more. The electrode wear amount of micro-EDM drilling is greater, making it difficult to control electrode feeding. Therefore, this study proposes an electrode wear estimation model and compensation method using a hole pass-through experiment. First, the exponential wear curve is fitted to the machining hole count based model and machining time based model. After that two models are compensated in accordance with the EDM environment, the memory-less property is adopted.

The proposed methods were validated by machining the holes with a commercial micro-EDM drill. The experiments show that the machining time based model more rapidly converges. After three compensations, the model estimates the electrode wear ratio within a 3 % error margin. A future study may apply the proposed method to blind hole machining when high accuracy is required.

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## References

1. Lee C-S, Kim J-M, Heo E-Y, Kim B-M, Kim D-W (2011) A study on the machinability of micro channels using micro-EDM. In: The 21st international conference on flexible automation and intelligent manufacturing, TAIWAN, pp 401–408
2. Lee C-S, Heo E-Y, Hong M-S, Kim J-M (2011) A study on the optimal machining conditions of micro holes in micro-EDM processes. In: The 21st international conference on flexible automation and intelligent manufacturing, Taiwan, pp 409–414
3. Masuzawa T, Kuo CL, Fujino M (1994) A combined electrical machining process for micronozzle fabrication. CIRP Ann Manuf Technol 43(1):189–192
4. Lin JL, Wang KS, Yan BH, Tarng YS (2000) Optimization of the electrical discharge machining process based on the Taguchi method with fuzzy logics. J Mater Process Technol 102:48–55
5. Jia ZX, Zhang JH, Ai X (1997) Study on a new kind of combined machining technology of ultrasonic machining and electrical discharge machining. Int J Mach Tools Manuf 37(2):193–197
6. Kremer D, Lhiaubet C, Moisan A (1991) A study of the effect of synchronizing ultrasonic vibrations with pulses in EDM. CIRP Ann Manuf Technol 40(1):211–214
7. Kim YT, Park SJ, Lee SJ (2005) Micro/meso-scale shapes machining by micro-EDM process. Int J Precis Eng Manuf 6(2):5–11
8. Masuzawa T, Fujino M, Kobayashi K (1985) Wire electro-discharge grinding for micromachining. CIRP Ann Manuf Technol 34(1):431–434
9. Masuzawa T, Kuo CL, Fujino M (1994) A combined electrical machining process for micronozzle fabrication. CIRP Ann Manuf Technol 43(1):189–192
10. Yu ZY, Masuzawa T, Fujino M (1998) Micro-EDM for three dimensional cavity development of a uniform wear method. CIRP Ann Manuf Technol 47(1):169–172

11. Lonardo PM, Bruzzone AA (1999) Effect of flushing and electrode material on die sinking EDM. CIRP Ann Manuf Technol 48(1):123–126
12. Kim BH (1999) Micro-hole machining using MEDM with a screw-type electrode. Master's Thesis, Seoul National University
13. Masuzawa T, Ku CL, Fujino M (1990) Drilling of deep micro-holes by EDM using additional capacity. Int J Jpn Soc Precis Eng 23(4):275–276
14. Mohri N, Suzuki M, Furuya M, Saito N (1995) Electrode wear process in electrical discharge machining. CIRP Ann Manuf Technol 44(1):165–168

# Topography-Selective Removal of Atmospheric Pressure Plasma Polishing

**Jufan Zhang, Bing Li, Wei Dang and Ying Wang**

**Abstract** Atmospheric pressure plasma polishing (APPP) is an efficient method to produce damage-free ultra-smooth surfaces, due to its chemical nature. APPP works intelligently on distinguishing surface micro-topographies, thereby realizing diverse reaction rates on different surface morphologies. Since the convex surface structures are always removed faster than the concave structures by dry etching process, the whole surface roughness can be reduced further to form ultra-smooth surfaces. Quantum chemistry simulation of two groups of models has been utilized to prove the conclusion in theory. Afterward, practical machining experiments have been conducted, in which the sample is detected every 40 s by atomic force microscopy to testify the decrease of surface roughness. Experimental results accord well with theoretical simulation. The machined sample is also detected by scanning electronic microscopy and nano-mechanical test system. The mechanical properties are demonstrated to be improved by APPP process, especially the residual stress is reduced by about 4.2 GPa after 60 s machining. The micro-topography is also indicated more regular, and finally reaches below Ra 0.5 nm surface roughness.

## 1 Introduction

Development of modern optical industry demands perfect surface performance and presents a number of stringent challenges to optics manufacturing technologies. Not only extremely low surface roughness at nanometer level is required to achieve high reflectivity, but also minimum surface/subsurface damage is strived for to obtain expected performance and prolong service life [1, 2]. Especially in recent years,

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SiC, KDP, and many other hard brittle functional crystal materials have come into wide use in many fields, which makes conventional manufacturing technologies incompetent for achieving such high standard of surface quality [3–6]. Atmospheric pressure plasma polishing (APPP) is an innovative and efficient method to achieve ultra-smooth surfaces. It removes surface materials by chemical reactions caused by reactive atoms produced in the plasma discharge in atmospheric environment. The material is removed at atom scale which is helpful for obtaining low surface roughness and high surface accuracy. At atom scale, classical Newtonian mechanics is not suitable for analyzing interaction between atoms, while quantum chemistry theory is justified effective [7, 8]. Thus, quantum chemistry simulation is utilized to prove the selectivity of APPP process on surface topography, which supports the explanation of formation of ultra-smooth surfaces. The removal of surface defects also helps improving surface properties, like increasing hardness and decreasing residual stress, which are testified by experiments.

## 2 Principle and Facility of APPP

Atmospheric pressure plasma polishing (APPP) utilizes atmospheric pressure plasma to excite reaction gas to generate reactive radicals. Then reactive radicals react chemically with the surface atoms to accomplish atom-scale material removal. The products are always volatile gases that tend to vent to avoid introducing new surface contamination. For example, to machine single crystal silicon wafer, helium (He) gas is usually selected as plasma gas while carbon tetrafluoride ($CF_4$) gas works as the reactive precursor. $CF_4$ molecules are dissociated due to the excitation of plasma and release radical fluorine atoms which are high chemically reactive. The radical fluorine atoms react with surface silicon atoms thus producing gaseous $SiF_4$, as shown in Eqs. (1) and (2). Figure 1 illustrates the general process of the chemical reaction occurring on the surface.

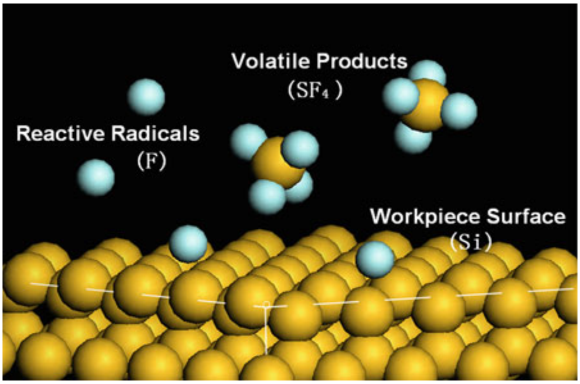
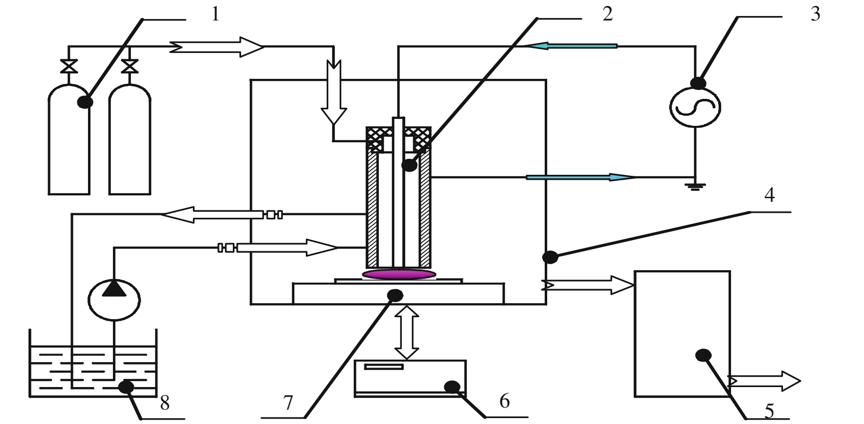



**Fig. 1** Principle of APPP




1.Gas Supply; 2.Plasma Generator; 3.Power Supply; 4.Sealed Chamber;
5.Residual Gas Treatment; 6.Motion Control; 7.Workbench; 8.Cooling System

**Fig. 2** Photograph of machining facility

$$CF_4 + e^{-*} \rightarrow CF_3 \cdot + F \cdot + e^- \quad (1)$$

$$Si + 4F\cdot \rightarrow SiF_4 \quad (2)$$

Besides plasma generator, APPP system also includes gas supply and flux control system, power supply and matching system, cooling system, residual gas treatment system as shown in Fig. 2.

## 3 Simulation and Calculation

APPP depends on the chemical reaction between surface atoms and excited reactive radicals to achieve material removal. Further, provided that APPP performs selectivity on surface topography, surface roughness can be changed. For simplification, surface topography can be divided into two sorts: convex topography above surface plane and concave topography below surface plane. (Since APPP is mainly used as final finishing step of optical surfaces which have already been machined by precision grinding or similar process, usually sample's surface topography is relatively regular with low roughness at microns or hundreds of nanometers. Thus, the simplification is acceptable for qualitative analysis.) As long as convex topography reacts faster than concave topography, the roughness can be reduced further and the whole surface goes toward a new equilibrium state of lower roughness. Of course actual surface status is much more complex than that described above. But here, only the influence of surface geometric topography on removal rate is focused on to explain the formation process of ultra-smooth surfaces in APPP. It makes the issue more simple.

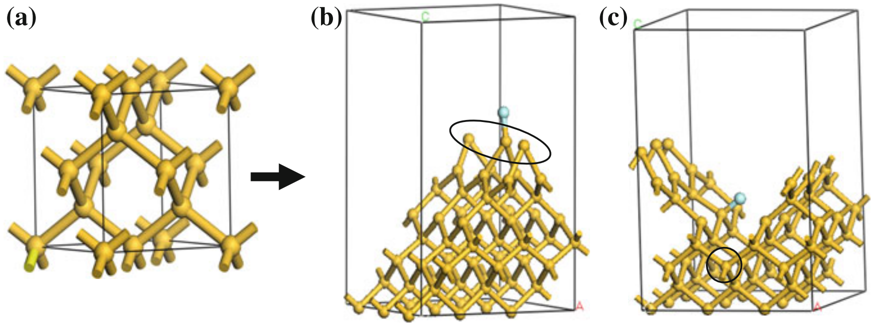



**Fig. 3** Models of silicon surface topographies. **a** Single Si cell structure. **b** Model of convex topography. **c** Model of concave topography

Simulation is implemented by CASTEP module of Material Studio software (4.0, Accelrys Software Inc.) which has already been used in many fields. Since verification experiments are planned to be performed on single crystal silicon wafer with $He/CF_4/O_2$ gas recipe, simulation mainly focuses on the interaction between silicon (Si) atoms and fluorine (F) atoms.

Based on reasonable simplification, and using the periodic repetition settings of CASTEP, the typical single crystal silicon (100) surface topographies can be modeled from silicon cell, as Fig. 3 shows.

In Fig. 3, the yellow balls represent silicon atoms. Chemical reaction can be regarded as bonds breaking and connecting between atoms. Since only the stable status is concerned during simulation, analysis can be completed by comparing system parameters of initial states and end states. Here, the end state after reaction can be modeled by selecting atoms in the most representative positions in initial models to form Si–F bond. The selected atoms are shown in Figure 3, with which the blue fluorine atoms connect. In Fig. 3b, it is obvious that the top atoms are most representative. While, in Fig. 3c, the bottom atoms should be selected. But it is found that these atoms have already formed four bonds. Thus, if they are involved in forming new stable bonds, extra energy is needed to break the existing Si–Si bonds. In theory, it is not preferred by spontaneous law of chemical reaction. Instead, the atoms at above layer still have free outmost electrons for bonding. These positions seem more favorable. So accordingly, the bonding atoms are selected as Fig. 3b, c shows.

For this group of models, the system energy is focused on to explain the influence introduced by fluorine atoms. Calculation on binding energy indicates that the bonding makes energy released. Binding energy is defined as the difference of system energy before and after reaction, which reflects the occurring possibility of certain chemical reaction. If the value is negative, usually it means the reaction releases energy and the system becomes more stable. Generally, the bigger the absolute value is, the more probably the chemical reaction occurs. Based on Table 1, the binding energy of Fig. 3b model is calculated as

**Table 1** Calculation results of system energy (eV)

| | Before bonding | After bonding |
|---|---|---|
| Convex model | −6,468.816584982 | −7,146.028610578 |
| Concave model | −6,469.286587956 | −7,146.361264707 |
| Fluorine atom | −329.49983897 | −329.49983897 |

$$\Delta E_{convex} = E_{convex+F} - (E_{convex} + E_F) \approx -347.7\,\text{eV} \quad (3)$$

Similarly, the binding energy of Fig. 3c model is −347.5 eV. For one bond with single F atom, binding energy of convex model is 0.2 eV higher than that of concave model, which is thought to be distinct difference since the highest energy provided by one single fluorine atom is only 1 eV. It means convex model has higher reaction probability in statistics. So in theory, convex topography reacts more than concave topography in the same time, and of course it is removed faster in machining process.

Another model is also presented here to demonstrate the reaction difference, as Fig. 4 shows. The model is built as an atomic step. It is inferred that the atom in the middle of surface plane should have lower reaction probability than the atom on the edge, as cycled in Fig. 4a. And the step is thought not to be removed evenly layer by layer. Instead, the edge should react faster, and the shape of the step structure should change gradually, and finally disappear. By calculation with similar equation as Eq. (3), it is indicated that the binding energy of edge atom is really bigger than that of middle atom, which supports the hypothesis.

For actual macro-scale surface with millions of atoms, the difference value will be much bigger, because much more atoms will participate in the reaction and the reaction process is much more complex than that in simulation. But as the computation load is too high to build a huge model to simulate actual condition, especially for quantum chemistry tools, more detailed work will be undertaken by high performance computers later. Nevertheless, for qualitative analysis, these simplified models are persuasive enough. And some other positions have also been selected for simulation to testify the conclusions further.

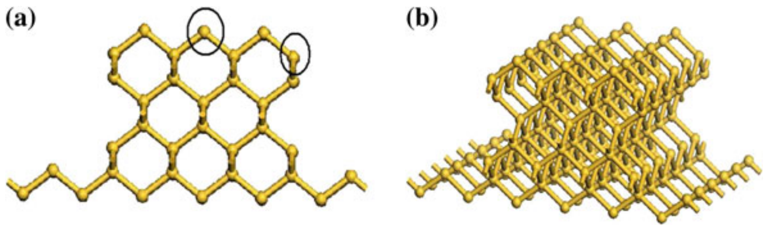



**Fig. 4** Model of atomic step

## 4 Experiments and Discussions

To testify the simulation results, machining experiments on single crystal silicon wafers with lattice direction (100) have been performed. Power supply is 400 W, with 0.2 % $CF_4$. According to theoretical analysis, convex topography should be removed faster than concave topography. Thus in experiments, the average roughness ($R_a$), average maximum height ($R_{pm}$), and average maximum depth ($R_{vm}$) were measured at 0, 40, 80, and 120 s for comparison by atomic force microscopy (AFM, Dimension 3,100, Digital Instruments Inc., USA). The measurement results are shown in Fig. 5.

Comparing the values at different intervals, it is clear that the average surface roughness decreases gradually with machining progressing, which indicates the surface topography goes smoother. And before machining, the surface is relatively rough with an average height of 5.125 nm between highest and lowest points. With reaction going, the difference becomes weaker and finally reaches 1.993 nm. It proves the roughness caused by topography difference is reduced obviously. And

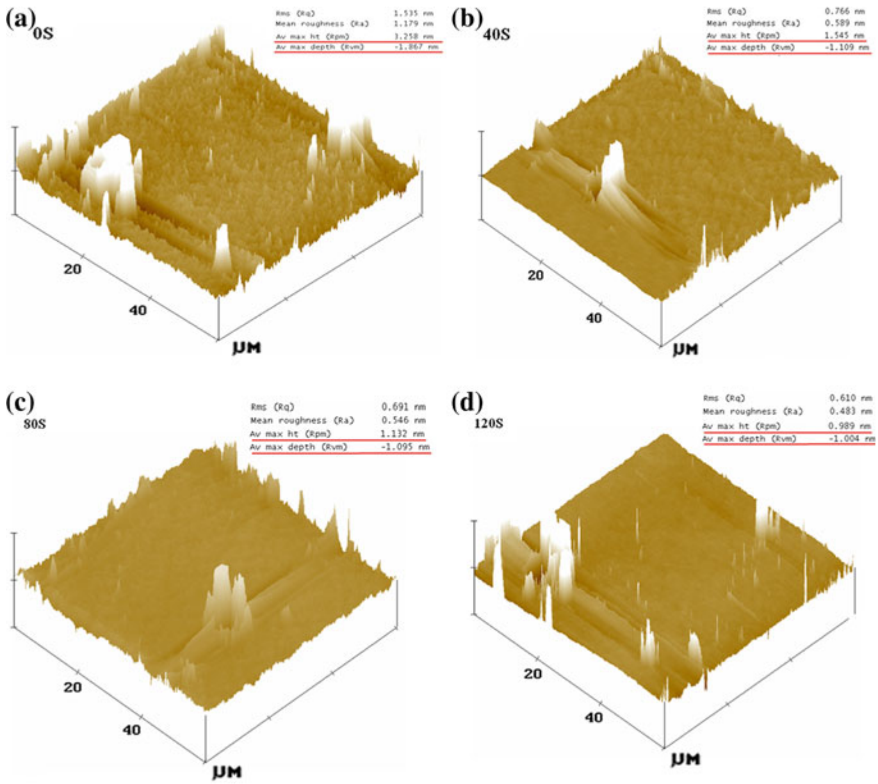



**Fig. 5** Surface roughness detection images by AFM

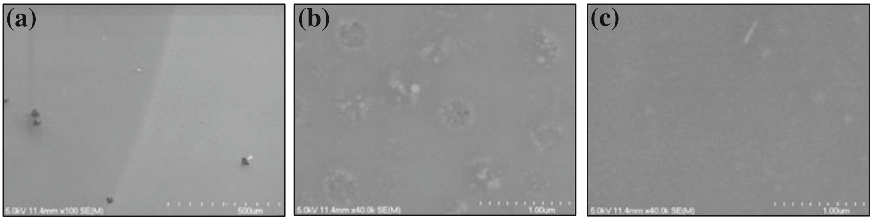



**Fig. 6** SEM detection images, **a** boundary between two areas, **b** before machining, **c** after machining

respectively comparing reducing rate of convex topography and concave topography, it can be seen that in the same interval, $R_{pm}$ is always reduced more than $R_{vm}$, which accords well with the simulation results.

Moreover, scanning electronic microscopy (SEM, AIS2100, MIRERO-SERON, South Korea)) is also used to detect the surface topography, as Fig. 6 shows. It is clear that under low magnification, there is obvious boundary between machined area and original area. In original area, the surface seems much rougher even with many visible defects under 40,000-magnification. After machining, the surface becomes much smoother and no obvious defects can be found. Thus, APPP is capable of improving the surface topography.

Furthermore, SEM detection has proved the surface defects have been removed to some extent. As the result, the mechanical properties of the sample surface should be improved, too. The nano-mechanical test system (Hysitron, TriboIndenter) is used to test the reduced modulus and hardness, based on which the decrease of residual stress can be calculated quantitatively. Measurement results are listed in Fig. 7.

Figure 7 lists the detection results of some randomly selected points. It is easy to find that the hardness rises by about 25 % while modulus rises by more than 40 %. So the rigidity of the surface has been improved. By method of Eqs. (1) and (2) which has already explained in detail in Refs. [9–11]. The reduction of residual stress can be calculated as

$$\sigma_R = \begin{cases} H_0\left[\left(c_0 + \frac{1-c_0}{E^*}E_0^*\right)^2 - 1\right] & \sigma_R > 0 \\ \frac{H_0}{\sin\alpha}\left[1 - \left(c_0 + \frac{1-c_0}{E^*}E_0^*\right)^2\right] & \sigma_R < 0 \end{cases} \quad (4)$$

$$c_O = \frac{h'_c}{h_{nom}} = \frac{h_c + h_{ini}}{h_{\max} + h_{ini}} \quad (5)$$

By calculation, the average residual stress is reduced by about 4.3 GPa. And the maximum reduced stress is 5.1 GPa, while the minimum value is 3.1 GPa. Thus, APPP is valid in removing surface damage layer.

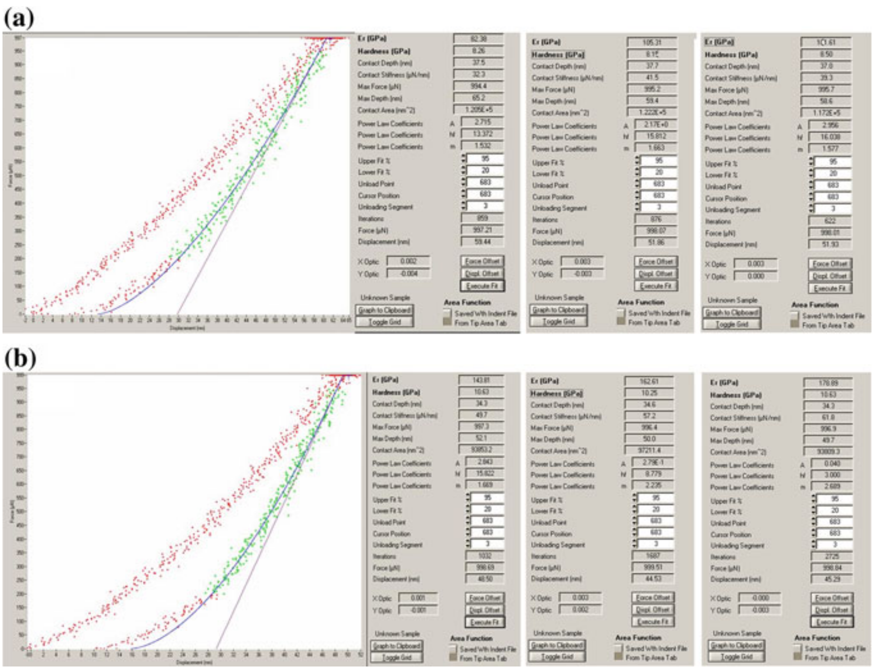


**Fig. 7** Test results of nano-mechanical test system, **a** before machining, **b** after machining

## 5 Summary

By quantum chemistry simulation, it is proved in theory that APPP has selectivity on surface topography. The convex topography has higher reaction probability than concave topography. Thus for actual macro-scale surface with millions of atoms, convex topography should be removed faster than concave topography. Consequently, surface roughness of optical surfaces can be decreased further to form ultra-smooth surfaces. The detection by SEM also proves obvious improvement on surface topography. Mechanical properties are also demonstrated to be enhanced by APPP, as the average 4.2 GPa reduction of residual stress is indicated.

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## References

1. Zhang JF, Wang B, Dong S (2007) A new development of ultra-smooth surface machining technology. Opt Tech 33(S1):150–154
2. Li BG, Xiong CY, Li CG, Zhang QR (2006) Machining technology of super smooth surface. Manuf Technol Mach Tool 6:60–66
3. Golini D, Jacobs SD (1991) Physics of loose abrasive microgrinding. Appl Optics 30(19):2761–2777
4. Gao HG, Cao JL, Zhu Y et al (2000) The development and application of ultra-smooth surfaces. Physics 29(10):610–614 (in Chinese)
5. Gao HG, Chen B, Cao JL (1995) Fabricating technology for supersmooth surfaces. Opt Precis Eng 3(4):7–14 (in Chinese)
6. Li XS, Ge HZ (1998) Machining technologies for ultra-smooth surfaces. Laser Optronics Prog 11:1–9 (in Chinese)
7. Wang XJ, Selvam P, Lv C et al (2004) A theoretical study on the cyclopropane adsorption onto the copper surfaces by density functional theory and quantum chemical molecular dynamics methods. J Mol Catal A Chem 220(2):189–198
8. Shuller L, Ewing RC, Becker U (2007) Np incorporation into uranyl alteration phases: a quantum mechanical approach. Mater Res Soc Symp Proc 985:407–412
9. Wang B, Zhang JF, Dong S (2008) Chemical and physical characteristics of the single crystal silicon surface polished by the atmospheric pressure plasma polishing (APPP) method. Adv Heterogen Mater Mech 378–381
10. Carlsson S, Larsson PL (2001) On the determination of residual stress and strain fields by sharp indentation testing: part II: experimental investigation. J Mater Res 49(12):2193–2203
11. Cao YZ, Wang YS, Dong S et al (2007) Residual stresses around femtosecond laser ablated grooves in silicon wafer evaluated by nanoindentation. Proc SPIE 6724:672417-1

# A PLCopen-Based Approach for Utilizing Powerful Industrial Robot Functions in PLC-Controlled Applications

**Fan Dai and Oliver Becker**

**Abstract** Conventionally, industrial robots are programmed in special proprietary languages. With the growing integration of industrial robots into PLC controlled machines and manufacturing lines, programming of industrial robots is done in tight relation with PLC controlled devices. In order to reduce engineering complexity as well as training effort for service personal, machine builders, and line integrators request more and more robot programming directly in a PLC language. The PLCopen working group motion control therefore worked out a specification for coordinated motion control, which is also applicable to industrial robots. However, some important details for the implementation are kept free for the manufacturer of controllers and robots. Some other aspects relevant for state-of-the-art industrial robots are not addressed at all. In order to optimally utilize the capabilities of industrial robots, some extensions, and adaptations are necessary. This article discusses the related aspects and describes an experimental implementation.

## 1 Introduction

Industrial robots are increasingly used as part of machines that were traditionally controlled by programmable logic controllers (PLC), because they are more flexible than specialized mechanisms. Furthermore especially in applications with multi-axis coordinated motion they are often much cheaper than special constructions. However, programming and commissioning of robot applications require expert knowledge that is not common for PLC engineers.

In the past, PLC and robot technologies have been developed almost separately due to different application requirements. This led to different control architectures, programming concepts, and programming languages. Engineers of the

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respective domains gained different skills and viewpoints, depending on their education and main area of work, thus taking either PLC-centric, robot-centric, or integrator's view. As a consequence, machine logics and robot control are programmed separately on different controllers or at least in different tasks. Today PLC and robot controllers exchange typically individual signals only, which are defined in close cooperation of robot and PLC programmers (e.g., [1]). This best-practice is not only laborious but also limits the performance of the complete system.

Machine builders traditionally have a PLC centric view, because robots were only occasionally used as part of the machine. But there is a clear trend to replace special mechanics with standard robots, especially more and more Delta robots are used in packaging lines and machines. Seamless integration of robots into the machine is thus important for machine builders, and herewith the programming of the machine and the robot in a common language. This allows consistent programming, simplified maintenance and reduced training costs for service personal. Since machine builders primarily use PLCs for machine control, there is a demand to enable programming of robot applications in PLC languages using PLC programming tools [2].

## *1.1 Controlling Robot Applications via PLC*

Industrial robotics technologies have been developed continuously in the last decades. Today's powerful robot controllers are optimized for different automation tasks with consideration of the special robot application requirements. These include high path tracking accuracy under complex conditions like compliant mechanical robot structure, varying tool loads etc. Also high repeat accuracy of motion, online debugging, and optimization of motion sequences, safe behavior like stopping on path after collision detection or emergency stop and complex error management are important requirements. Therefore, robot controllers cannot be simply replaced with a traditional PLC by adding motion control functionality. Instead, in short or mid-term scenarios praxis-proven robot control technology will be combined in a meaningful way with a PLC without re-implementing them:

- Programming the application on a PLC which acts as master while the robot controller executes the motion commands;
- A SoftPLC running as parallel task to the robot motion control on the same hardware. Again, the application is programmed using a PLC language.

The solutions found today on the market introduce proprietary PLC function sets mapped to their robot commands (e.g., via command register), or allow only limited utilization of robot motion functions in a PLC program.

Of course, there are also certain robot applications which can be adequately implemented on a modern PLC with known techniques from numerical control

(NC) or general motion control (GMC). Examples are applications without high safety requirements and only simple motion functionality, which causes no significant mechanical resonances. Pick and place applications which are performed with Delta robots enclosed in machine housings are prominent realizations. Therefore, more and more PLC vendors introduced successfully control solutions for simple kinematics including Delta robots.

### *1.2 Motion Programming According to PLCopen*

Due to the wide acceptance of the PLC languages defined in IEC 61131 [3] and the increased usage of PLCopen functionality for motion control purposes, PLCopen part 4 "coordinated motion" [4] provides function blocks for the integration of robots into a PLC environment. The PLCopen specification which is based on IEC 61131 defines function blocks for:

- The definition and parameterization of kinematic structures;
- Definition of coordinate systems;
- Several motion commands;
- Synchronization of robot motion with external axes.

In addition, logics and motion commands can be mixed easily. This simplifies application programming which is based on tight PLC-robot integration significantly.

PLCopen also addresses a solution to combine the different programming philosophies of PLC and robot programming. The PLC-centric philosophy assumes quasi-parallel execution of logic tasks which is realized by cyclical execution of all function blocks of a PLC program. In contrast, the focus of the robot centric philosophy is on programming motion sequences which are activated by dedicated events. According to PLCopen specification, both philosophies are integrated by defining a motion sequence connecting the desired motion function blocks through their respective inputs and outputs either by graphical lines or suitable variables. For this purpose, every function block exhibits an "execute"-input for activation and the outputs "active", busy" or "done" in order to indicate its respective status. Both input and outputs of each function block are evaluated cyclically in the task frequency of the logics task.

The following figure shows an example of PLCopen function block for the control of coordinated motion of several axes that are grouped into a so-called axes group (Fig. 1):

This function block has the typical input and output parameters of PLCopen function blocks that define a spatial linear motion. Motion sequences can be defined by connecting several such function blocks. They can be further more combined with other IEC61131 function blocks, e.g., logics operations to build more complex motion programs.

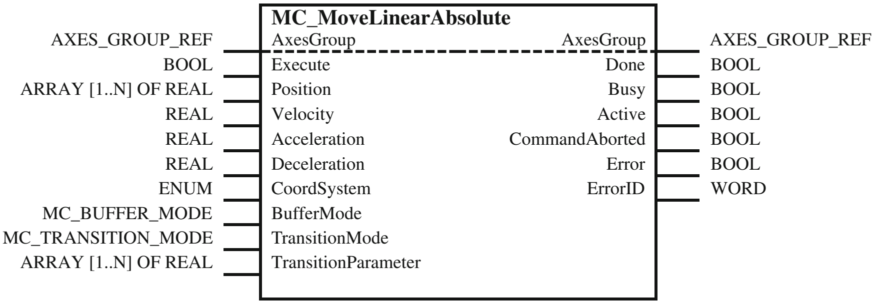


**Fig. 1** PLCopen function block for linear motion

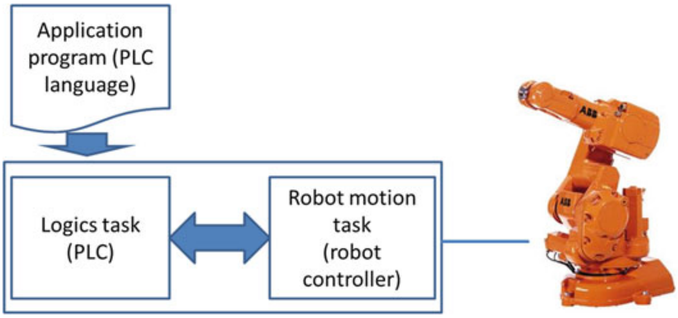


**Fig. 2** From PLC application program to robot motion

When comparing the PCLopen specification with the functionalities of a state-of-the-art industrial robot, however, one can identify that some implementation details are kept vendor specific. Some other aspects are not sufficiently considered, e.g.,

- Support for online optimization of movements (including teach-in of motion targets);
- Specification of robot joint configurations for the motion targets;
- Generating accurately digital signals on the path;
- Specification of additional coordination systems like tool coordinate systems.

In the following chapter of this article, a PLCopen-based approach for utilizing powerful industrial robot functions in PLC-controlled applications is described, including proposal for extensions of the existing PLCopen specification.

This article focuses on today's situation and describes, besides the programming concept, also the interfacing concept between a PLC and a robot controller, where the PLC acts as the master controller of a robot application (Fig. 2). Since the proposed concept solves the problem of coupling the cyclic logics task with the event-based motion control task of a robot, it is independently from the hardware architecture. Within this article the terms “PLC” for the logics task, and “robot controller” for the robot motion task that can run on the same controller hardware are used for simplicity.

## 2 Applying PLCopen to Robot Programming

### *2.1 Creating Smooth and Precise Robot Motion*

While the basic PLCopen concept works in general well for simple servo axes, dedicated robot specifics have to be considered when coupling a robot with a PLC. State of the art industrial robots are well known for exhibiting high path accuracy that is independent from the path velocity. This is achieved by a dynamic look-ahead algorithm that reduces the path velocity if, e.g., motor limits are exceeded. In case the robot internal sequence of motion commands, the so called “motion queue”, doesn’t contain enough target values, the look-ahead algorithm also slows down the robot to avoid undesired overshoot. Consequently the robot stops at the last target position of the motion queue regardless of the programmed path velocity. Smooth and precise robot motion therefore requires sufficient fast generation of new target values. On the other hand, not too many target values should be generated in advance in cases where the robot trajectory shall be modified on short notice, e.g., by a new sensor information. These conflicting requirements are addressed and fulfilled with the procedure described below.

The PLCopen commands are stored within two queues, a command queue on the PLC side and a motion queue on the robot controller side. Both queues are synchronized using either fieldbus or inter-process communication of the PLC and the robot controller. A motion command is put into the PLC queue once the corresponding function block is activated, which is reflected by setting the “busy” output of the function block to “high”. It remains in the queue until the corresponding robot motion is finished. Afterward, the entry can be deleted or overwritten. Analogously, all other robot commands that are sent from the PLC to the robot controller are also put into the queue. They are however processed immediately by the robot controller. Therefore, the queue on the robot controller side contains motion commands only. If the status of a motion command is changing, the robot controller sends the new status to the PLC using the respective command IDs as shown in Fig. 3. The outputs of the motion blocks are updated accordingly. The main idea to achieve good robot performance is the meaningful usage of the function block outputs in order to suitably fill the robot motion queue as illustrated in the example in Fig. 3.

In this example, the “execute” input of the second function block is connected with the “busy” output of the first one. This means, that the second function block is activated as soon as the first one is being processed and therefore sends its motion command directly after the first function block to the queue. In contrast,

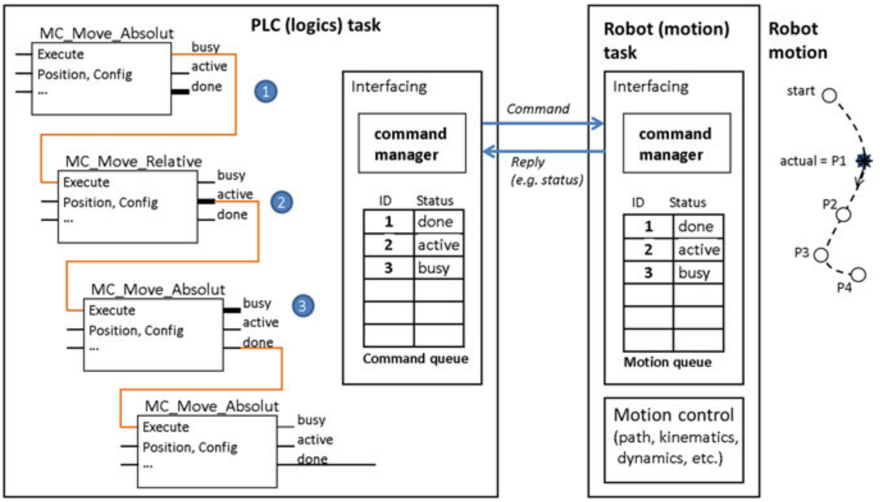


**Fig. 3** Processing function blocks for a motion sequence

the third function block is activated only after the corresponding motion defined by the second function block is being executed ("active" = robot is moving). The fourth function block waits until the execution of its predecessor is finished ("done"). The status of each motion execution is fed back from the robot controller to the PLC, and is considered in the next PLC task cycle. Using this "active-busy-done" concept the PLC programmer can decide if the motion queue shall be filled as fast as possible by using the "busy"-outputs of the blocks in order to guarantee smooth robot motion. In this case the robot follows the defined path with the commanded velocity autonomously.

If the path shall be influenced by a "last minute" decision, the time instant of the decision can be defined by the PLC programmer using the "active" output of a motion block that is close the desired junction. Dependent on the parameterization of robot speed and moving distance, the robot motion can still be smooth also in this case. If the robot is supposed to stop after a motion command is finished, the PLC programmer has to use the "done" output. No explicit stop command is necessary in this case.

Figure 4 shows an example for last-minute decision based on sensor signal. While the robot is performing the first segment of motion, the PLC can check the sensor signal and fill the motion queue with the appropriate succeeding segment by connecting the active output of the first segment with the logics operators. To achieve a smooth transition, it requires of course that there is still enough time to process the second segment before the look ahead algorithm of the motion task reaches the end of the first segment.

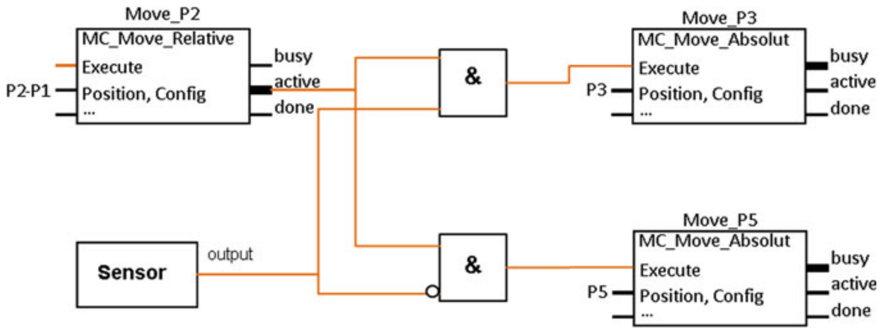


**Fig. 4** Defining alternative motion based on sensor signal

## *2.2 Enhancements to PLCopen Specification*

Besides the basic concept of interfacing PLC and robot control to build continuous motion sequences, additional aspects were added to the existing PLCopen specification to support further well-known industrial robotics techniques.

For example, robot kinematics often has singularities and can reach some positions with different joint configurations. It is therefore important to allow specifying joint configuration in order to define Cartesian positions as motion target for robot motion unambiguously. This is for example possible for ABB robots by specifying the quadrants of related joints. Therefore an optional "Configuration" input to all motion blocks is proposed.

Additionally, an optional input parameter called "Teach-Identifier" is foreseen. Teach-in of motion positions is a very important, well known and proven method for defining or optimizing robot motion. In the industrial practice, it is the most intuitive method to adjust a robot program to the real environment, where the robot is moved, e.g., via joystick to the desired position, and the position value is taken over as parameter for the motion command. Teach-in is done in a special operation mode, the "teach mode", where the well-known tools of industrial robotics can be used. If the optional string-input is not parameterized, the motion block behaves like a conventional block as specified by PLCopen. However, if the input is parameterized, the position and configuration input of the block is interpreted as "default" position and configuration. The actual, e.g., taught, value will be stored within a teach table. The string itself can be used to indicate to the operator which position has to be taught. Figure 5 shows a function block for linear motion with the extended parameters.

Another important function of today's robot controllers is to precisely raise digital signals during robot movements on the path which is implemented as well in the proposed concept. Since the desired accuracy cannot always be reached using standard PLC cycle time, this task is left to the motion task, requiring a dedicated function block. For example, depending on the parameter "Switch-Mode", a digital signal can be set, when the robot is 20 ms or 20 cm before the

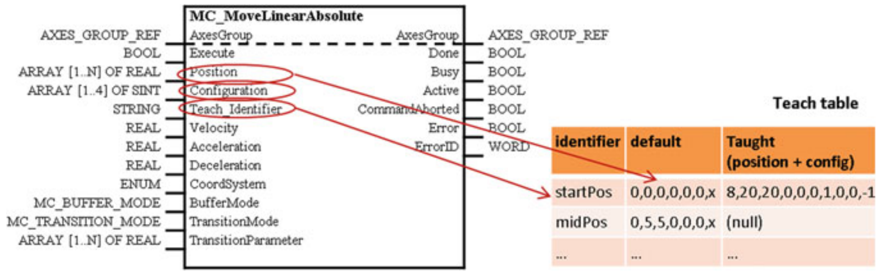


**Fig. 5** An extended function block for linear motion

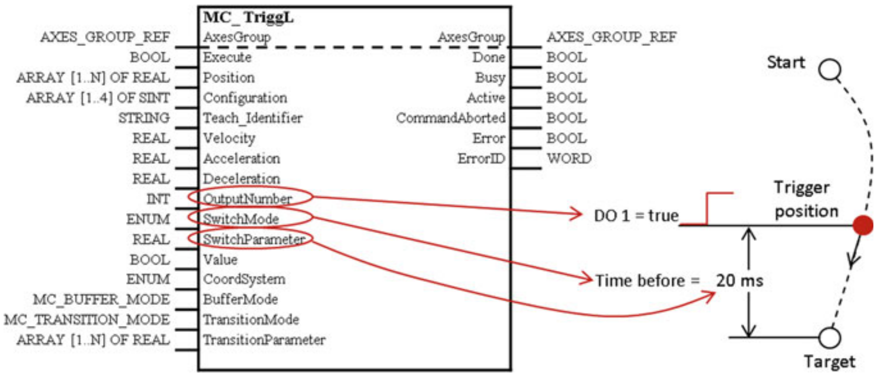


**Fig. 6** A function block for linear motion which can trigger signals during movement

target position according to the value of "SwitchParameter". Figure 6 shows the function block for linear motion that can trigger a signal on the motion path. Further on, enhancements regarding the definition of coordinate systems are specified, e.g., for the definition of a tool coordinate system.

## 3 Test Implementation

The above described concept and enhancements of the PLCopen specification were experimentally implemented into the Factory Automation Test and Integration Environment (FATIE) at ABB Corporate Research in Germany [5]. FATIE represents a robotized automatic packaging line. Ref. [6] describes the overall application in detail. Within this application, an IRB140 robot with IRC5 robot controller and integrated AC500 PLC (Figs. 7 and 8) was used to verify the above described concept.

The PLCopen-based robot program is part of the packaging application controlling the IRB140 robot as shown in Fig. 8. The application program is

**Fig. 7** The IRC5 robot controller with integrated AC500 PLC

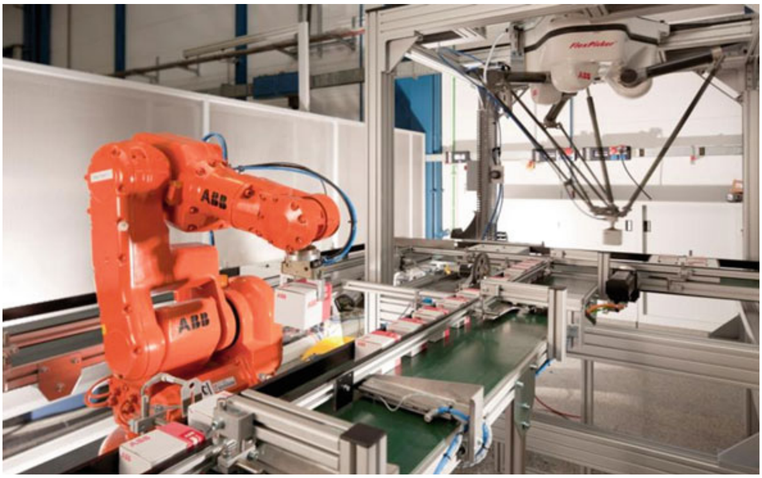

**Fig. 8** The test setup at ABB Corporate Research

completely implemented in IEC61131 languages with the respective PLCopen motion functionality on the AC500 PLC, which is installed as pre-configured module in the IRC5 robot controller cabinet. Additional I/O modules or other external devices can be connected to the PLC in the normal way. Application programming is done with the standard ABB PLC programming tool Control Builder Plus. Communication between IRC5 and AC500 is based on Profinet. Figure 9 shows an extract of an application program that was built up in the lab,

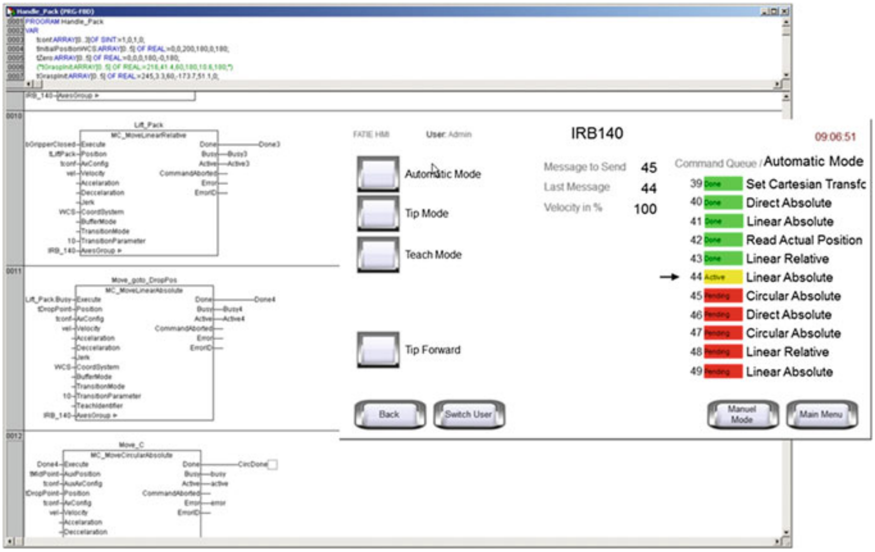


**Fig. 9** Screenshots of the robot program in IEC61131 editor and the operator interface at runtime

together with the PLC operator interface that also shows the motion block states in order to monitor the motion queue.

The robot motion control task runs on the IRC5 robot controller, with a communication task that implements the data exchange with the PLC and manages the motion command queue. The application contains a combination of robot motion, processing of digital sensor information and actuation of several pneumatic actuators. It implements pick and place operations utilizing different motion functions, e.g., linear or circular, absolute or relative motion, combined with sensor inputs that define last-minutes decisions. The robot could move with full (programmed) velocity of 2 m/s without delay, i.e., due to the described concept the robot motion was very smooth during the whole sequence. Teach-in of position via PLC operator panel using the introduced function blocks could be also verified.

In addition to this test scenario, proof of concept for running PLC and robot motion control tasks on the same computation hardware could be done using a SoftPLC.

## 4 Conclusions and Outlook

This paper described a concept to program and control robot applications via PLC, using only the well-known PLC languages of IEC 61131 within the PLC environment. No special robot knowledge is required any more for setting up the addressed robot applications. Thus, any PLC programmer who has general motion control knowledge is enabled to set up or maintain a robot application.

The functional integration of PLC and robot controllers opens up the diversity of PLC functionalities like a large number of I/Os, complex logical operations, access to a large variety of sensors and control of different types of auxiliary axes to robot applications. In addition, using the PLC as application master for robots enables easy realization of applications that are difficult to solve with regular PLCs capabilities only.

Evaluations on test implementations have shown the general feasibility and the high potential of the described concept for PLC controlled automation applications. Further studies will be done with typical applications in order to identify additional development needs and appropriate concepts for easy implementation of such applications utilizing the described programming concept. That may include methods for easy integration of sensor systems, methods, and tools for easy application engineering and commissioning.

To be mentioned is, of course, that adding robot programming capabilities to IEC61131 programming has also its limitations compared with state-of-the-art robot programming languages. For example, in a robot-centric application with complex paths and motion-related events, PLC programming can become difficult to achieve desired performance. The resulting PLC program also tends to be more complex than a traditional robot program. Therefore, state-of-the-art robot programming languages will still be used in many situations.

Looking into the future, modern programming paradigms like object-oriented or state-based programming languages are being introduced to PLC programming. For the convergence of PLC and robot programming and control, in a long-term perspective, even new paradigms may be developed that supports the implementation of automation applications in a much more efficient way. All this requires further R&D efforts from the academia and industries across the disciplines.

## References

1. Ljungkrantz O, Åkesson K, Fabian M (2007) A study of industrial logic control programming using library components. In Proceedings of the 3rd Annual IEEE Conference on Automation Science and Engineering, pp 117–122, Scottsdale, AZ, USA
2. Wicks M (2011) PLC-based robotic controls versus oem robotic controls: what's the best choice for your application, white paper. Intelligrated Inc., USA
3. IEC 61131-3 (2003), Programmable controllers—part 3: Programming languages, IEC, Mai 2003
4. PLCopen (2008) Technical Paper, PLCopen Technical Committee 2: Task Force, Function Blocks for motion control: part4—Coordinated Motion, version 1.0, PLCopen Gorinchem, The Netherlands, Dec 2008
5. Becker O, Dai F (2010) Integration of key components in factory automation applications. ABB Research Center Germany—Annual Report
6. Dai F, Becker O, Rüdele H (2012) PLCopen-konforme Programmierung von Industrierobotern in IEC 61131 Sprachen, Automation 2012, 13–14. June 2012, Baden–Baden, Germany

# On Analyzing the Semantics of IEC61131 -3 ST and IL Applications

**Mario de Sousa**

**Abstract** The IEC 61508 standard recognizes the programming languages defined in IEC 61131-3 as being appropriate for safety-related applications, and suggests the use of static analysis techniques to find errors in the source code. In this context, we have added a semantic verification stage to the MatIEC compiler—an open source ST, IL, and SFC code translator to ANSI C. In so doing, we have identified several issues related to the definition of the semantics of the IL and ST programming languages, as well as with the data type model defined in IEC 61131-3. Most of the issues are related to undefined semantics, which may result in applications generating distinct results, depending on the platform on which they are executed. In this paper we describe some of the issues we uncovered, explain the options we took, and suggest how the IEC 61131-3 standard could be made more explicit.

## 1 Introduction

Due to their robustness and flexibility, Programmable Logic Controllers (PLCs) have been used in many domains. However their use in high integrity and safety critical systems has often been conditioned on the requirement of having external equipment to monitor their correct behavior. This is mostly due to the difficulty in producing and verifying the correctness of their programs, since the hardware aspects have been mostly resolved through the use of hardware redundancy. The commercial availability of SIL 3 (SIL—Safety Integrity Level) rated PLCs on the market has not changed this, as what is SIL 3 rated is the hardware and the operating system of the PLC itself. In order to achieve the required SIL of the final

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system in which the SIL 3 PLC is integrated, then the program that is installed on the PLC also needs to be highly dependable. An example is a recently developed railway signaling that has been based on configurable PLC programs with the objective of being highly flexible and easily adaptable to the distinct railway lines configurations (the author worked as a consultant in this project).

In order to achieve this high reliability of the software, appropriate software development methods must be used. However, one of the main issues that affects the reliability of the final program is the programming language in which it is written. With the advent of the IEC 61131-3 standard, and its ever growing adoption by almost all PLC manufacturers, developing these highly dependable PLC programs is no longer out of the question. In fact, the IEC 61131-3 standard defines a common syntax and semantics for the programming languages commonly used for PLC programming. Although the programming languages defined in this standard are very similar to the programming languages previously used in programming PLCs, it was often the case the languages used by distinct PLC manufacturers differed in some sometimes small but very important ways.

## *1.1 PLCs and Safety-Related Applications*

Many previous works have already discussed how to design and/or restrict programming languages in order to make them useful for writing integrity applications. The IEC 61508 standard [1] (that defines the Functional Safety of Electrical, Electronic, and Programmable electronic Safety Related systems) already classifies common programming languages—interestingly it considers PLC programming languages as recommended for the development of high integrity systems, especially if these are somehow limited to a safe subset of the language. However, the standard itself does not specify the safe subset, nor does it reference any other document or standard where a subset of the IEC 61131-3 has been defined.

Somewhat relatedly, the PLCOpen consortium has published a document [2] defining several Function Blocks that are useful in implementing safety related functions. This document also extends the elementary data types defined in IEC61131-3—it defines an extra 'safe' version of each elementary data type, named SAFEINT, SAFEBOOL, etc. Apart from the extensions made to the base IEC 61131-3, this document also defines some restrictions to the IEC 61131-3 [3] languages and their development environments, with the intention of limiting the possibility of the use of unsafe programming practices that may result in such things as race conditions on preemption based systems.

One may consider that this would be a possible definition of the required subset of the IEC 66131-3 programming languages, however, what we have uncovered is that the IEC 61131-3 standard leaves some details of the specified languages with undefined semantics, and therefore one of two possible routes needs to be taken; either (a) the IEC 61131-3 standard needs to be modified and corrected so as to better specify the undefined behavior, or (b) a more restricted subset of the programming languages needs to be defined.

In this paper we have opted mostly for the first option (a). We have done this by suggesting changes to the standard that would be sufficient to correctly defined the as yet undefined semantics. Additional, we have validated the proposed semantics by extending an existing open source compiler (MatIEC [4]) of IEC 61131-3 languages in such a way as to implement the proposed semantics. Other changes made to the compiler add warnings to the user whenever the user makes use of language features that are not well defined in the original standard.

## 1.2 Previous Work

Most previous work related to analysing the IEC 61131-3 standard has focused mostly on the syntax of the languages, and the ambiguities therein. These have been described by de Sousa [5] and Plaza et al. [6].

A lot of work has been done regarding the formalization of programs written in the IEC 61131-3 languages, so they may be later formally verified (see [7] for a good overview of previous work in this area). However, this approach does not focus on analysing the IEC 61131-3 programming languages themselves.

At least two isolated groups have worked on formally defining the semantics of a sub-set of the IEC 61131-3 languages. Fett et al. [8] seem to have generated a compiler form this specification. However, in the literature it is not possible to find the details of the specification that was produced, nor a definition of the exact subset of the languages that was considered. On the other hand, Kourlas [9] focused on defining the semantics of only Function Block Diagrams (FBD), and criticize the standard for not defining their model of computation. Nevertheless, it is our view that this model is in fact defined, since the execution of the FBD is controlled by the Program Organization Unit (POU) in which it is declared, and the task in which the containing POU is executed.

## 1.3 Paper Organization

After this introduction, this paper continues with a Sect. 2 with an overview of the IEC 61131-3 data standard. In the following Sect. 3 the detected semantic ambiguities are explained, while Sect. 4 focuses on the MatIEC compiler and its overall architecture, with a focus on how the previously mentioned ambiguities where handled. Conclusions and outlook for future work is the object of the last section.

## 2 The IEC 61131-3 Standard

The IEC 61131-3 standard defines 4 programming languages (ST—Structured Text, IL—Instruction List, LD—Ladder Diagram, and FBD—Function Block Diagram), with an additional state based sequential programming model (i.e., SFC—Sequential Function Chart) which is often called a 5th programming language.

What is unique in this standard is that these 5 programming languages share the exact same data type model, as well as the same architectural or structural model. By structural model we mean the entities used to structure the code, namely the Program Organization Units (POUs): Functions, Function Blocks, Programs, and Configurations.

By sharing the same data type model, as well as the same structuring model, it becomes possible to write a single application using several distinct programming languages simultaneously, as long as each POU uses a single programming language.

### *2.1 Data Type Model*

The IEC 61131-3 standard defines several elementary data types, which may be used to store unsigned integer values (USINT, UINT, UDINT, ULINT), signed integers (SINT, INT, DINT, LINT), real values (REAL, LREAL), boolean values (BOOL, BYTE, WORD, DWORD, LWORD), character strings (STRING, WSTRING), and time related values (TIME, TIME_OF_DAY, DATE_AND_TIME, and DATE). Note that a BYTE is only considered as a sequence of 8 boolean bits, with no inherent quantity involved, which clearly distinguishes it from a SINT.

The standard also specifies the use of strong data type consistency. This means that a variable of a specific data type can only take values of that same data type, and may therefore never be used as another data type. For example, a variable of type SINT cannot be used where a variable of data type INT is expected. This strong type consistency is good for checking program correctness, and appropriate for safety-related applications. However, it places many obstacles for the programmer who may need to use explicit type conversion functions (e.g., SINT_TO_INT) many times throughout their code.

In order to overcome this obstacle, the newer version of the IEC 61131-3 standard that is currently being drafted, will allow limited automatic type conversions (or type casts), and only where no information is lost. So, for example, a SINT may be used in place of an INT, but not the other way around. Since the current version of the standard does not support implicit type conversions, it may be considered as implementing a safe type system. Since the newer version also guarantees that that no information is lost in the implicit type conversions, it too will maintain the type safety of the type system.

The IEC 61131-3 standard also allows the user to define additional data types. These may be (a) derived from the elementary data types, or may (b) be constructed from complex structures based on these types. Examples of the first (a) data types, are simple renaming of an elementary data type, the changing of the default initial value, or the definition of a sub-range. For example:

```
TYPE
  analog_t: REAL;
  real1 : REAL := 1;
  current_t: USINT (4 .. 20);
END_TYPE
```

Examples of the second (b) are arrays, structures, and enumerations.

```
TYPE
  complex: STRUCT
              r: REAL;
              i: REAL;
           END_STRUCT;
  sample: ARRAY [-10 .. 0] of LREAL;
  colour: (black, brown, red, yellow);
END_TYPE
```

## 2.2 The Programming Languages

As previously stated, the IEC 61131-3 standard defines 4 programming languages. The two graphical languages, LD and FBD, are somewhat similar to designing an electrical circuit. With LD the circuit is based on series and parallel connections of relay contacts (representing reading of boolean variables) which energize the relay coils (writing to boolean variables). With FBD the electrical circuit is more akin to a digital circuit diagram using small scale integration integrated circuits (counters, timers, mutiplexers, etc.).

The two textual languages are very dissimilar. IL is comparable to assembly level, with several simple operations that only take one operand. The operation takes as parameters the operand and the value in an accumulator variable, with the result being in the same accumulator variable. However, this has been extended to allow the invocation of functions, and conditional jumps.

The ST textual language allows for a higher level of programming, as it is somewhat similar to the PASCAL programming language. It is a sequence of statements, including assignments, iterations (for, repeat, while), and conditional execution (case, if/then/else). In all these statements, complex expressions may be used, that in turn may include function invocations.

These programming languages, especially the FBD and ST programming languages, were considered suitable for high integrity systems mainly due to their simplicity, and presumed fact that they were well defined.

## 3 Semantic Ambiguities

Several issues with the IEC 61131-3 standard have however already been raised in previous work, but these are mostly related to ambiguities or errors in the syntax. Here, we will point out ambiguities related to the semantics of the languages.

### 3.1 Semantic Ambiguity 1: Data Type Equivalence

In terms of data type equivalences, the standard clearly states that data types that are directly derived from another base data type (e.g., renaming, or re-defining a new default initial value) are equivalent to the base data type. However, the standard is silent in relation to the remaining complex user defined data types, such as structures, arrays, and enumerations. In particular, it does not specify any data type equivalence rules for derived data types that are recursively defined based on other derived data types.

Common type equivalence rules for programming languages are the "structure equivalence", and the "name equivalence". In the first, data types with the same structure are considered equivalent, whatever the name used to identify the type and its sub-components, while in the second "name equivalence" the data types must have identical names.

In this case, and taking into account that the standard seems to want to define a strongly typed language, but nevertheless allows for data type equivalence as long as the base structure is not changed, we have previously proposed that the data type equivalence rules should be extended to allow something in between the two above mentioned rules [10]. In particular, derived data types that are directly derived from other complex derived data types shall be considered equivalent. However, derived data types that are newly defined are always considered distinct from all other datatypes, even though they may have the same internal structure as another derived data type.

For example, consider the following data types:

```
TYPE
  c1 : STRUCT r: REAL; i: REAL; END_STRUCT;
  c2 : STRUCT r: REAL; i: REAL; END_STRUCT;
  c3 : STRUCT x: REAL; y: REAL; END_STRUCT;
  c2a: c2;
  c3a: c3;
END_TYPE
```

A programming language with structural equivalence data types will consider all the above data types as being equivalent. On the other hand, a name equivalence data type model will consider all the above data types distinct. With our proposed data type model for the IEC 61131-3, the data types c1, c2, and c3 are all distinct, while c2a and c2 are equivalent, as are c3 and c3a.

## 3.2 Semantic Ambiguity 2: Scope of Enumeration Identifiers

Identifiers in a programming language are used to identify specific program entities, for example: a data type name, a function name, a program name, etc. On the other hand, keywords are reserved identifiers that usually have a special meaning in the programming language, for example: Type, End_type, Array, Struct, etc. We have previously mentioned in [5] that the way IEC 61131-3 handles identifiers and reserved keywords is broken. However, we have recently realized that the use of identifiers related to the definition and use of enumerations is also ambiguous.

The issue here is that the standard allows the definition of derived data types that are an enumeration of several identifiers. For example:

```
TYPE
  colour_t: (black, brown, red, yellow);
  cable_t:  (black, red, brown);
END_TYPE
```

Additionally, variables may be defined to be of an anonymous data type.

```
Function foo : INT
  VAR product_colour: (black, white, gray); END_VAR
 ...
End_Function
```

In the above example, we have a derived data type ‘colour_t’, and a variable ‘product_colour’, is of an enumerated data type that dos not have a name, i.e., it is anonymous. Following the previously specified data type equivalence rules, the variable ‘product_colour’ is not compatible with variables of ‘colour_t’ data type. In particular, the enumeration constants used for the ‘colour_t’ are clearly distinct from the enumeration constants for the anonymous data type. This is also true for the ‘black’ enumeration constant, that shows up in both enumeration data types.

And Herein lies the issue. Although the standard clearly defines the scope of the ‘colour_t’ identifier as being global (more precisely, globally valid within the library in which it is defined), and the identifier ‘product_colour’ as being in scope merely within the function named ‘foo’, it does not specify the scope of the enumeration constants, although it does explicitly allow these to be re-used. If one is to assume that the enumeration constants in the globally defined data types also have a global scope, and the ‘black’ enumeration constant has local scope (local to ‘foo’), then every reference to the ‘black’ enumeration constant is now ambiguous, since it may reference one of two (or possibly three) distinct data types.

For the globally valid named data types, the standard includes a special syntax that allows the enumeration constants to be disambiguated. For example:

```
colour_var : = colour_t#black;
cable__var : = cable_t#black;
```

However, the standard simply states that ‘ It is an error if sufficient information is not provided in an enumerated literal to determine its value unambiguously”. The question arises if in the following case

```
colour_var : = black;
cable__var : = black;
```

the assignments are unambiguous. In reality, it is clearly possible to determine the referenced data type in the above case, from the data type of the variable in the left hand side of the assignment statement. However, since the standard states that the information must be present in the 'enumerated literal', which is not the case above, then one must conclude that the above assignments must be considered erroneous.

The issue arises when code inside the 'foo' function wishes to reference the 'black' enumeration constant belonging to the anonymous data type. This data type is anonymous, so it is not possible to disambiguate the 'black' constant using the above mentioned syntax. However, one may argue that the 'black' identifier, used inside the 'foo' function, hides the 'black' identifiers with global scope. In this case, the assignment (inside the 'foo function)

```
product_colour : = black;
```

would have to be considered valid. Nevertheless, since the standard is silent on the issue of whether the locally scoped 'black' identifier hides the globally scoped 'black' identifiers, one may conclude that this is not the case. This has the implication that the locally scoped 'black' enumeration constant has no way of being referenced. The programmer would need to either (1) rename the locally scoped enumeration constant, or (2) to define the data type as a non-anonymous data type.

The first option (1) is usually possible, as long as the programmer has access to all the source code. However, if he is importing the previously defined 'foo' function into his code, it does not make much sense that he be required to change the code of the 'foo' function so it may be used within his library, so it is not really an ideal solution. The second option (2) is also not ideal, since derived data types may only be defined with a global scope, and may not therefore be defined inside the 'foo' function itself, which is clearly what the intention of the above code (using the anonymous data type) would be.

Since neither of the above two solutions is ideal, we have opted to allow the hiding of the globally scoped 'black' enumeration constants in MatIEC, and therefore allow the following assignment within the 'foo' function.

```
product_colour : = black;
```

However, in this case, we issue a warning clearly stating that this use of the 'black' identifier is dangerous and potentially ambiguous in other IEC 61131-3 development environments.

### 3.3 Semantic Ambiguity 3: Evaluation Order of Function Invocation Parameters

The IEC 61131-3 standard allows functions to be called using any of the 4 programming languages. However, function invocation using either one of the textual languages allows for more complex situations to arise. In this case, the IEC 61131-3 textual languages allows ambiguities to arise due to the fact that the standard does not specify the order by which function invocation parameters are evaluated. For example (using the ST syntax):

```
var1 : = foo(bar(in : = 33, out => var2), var2);
```

In the above example, the ‘foo’ function is being called with 2 parameters being passed. The second parameter of the ‘foo()’ invocation is simply the value of the ‘var2’ variable. The first parameter is set to the result of another function invocation, namely ‘bar()’. The ‘bar()’ function invocation also takes two parameters; the first is the constant ‘33’, and the second is the variable ‘var2’. However, in this case the variable ‘var2’ is being used to store the result of the output parameter ‘out’.

Notice how the second parameter being passed to the ‘foo()’ function invocation will have a distinct value, depending on the order in which the two parameters are evaluated; is the value of ‘var2’ first passed to the second parameters of foo(), or is the bar() function invoked first?

The IEC 61131-3 standard leaves this order of function parameter evaluation completely unspecified (even though the order of evaluation of expressions with multiple operators is very clearly defined). This issue is not specific to the IEC 61131-3 standard, as this is also common in other widely used programming languages. One way of resolving this issue is to simply define a function parameter evaluation order, whichever it may be.

However, since this issue is common in other programming languages, and the evaluation order, if it exists, is usually not well known among software practitioners, it is much safer to simply avoid the use of the above situation. With this in mind, we have augmented the MatIEC compiler with code that is capable of detecting the above situations, even if they occur inside even more complex function invocations with multiply embedded invocations, and therefore issue a warning to the programmer.

The detection of this situation is based on an extension of the constant folding and constant propagation static code checking algorithms.

## 4 The MatIEC Compiler

As was stated previously, the MatIEC compiler is a code translator for ST, IL, and SFC programs into ANSI C. It was originally developed for a now defunct project named MatPLC, which intended to produce an open-source PLC. It was later integrated into the Beremiz project (www.beremiz.org), which offers an integrated development environment (IDE) for developing IEC 61131-3 applications, including a graphical editor for SFC, LD, and FBD programs.

Currently the MatIEC compiler is also being used by a few companies for their commercial products, either together with the Beremiz IDE, or with other proprietary IDEs. Typically, the IDEs convert graphical SFC programs to their textual representation, and FBD and LD programs to either IL or ST, which are all later compiled by the MatIEC compiler. The compiler itself is organized in four stages: lexical analyzer, syntax parser, semantics analyzer, and code generator.

The lexical parser analyzes the source code and breaks it up into lexical tokens, removing on the way all comments and white-spaces between the tokens. The syntax parser groups the tokens into syntax constructs, and builds an equivalent internal abstract syntax tree data structure. The semantic analyzer walks through the abstract syntax tree and determines whether all semantic rules have been obeyed. The code generator, walks through the abstract syntax tree once again, and produces the final equivalent C code. This architecture allows us to easily write a new code generator for whatever output language desired, without having to rewrite all the lexical, syntactic, and semantic parsers.

Our abstract syntax tree has been implemented as a tree of C++ objects, and the code that handles these objects follows the visitor design pattern [11]. This enables us to easily add or remove stages to our architecture without having to edit the abstract syntax tree classes themselves. Other future possible additions to the architecture include a code optimization stage.

### *4.1 Lexical Analyzer*

The lexical analyzer was implemented using the flex utility that generates lexical analyzers from a configuration file. The configuration file includes the extended expression definitions of the language's tokens.

This stage is the most straightforward, but is still nevertheless relatively complex due to its capability of parsing ST, Il, and SFC code intermixed in the same input file. To do this we were required to use a state machine since not all languages have the same definition of tokens. For example, the end-of-line (EOL) token is considered white space in ST, but is relevant for parsing IL code.

### *4.2 Syntax Parser*

The syntax parser was implemented using the GNU bison utility. This program generates a syntax parser from the syntax definition of the language being parsed. Although it too may have seemed straightforward at first, many issues had to be overcome but which are not the object of this paper.

## 4.3 The Semantic Checker

Due to a lack of time and resources, the semantic checker was left to a later stage, and only now has a first working version been implemented. The current version focuses mainly on data type consistency checking, but has already been extended to include constant folding and constant propagation.

Constant folding is the act of evaluating at compile time the result of every expression that has a constant value. For example, the code

```
x[42 + 9] : = 99/3;
```

is replace with

```
x[51] : = 33;
```

This allows us to better determine at compile time whether the ranges of arrays are being exceeded, or if the limits of a subrange variable is being exceeded. However, for situations with code

```
a : = 9;
x[42 + a] : = 99/a;
```

the folding cannot be done since the expression contains a variable, even though the variable will always contain the same constant value in the code line being analyzed. To cover these situations, we have implemented a constant propagation algorithm, that follows, for each location of the code where a variable is used, the possible values that the variable takes.

This algorithm is then expanded to take into account that the evaluation of function invocation parameters may be any, and then checks whether the results are always the same, whatever the evaluation order.

## 4.4 The Code Generators

IL and ST code transcription to C is rather straightforward as many of the constructs used in ST and IL are also available in C. Considering the POUs, Functions are mapped directly as C functions, while Function Blocks (FB) are mapped onto a structure that stores the FB's internal state (variables), as well as a C function containing the FB's code.

The resulting C code is practically self-contained and self-referencing, which allows it to be completely portable to any platform with a C compiler. The single instance that makes the code platform dependent is how located variables are mapped onto physical Input/Output.

The author is currently working on an intermediate code generator, so it may be integrated into the llvm family of compilers. This will allow for debugging features such as line by line code stepping, variable and parameter analysis, stack trace analysis, etc.

## 5 Conclusions

Although the IEC 61131-3 languages are suggested as being appropriate for high integrity applications, we have found that they are not however completely defined, with semantic ambiguities left undefined. To fix these ambiguities, we have either proposed a solution which has been validated by implementing it in the MatIEC compiler, or we have decided to leave them undefined, but have created a check that warns programmers that their programs relies on undefined behavior.

However, the MatIEC does not yet do a complete semantic analysis of all source code. In the future we intend to continue to implement more checks of semantic correctness, as well as augment the MatIEC compiler with coding style verifications, which is common in high integrity applications..

## References

1. International Electrotechnical Commission (1998) Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems, December 1998
2. PLCopen: Technical Committee 5 (2006) Safety Software Technical Specification, Part 1: Concepts and Function Blocks. Version 1.0, Jan 2006
3. International Electrotechnical Commission (1993) International Standard IEC 61131-3, Programmable Logic Controllers Part 3, Geneva
4. de Sousa M, Tisserant E, Bessard L (2007) An open source IEC 61131-3 integrated development environment. In 5th IEEE International Conference on Industrial Informatics 2007 (IEEE INDIN'07), pp 183–187
5. de Sousa M (2010) Proposed corrections to the IEC 61131–3 standard. Comput Stand Interfaces 32:312–320
6. Plaza I, Medrano C, Blesa A (2006) Analysis and implementation of the IEC 61131–3 software model under POSIX real-time operating systems. Microprocess Microsys 30:497–508
7. Younis MB, Frey G (2003) Formalization of existing PLC programs: a survey. In: Proceedings of CESA, Lille (France) CD-ROM. Paper S2-R-00-0239, July 2003
8. Egger G, Fett A, Pepper P (1994) Formal specification of a safe PLC language and its compiler. In: SAFECOMP'94, Proceedings of the 13th international conference on computer safety, reliability, and security, Anaheim, Kalifornien, USA
9. Tourlas K (1997) An assessment of the IEC 61131-3 standard languages for programmable controllers. In: SAFECOMP'97, Proceedings of the 16th international conference on computer safety, reliability, and security, York, United Kingdom, Sept 1997
10. de Sousa M (2012) Data-type checking of IEC 61131-3 IL and ST programs. In: 17th IEEE International conference on emerging technologies and factory automation (IEEE ETFA'12)

11. Design Patterns for Flexible Manufacturing (2007) Dennis Brandl, ISA-Instrumentation, Systems, and Automation Society, ISBN-13: 978-1-55617-998-3
12. Aho AV, Lam MS, Sethi R, Ullman JD (2006) Compilers: principles, techniques, and tools, 2nd Edn. Sept 10, 2006, ISBN-13: 978-0321486813

# Standard Function Blocks for Product Oriented Programmed Process Data Access

**Julio Garrido Campos**

**Abstract** The paper presents neutral open function blocks to implement programmed data access logic into controllers programs. The paper proposes an approach similar to the successful IEC MotionControl function blocks technology, which has been defined for neutral programming of axis control. In the same way, neutral access blocks could be programmed for data access and recording, and specific brand controllers would implement them and use to build the manufacturing program. A prototype implementation is presented for CAD/CAM/CNC environments to automate manufacturing processes data access and recording in order to support services of production activity supervision, manufacturing data traceability-recording of relevant information of manufacturing processes for future review in case of fault-etc.

## 1 Introduction

Today, data from manufacturing processes is no longer just used by process controllers–any kind of Real-time controller such as Programming Logic controller PLC, Industrial PC, embedded systems, etc.—but it is accessed by higher hierarchical processes for tasks such us monitoring, process supervision, productivity, quality, traceability, etc. This process data access has been traditionally carried out as an internal company process. The three main data access activities–setting up data access requirements, data recording at manufacturing, and data communication, long term storage and review–have had being performed by the own manufacturing company. With the growing collaboration and integration of supply chain in extended enterprises, data access focus has changed to external or

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chain visibility. Process data should be available and significant no matter the data origin, the manufacturing complexity or the supply chain complexity. In extended supply chains and collaborative manufacturing environments based on dynamic and flexible enterprise relations, this objective is sometimes difficult to achieve as the responsibility of the data access activities is distributed along the supply chain companies. The responsibility for the process data has to be shared along the supply chain. For instance, setting up data access requirements is the responsibility of the main company, whereas the responsibility for the correct interpretation of these requirements, and the manufacturing data collection lies in the supply chain manufacturing facilities.

Also, the need to increase quality and new legal requirements has challenged a growing number of industrial sectors to consider process data traceability a crucial task [1, 2]. Difficulty to implement traceability may increase when manufacturing complex and heterogeneous products, as the manufactured product, the supply chain, the traceability, and quality requirements can constantly change. Different manufacturing companies may use different data access and traceability systems, and this often leads to traceability information dis-aggregation among different databases belonging to different suppliers and clients, resulting in availability and understandability data problems. Moreover the complexity of manufacturing processes makes it difficult for the one company to understand the manufacturing traceability data collected in other companies.

In these environments, the dispersion of responsibilities (the designing company is not the same that the manufacturing one) affects to the traceability data trustworthy and reliability. The challenge here is how to guarantee that both, the requirements and the traced data, are always understandable and accessible, regardless of the time passed and of client–supplier relationships dynamic character; but, at the same time, allowing the recorded data to be audited on-line by the responsible entity.

On the other hand, customized production environment is related to the problem of how implementing process performance data access without penalizing productivity. Traceability implementation in static productive environments (mass production) characterizes by proprietary systems, the traceability subsystem is established during the production take-off phase and it does not change until the production process is re-defined. That is, the traceability is tied to the manufacturing process, not to the product. Nevertheless, traceability would need to be adapted to each new piece in custom products manufacturing environments in order to maintain recorded data context with the product. The challenge here is how perform product oriented traceability system set-up without affecting productivity.

For first issue-data understandability—data recorded have to be related with the process description. This is documented by the "part program" ("user program"). Depending on the technology, it may be described by a standard specification. as for instance, G&M codes [3] or by the new STEP-NC standard [4, 5, 6] which are interpreted and executed by the CNC controller. In manufacturing-assembly-processes, new standards such us ISA95 [7] are been used for that process specification.

For second issue-access data automation- the paper proposes standardization of programmed data access and implementation data access and recording. That standardization proposal follows the model of a successful experience in motion control automation industry: the IEC 61131 MotionControl functions blocks. In a similar way, new function blocks for data access and recording would be inserted in standard IEC PLC programs to automate any kind of machine, from regular machines to CNC machines [8].

This propose goes however beyond CNC manufacturing environments, which could be seen as an example application. The data access functions blocks would allow the treatment of data access activities within a control program, and insert data access decisions in the control algorithms.

The rest of the paper is organized as follows. Section 2 describes data and programming standards involved: ISA-95, MTConnect [9], OPC [10], etc. Section 3 presents new function block for data access and a prototype implementation scenario describing how they may interact with existing and news traceability nc_functions for STEP-NC with. The paper finishes with concussions in Sect. 4.

## 2 Manufacturing Data Standards: From Specification to Control

### *2.1 Standards for Enterprise Vertical Integration*

Vertical integration has been tackled in different industrial sectors by defining standard or sector-normalized models [11, 12]. Recently, the ISA-95 standard has attracted a great deal of interest in the automation world by defining a general model for manufacturing operations [7], [13]. The model defines levels that can be mapped to systems (ERP, PDM, manufacturing resource planning (MRP), or MES). A typical physical view of ISA-95 systems is shown in Fig. 1. It represents processes as a functional hierarchy model with five levels (0 to 4), but distinguishes two domains within a manufacturing company: the enterprise domain (Level 4 for business planning and logistics) and the manufacturing domain (Level 3 and lowers for manufacturing operations and control, and process control). The ISA-95 enterprise/control system standard defines data models as interfaces between Level 4 business functions and Level 3 manufacturing operation functions (Fig. 1) [13, 14]. Among information object models that describe production process resources and planning information ("Product Definition", "Materials", "Equipment", "Personnel", "Production Schedule", etc.), ISA-95 also defines a "Production Performance" model for Level 3 (manufacturing) information to be provided as feedback to Level 4 (business). However, communications between

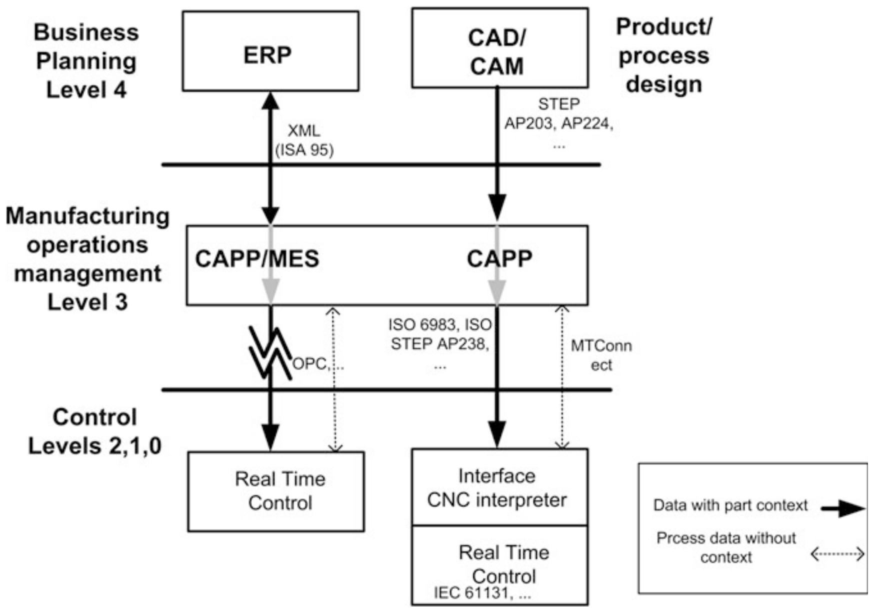


**Fig. 1** Machining data integration *left*, ISA95 architecture; *right*, STEP-NC architecture

Level 3 and controllers rely on custom/brand mechanisms [15] or on other standard protocols, such as OPC [10]—oriented to data access and transfer but not to information content description (Fig. 1).

## *2.2 Process Data Access Standards*

The communication between process supervision applications (MMI Man Machine Interfaces, SCADA applications, etc.) and controllers (PLC's, embedded systems, Industrial PC's or PC's with real time software, NC, or CNC controllers, etc.) is, most of the times, brand dependent. The supervision platforms needs brand specific drivers to get access to controller variables. There are some open access technologies such as OPC (OLE for Process Control [10], web services, etc. With them, PLC may be integrated with higher level information processes and provides on-line client–server access to controller internal data [10]. New open communication standard such as MTConnect will allow devices, equipment, and systems to output data in an understandable format that can be read by any other device using the same standard format to read the data. MTConnect is an open and extensible protocol that allows the exchange of dynamic sensor data, configuration data, and control information among MTConnect-compliant machines, software applications, and controllers. MTConnect messages are encoded using XML, with a self-describing structure for each data item. Openness of PLC's, CNC's and

```
If variable > Trace hold then          If variable.buffer.full=true then
   variable.record.on:=true;              Process.halt:=true;
End_if                                 End_if
```

**Fig. 2** *Left* Programmed data access code. *Right* Programmed data access logic

servo drives, plus standard and open industrial field-buses as Profibus Sercos, EtherCat, CanOpen, etc. make available running and configuration data of from field devices to the processes controllers [15].

All these systems are data access and communication mechanisms that support interoperability. Ultimately, however, the management of multivariable raw data requires metadata to describe the context of the measurements.

Also, these systems have to be set-up. Te data access setting up process in not transparent and it is performed from outside the control program. To set up an OPC data access chancel, for instance, an OPC server has to be set up first in a supervision platform (a PC with a regular operation system) and connected to the controller. A similar procedure has to be carried out if a brand specific data access is performed: a specific driver is used from a compiler (C++, Java, etc.) or from a commercial SCADA system to get access to the controller. At end, the controller does not know or decide nothing about the data access or monitorization procedure. It can't be programmed data access logic as in next example in Fig. 2. The example represents two uses for programmed data access function blocks functionalities: programmed data access and programmed logic related with data access. The first is an example of programming the recording start process of a variable if a trace hold is reached. The second is the use of a data access condition into the control program. More specifically, it states that if a particular data buffer at the PLC is full (because a high level process such as a MMI does not accessed it for reading and emptied it), then the regular control process must be stopped, as there is no space fore new recorded data. This way, the recording of critical data to trace the manufacturing process may be assured from the beginning, at designing phase.

### *2.3 Programing Control Standards*

IEC 61131-3 [16] is the international Standard for PLC's programming. It defines syntax and structure and mayor PLC manufacturers already allow programming their controllers with it. It is a successful technology and it is still growing new parts in progress. Since 2001, a specification of an independent library of function blocks for motion control. It included motion functionality for single axes and multiple axes, several administrative tasks, as well as a state diagram. This specification provides the user a standard command set and structure independent of the underlying architecture. This structure can be used on many platforms and architectures. In this way one can decide which architecture will be used at a later stage of the development cycle. Advantages for the machine builder are, among

| *Administrative* | | *Motion* | |
|---|---|---|---|
| ***Single Axis*** | ***Multiple Axis*** | ***Single Axis*** | ***Multiple Axis*** |
| MC_Power | MC_CamTableSelect | MC_Home | MC_CamIn |
| MC_ReadStatus | | MC_Stop MC_CamOut | MC_GearOut |
| MC_ReadAxisError | | MC_Halt MC_GearIn | MC_GearInPos |
| MC_ReadParameter | | MC_MoveAbsolute | MC_PhasingAbsolute |
| MC_ReadBoolParameter | | MC_MoveRelative | MC_PhasingRelative |
| MC_SetPosition | | … | ... |
| ... | | | |

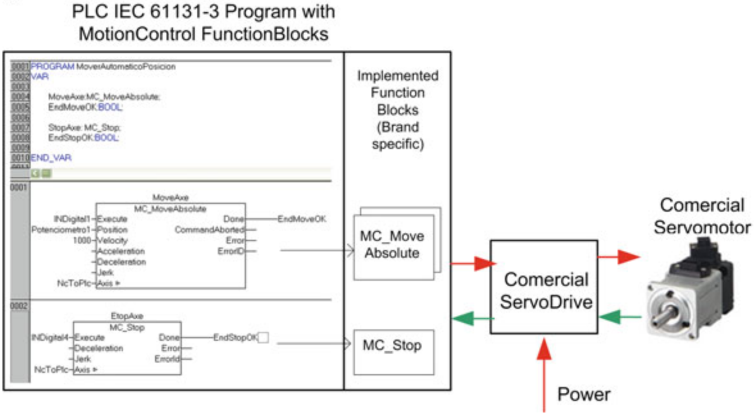


**Fig. 3** *Up* Main IEC motion control function blocks; down, programmed standard motion control block and implemented motion control blocks architecture

others, lower costs for supporting the different platforms and the freedom to develop application software in a more independent way, without limiting the productivity of the machine. In addition to those benefits, system maintenance is easier, and the education period is shorter. This is a major step forward and is more and more accepted by both users as well as suppliers. Figure 3 list main Motion Control Function Blocks and illustrates an implementation architecture.

## 3 Programmed Data Access and Implementation

All data access methods described (Sect. 2.2)-OPC, MTConnect, etc.—support interoperability, distributed data access, etc. Ultimately, however, the management of multivariable raw data requires metadata to describe the context of the measurements. Moreover, those data monitoring mechanisms can't be inserted in a part program or a automation PLC program. There is no way or perform programming data access and store.

To overcome both limitations, the paper proposes an IEC 61131-3 extension for Data Access Function Blocks. This extension try to reproduce the extremely successfully experience of the IEC Motion Control Function Blocks technology. Moreover, the Object Orientation of the new version of the IEC 61131-3 (version

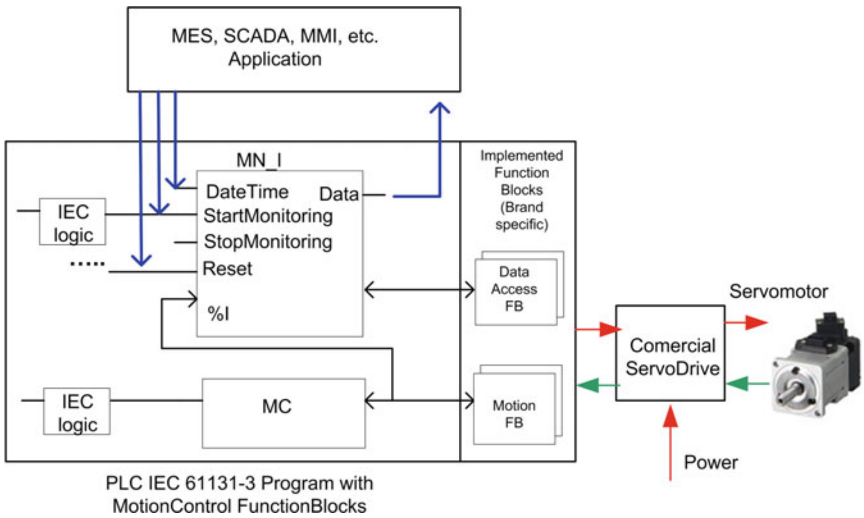


**Fig. 4** Example of a monitoring function block

3) incorporates, among other things, classes definitions with inheritance capability. That would allow expanding the "field variables" with new capabilities. Next (left) is an example of current regular IEC 61131-3 INPUT variables definition (axe, digital input, etc.), and on the right there is an equivalent definition using an inherited input variable with storing capability. A similar declaration would be used with special defined modules. An example of one those modules is presented in Fig. 4. The DataTime input is used to give the module the date and time of the StartMonitoring order, which is provided with a trigger signal at StarMonitiring input. It is important also the IdOperation input, which is used to provide the part or process identification to attach the recorded data.

An important characteristic of the modules is that it would be possible to control from a higher interface (a MES application, a Man Machine Interface, etc.), or it may be controlled by the "control program", which means that they may be "programmed". Figure 4 represents both options.

| Regular declaration | Declaration with inherited Types ("MN") for monitoring |
|---|---|
| PlcToNc AT %Q*:<br>PLCTONC_AXLESTRUCT; | PlcToNc AT %Q*:<br>MN_PLCTONC_AXLESTRUCT |
| NcToPlc AT %I*:<br>NCTOPLC_AXLESTRUCT; | NcToPlc AT %I*:<br>MN_NCTOPLC_AXLESTRUCT; |
| INDigital1 AT %I*:BOOL; | INDigital1 AT %I*:MN_BOOL; |
| OUTDigital1 AT %Q*:BOOL; | OUTDigital1 AT %Q*:MN_BOOL; |

### 3.1 *Sample Implementation: Standard/Neutral Data Access Programing with Product/Process Context*

Manufacturing traceability means recording product manufacturing information on raw materials, employees, machines, tools, storage, transport conditions, but also manufacturing process performance [17, 18]. The objective is to be able to react to defects or incorrect behavior that originated in the manufacturing process for final products [19]. If a part is reported as defective, traceability records can be reviewed to obtain information on, for example, the raw material lot used to make a specific part (trace-back or tracing). Such information may be used to avoid massive product recalls by precisely delimiting individual products made in the same conditions [20].

In the field of CNC machining, a set on new traceability nc-functions have been discussed to be included in future editions of STEP-NC in order to automate activities. These functions would be inserted in the executable CNC program which is communicated to the CNC. They have been divided in three groups: Group I to get single values, Group II to perform concurrent data acquisition, and Group III functionality to test a specified "condition" and perform some actions depending on the tested condition (and data storage/logging is also optional). Figure 5 is an example of some of these new proposed nc-functions [21, 22].

As result, the controller automatically interprets and performs recording data accessing and storage processes while manufacturing. A simple application example for the above scenario could be to trace the execution of a specific machining workingstep which is considered as critical. The corresponding nc-function is inserted (programmed) in the part program. The data access is automatically performed by the PLC program through a call to the corresponding data access function block.

With monitoring and traceability nc_functions inserted in a CAM part program, traceability and monitoring actions can be programmed and automatically executed

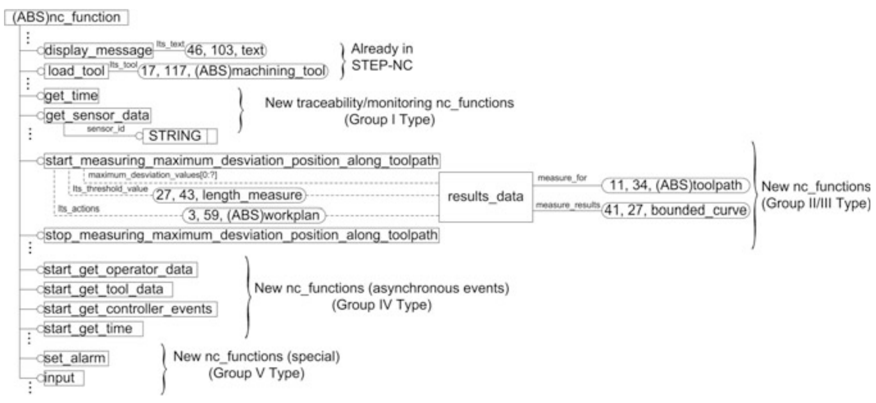


**Fig. 5** Monitoring nc functions

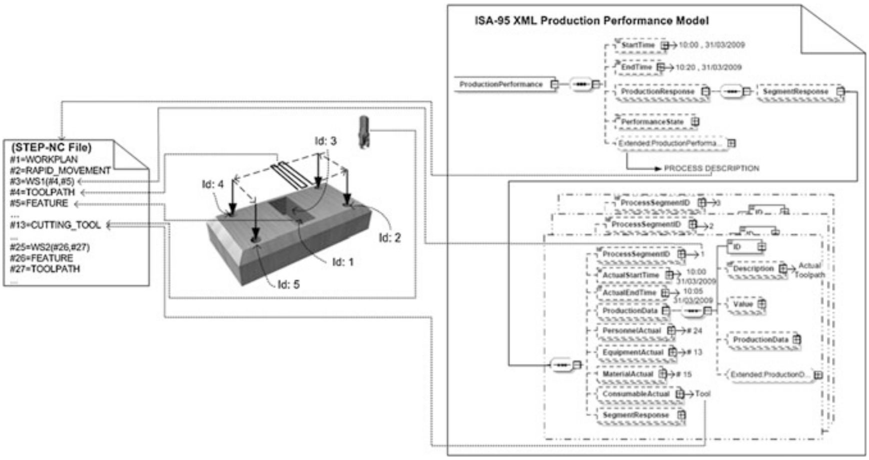


**Fig. 6** Manufacturing data

by the controller. If data records are linked to a standard machining process specification that is understandable worldwide (the STEP-NC part program), records may be understood and correctly analyzed. The specification for the machining process is the metadata needed to interpret data coming from the process. Since the new standard STEP-NC completely documents the manufacturing process, it may be used as the metadata to describe the same process.

ISA-95 has defined models to store data recorded during the manufacturing process to be used in production process control and in optimization and quality control activities such as traceability—namely, the production performance model (XSD schemas for XML data files) [23, 24]. These can be used to store data coming from the execution of the traceability nc_functions, provided that the STEP-NC part program is also referenced and provided that each data record is linked with the corresponding STEP-NC object (a nc_function id, a tool path id, a feature id, etc.).

Figure 6 shows an example of an ISA-95 production performance structure used to store data coming from the execution of a STEP-NC file (AP-238), maintaining a link between them and relating the data records in the XML file to the corresponding objects in the AP-238 file.

## 4 Conclusion

Data access functions blocks represent the ability to insert data access actions and data access logic into control programs.

Programmed data access logic represents the possibility of automate data access process. For instance, if a motion control subroutine has to be executed as result of a CNC program code, a data access subroutine or code could be also automatically be executed if a monitoring nc-function be present in the same CNC program.

Sample implementations of data access functions blocks have been developed and inserted in IEC programs. They have been implemented in a Beckhoff embedded PC platform. This example also include a integration between a CNC program (a nc-function) and the motion control subroutine implementing the machining code of the CNC program

A detailed definitions of the blocks would include list of specific parameters as for instance: start_recording, stop_recording, reset buffer, etc.

## References

1. Chalmers D (2003) Food for thought: Reconciling European risks and traditional ways of life. Mod Law Rev 66(4):532–562
2. Brandl D (2005) Tracking and tracing made simple. Control Eng 52(4):16
3. ISO 6983-1:1982 (1982) Numerical control of machines—program format and definition of address words—part 1: data format for positioning, line motion and contouring control systems, ISO TC 184/SC 1, Geneva, Switzerland
4. ISO 14649-1 (2003) Industrial automation systems and integration—physical device control—data model for computerized numerical controllers: part 1: overview and fundamental principles, International Organisation for Standardisation (ISO), Geneva, Switzerland
5. ISO 10303-238:2007 (2007) Industrial automation systems and integration—product data representation and exchange: part 238: application protocol: application interpreted model for computerized numerical controllers. ISO TC 184/SC 4, Geneva, Switzerland
6. Xu XW, Newman ST (2006) Making CNC machine tools more open, interoperable and intelligent-a review of the technologies. Comput Ind 57:141–152
7. Scholten B (2007) The road to integration, ISA-Instrumentation, systems, and Automation Society, North Caroline
8. http://www.plcopen.org/pages/tc2_motion_control/ (accessed January 1, 2013)
9. http://mtconnect.org/media/MTConnectWhitePaper.doc. (accessed Jan 1 2013)
10. Dedinak A, Wögerer C, Haslinger H, Hadinger P (2005) Vertical *i*ntegration on *industrial exa*mples. IFIP international federation for information processing, Springer, Boston
11. Villa A (2001) Introducing some supply chain management problems. Int J Prod Econ 73(1):1–4
12. Lee J (2000) E-manufacturing: fundamental, tools, and transformation. Rob Comput Integr Manuf 19(6):501–507
13. Bolton R, Tyler S (2008) PQLI engineering controls and automation strategy. J Pharm Innov 3:88–94
14. Descourvières E, Gendreau D, Lutz P (2006) Data representation for the control of full-automated microfactories. In: Proceedings of the 5th international workshop on MicroFactories, IWMF′06, Besançon
15. Wosnik M, Kramer C, Selig A, Klemm P (2006) STEP-NC for integrated and Distributed Manufacturing Processes: Enabling feedback of process data by use of STEP-NC. Int J Comput Integr Manuf 19(6):559–570
16. http://www.plcopen.org/pages/tc1_standards/iec_61131_3/ (accessed Jan 1 2013)
17. Chiu M-L, Lan JH (2005) Information and IN-formation. Information mining for supporting collaborative design. Autom Constr 14(2):197–205

18. Cheng MJ, Simmons JEL (1994) Traceability in manufacturing systems. Int J Oper Prod Manag 14(10):4–16
19. Van Dorp JK (2002) Tracking and tracing: a structure for development and contemporary practices. Logistic Inf Manag 15(1):24–33
20. Jansen-Vullers MH, Dorp CA, Beulens AJM (2003) Managing traceability information in manufacture. Int J Inf Manag 23(5):395–413
21. Garrido J, Hardwick M (2006) A traceability information model for CNC manufacturing. Comput Aided Des 38:540–551
22. Garrido J, Hardwick M (2009) Manufacturing traceability automation using features and nc-functions. Int J Comput-Integr Manuf 22(2):112–128
23. Gifford C (2007) The Hitchhiker's guide to manufacturing operations management: ISA-95 Best Practices, ISA
24. URL: http://www.wbf.org/catalog/b2mml.php/ (accessed Jan 1 2013)

# CN2-SD for Subgroup Discovery in a Highly Customized Textile Industry: A Case Study

**S. Almeida and C. Soares**

**Abstract** The success of the textile industry largely depends on the products offered and on the speed of response to variations in demand that are induced by changes in consumer lifestyles. The study of behavioral habits and buying trends can provide models to be integrated into the decision support systems of companies. Data mining techniques can be used to develop models based on data. This approach has been used in the past to develop models to improve sales in the textile industry. However, the discovery of scientific models based on subgroup discovery algorithms, that characterize subgroups of observations with rare distributions, has not been made in this area. The goal of this work is to investigate whether these algorithms can extract knowledge that is useful for a particular kind of textile industry, which produces highly customized garments. We apply the CN2-SD subgroup discovery method to find rare and interesting subgroups products on a database provided by a manufacturer of custom-made shirts. The results show that it is possible to obtain knowledge that is useful to understand customer preferences in highly customized textile industries using subgroup discovery techniques.

**Keywords** Knowledge extraction processes · KDD · Data mining · Subgroup discovery · CN2-SD · Textile industry

## 1 Introduction

The textile industry is closely linked to consumer lifestyle. The variety of products offered together with the speed of response to changes in demand can be decisive in the success of this business. To differentiate from the competition in a

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segmented market requires that a company, among other things, develops products with a good *design*, that are customized according to customer preferences and provide high added value [1]. In this context the work of designers is extremely complex, particularly in areas of activity in which customer preferences change quickly, as is the case of the textile industry. Therefore, to enable companies to guide their strategies toward customer satisfaction, they must integrate models that characterize customer preferences and buying behavior into their product design processes.

One approach to develop those models is data mining (DM) [2, 3]. In data mining, data collected from past customer interactions can be used to identify patterns and trends. These patterns can be useful to understand past and current customer preferences and behavior, as well as to forecast what will happen in the future. This approach is typically used in areas such as marketing and sales. For instance, Gamberger [4] and Lavrac [5] used data mining techniques to obtain models to help decision support systems in marketing campaigns. DM techniques have also been widely used in the textile industry. An example is the study of Thomassey [1] that aims to find the common practices in this industry. Data mining is used to provide knowledge to help in the evaluation of sales forecasting methods used by some companies. However, to the best of our knowledge, DM has not been used for product design and development in the textile or other industries.

One task that is becoming increasingly popular in DM is subgroup discovery [6, 7]. The goal of subgroup discovery is to identify in a dataset, subgroups that have an unusual distributions, i.e., that are significantly different from the general distribution. Subgroup discovery has been used in multiple domains, including bioinformatics [8–10] and marketing [4, 5]. However, and again to the best of our knowledge, it has been applied neither for product design and development nor in the textile industry.

In this study, we show how subgroup discovery methods can be used to extract knowledge that is useful for designers in the textile industry. It, thus, has two contributions, namely to apply a DM approach, in particular, subgroup discovery, in the textile industry, and, in particular to support the product design process. We focus on a particular kind of textile industry, which produces highly customized garments. The case in study is the Bivolino company, that produces shirts.

In Sect. 2, we provide a short introduction on subgroup discovery. Section 3 presents the case study. Section 4 presents and discusses the results obtained and finally, Sect. 5 concludes the paper.

## 2 Subgroup Discovery

Kloesgen [6] and Wrobel [7] present subgroup discovery as a data mining technique for discovering relations between different objects with respect to certain properties of a target variable. As stated by Kloesgen [6], there is a growing need for statistical techniques capable of searching relationships or patterns of unusualness. However, the existing theoretical models could not achieve this purpose. In subgroup discovery, we assume that we have a population of individuals (objects, customers, etc.) as well as the properties of those individuals we are interested in [11]. The subgroup discovery task pretends the discovery of subgroups of the population that are statistically more interesting and unusual, namely with statistical distributions that show unique features with respect to the global distribution of the property under investigation [11].

Lavrac [12] also states that the above task aims at the identification of subsets of the population who are statistically different. In other words, it aims to find subgroups with relations that correspond to a pattern or model with rare or unusual statistical characteristics.

In this sense, Gamberger [13] formalizes rules ($R$) that describe a subgroup obtained by induction, which is described as follows:

$$R\colon Cond \rightarrow Class_{value} \tag{1}$$

where $Class_{value}$ is the value of the target variable (i.e., the variable of interest) in the subgroup discovery task and $Cond$ is a set of attributes that describe the statistical distribution of the subgroup in question. To illustrate this concept, let us assume a simplified version of the case study addressed in this work: we are looking for subgroups of customers relative to their weight category, which is either "normal" or "overweight." Let us assume further that the distribution of weight categories in the population is 70/30. A rule $R\colon has\_monogram \rightarrow overweight$ is interesting if the number of shirts sold with a monogram is significant (say, 5 %) and the class distribution is quite different from the whole dataset (say, 40/60). From the business point-of-view, this means that overweight customers seem to have a preference for monograms.

Subgroup discovery algorithms can be classified into 3 groups [14]: algorithms based on classification such as EXPLORA, MIDOS, SubgroupMiner, SD, CN2-SD, and RSD; algorithms based on association, including APRIORI APRIORI-SD, SD4TS, SD-MAP, DpSubgroup, Merge-SD, and IMR; and evolutionary algorithms, such as SDIGA, MESDIF, and NMEEF-SD.

Quality measures are a key factor in knowledge extraction, as they quantify the interest of the results obtained. In subgroup discovery, the quality measures assess the importance and interest of the obtained subgroups. Various measures can be used for this purpose. However, as the concepts of importance and interest are hard to define objectively, there is no bibliographic consensus about which best suits subgroup discovery [5, 6]. In this study, we use *WRAcc*, which is the measure of unusualness that the algorithm used, CN2-SD, tries to optimize. This measure is described later in this paper.

## 2.1 Business Applications of Subgroup Discovery

In *marketing* the application of the EXPLORA algorithm was briefly mentioned by Kloesgen [15], being made an analysis of the financial German market using data from different German institutions. To study this problem, various preprocessing methods were necessary to obtain interesting subgroups. Gamberger [4] applied the SD algorithm for the market analysis of certain brands. Lavrac [5] also study other problems of *marketing* campaign with the algorithm CN2-SD. In both studies, the goal was to find potential customers for different brands in the market. This issue was also studied by Flach [16] using the algorithm CN2.

In a study related with road accidents, Kavsek [17, 18] presents comparisons between SubgroupMiner, CN2-SD, and APRIORI-SD algorithms. Zelezny [19] applied the RSD algorithm to a database containing information about the traffic of calls in an organization. A total of four different versions of the RSD algorithm with different combinations of quality measurement were used in this study. Other study [20] with the goal of minimizing problems due to voltage drops in power distribution applies the CN2-SD algorithm to discover interesting and unusual subgroups.

## 2.2 CN2-SD Algorithm

The CN2-SD algorithm is an adaptation of the CN2 algorithm [21, 22] for subgroup discovery. Therefore, we describe the latter algorithm first. The CN2 algorithm tries to induce classification rules [21, 22] in the form of "if *Cond* then $Class_{value}$" or otherwise "$Cond \rightarrow Class_{value}$," where the condition (*Cond*) refers to the attributes/variables with their values and $Class_{value}$ refers the value, category or class of the target variable. The main difference between classification and subgroup discovery, which motivates the differences between the algorithms for them, is essentially that in classification is a predictive task while subgroup discovery is a descriptive task. In classification a good model should be able to assign the correct class value to a new example. In subgroup discovery, the main goal is to find interesting patterns in the training data. For instance, if two rules with different conditions and the same consequent cover an example, then one of them is redundant. However, for subgroup discovery purposes, they may both be interesting as they may provide two different and equally interesting perspectives on the problem.

The implementation of CN2 consists of two tasks: a low level task, that makes a beam search in order to find a single rule, maximizing the accuracy on the training data; and a high level task that performs a control procedure, which repeatedly executes the low level task to induce a set of rules, until a satisfactory model, i.e., set of rules, is obtained.

The accuracy (*Acc*) of a rule is defined as the conditional probability of a value of the target variable given the rule or condition (*Cond*), which is described as follows:

$$Acc(Cond \rightarrow Class_{value}) \; = \; p(Class_{value}|Cond) = \frac{p(Class_{value}|Cond)}{p(Cond)} \quad (2)$$

In other words, it is the proportion of training examples that verify the condition *Cond* that are also labeled with class $Class_{value}$. To avoid the high level task from finding the same rule repeatedly, the examples that are covered by a rule, i.e., that verify the condition in that rule, are removed.

The two most important changes of the adaptation of CN2 for subgroup discovery referred to as CN2-SD, are: the use of WRAcc to assess the quality of the rules and the weighted coverage algorithm.

According to Wrobel [7], the Weighted Relative Accuracy heuristic (*WRAcc*) can be defined as:

$$WRAcc(Cond \rightarrow Class_{value}) = p(Cond).(p(Class_{value}|Cond) - p(Class_{value})) \quad (3)$$

This is used in CN2-SD to assess the quality of the rules instead of accuracy. It combines two components: the measure of the generality of the rule or relative size of a subgroup, given by $p(Cond)$; and the unusualness measure of the distribution or relative accuracy. The relative accuracy is given by the difference between the accuracy of the rule, $p(Class_{value}|Cond)$, and a priori probability of class $Class_{value}$, defined by $p(Class_{value})$. In practical terms, the aforementioned heuristic defines a rule as interesting if its relative accuracy improves relatively to the a priori probability of the corresponding class. Given the example above describing what an interesting subgroup is, *WRAcc* is clearly more useful for this task than accuracy.

The removal of the examples that are covered by each new rule in CN2 is not suitable for subgroup discovery for two reasons. Firstly, as explained earlier, an example may be part of several subgroups. Secondly, the rules extracted later in the learning process may not represent an interesting subgroup. In fact, they may cover examples that were removed earlier and, thus, the quality of the rule is incorrectly estimated. A solution to this problem is the weighted coverage algorithm Gamberger [13]. Instead of removing the examples covered by a rule, this algorithm reduces their weight. This ensures that these examples are still taken into account but it leads the algorithm to give more attention to yet uncovered examples by reducing their importance. In this sense the algorithm specifies two weighting schemes, which specifies a new weight for each example with the emergence of a new rule. We note that the use of the weighted coverage algorithm requires an adaptation of the *WRAcc* heuristic. For more details, the interested reader is referred to the paper by Lavrac et al. [23].

Two variations of the CN2-SD algorithm have been proposed. The first can only be used with binary target variables [23] while the other can deal with categorical target variables [24].

# 3 Case Study

## *3.1 Business Understanding*

The case study used to investigate the usefulness of subgroup discovery comes from a particular sub-sector of the textile industry. Bivolino is a manufacturer of custom-made shirts. The customers can access the Bivolino site or one of its affiliates and design a unique shirt by choosing each one of its many components from menus with a large number of alternatives. This makes the production and logistics processes of the company very complex. Consequently, it also raises complex challenges to the company, to achieve its aims of improving the profitability, efficiency, and productivity, while keeping up with the needs and trends of its customers, in order to satisfy them.

In the above context and in order to identify and be aware of trends in certain population groups, we analyzed a database with 8.056 customer orders. The primary aim is to obtain valid knowledge to enable a better targeting of *design* efforts and strategies of Bivolino. A secondary goal is to find if some knowledge that is useful for *marketing* can also be found.

An important market in fashion and, in particular, for Bivolino consists of obese customers. The number of obese people in Europe has increased significantly in the last few years. However, many traditional brands have still not adapted to cater for these customers. Therefore, many obese customers prefer to buy their clothes online if they trust the company to provide them with clothes that fit well. Bivolino has successfully developed a system that ensures this and has, therefore, gained a significant market share in that segment.

The results will be evaluated according to several measures: size of the subgroups, deviation of the distribution of the subgroups relatively to full dataset. Additionally, a more subjective analysis will be made to evaluate the usefulness of the rules to support the *design* and *marketing* processes of the company. These criteria will assess the ability of those rules to provide new knowledge that is not trivial or obvious.

## *3.2 Data Understanding and Data Preparation*

Each example in the data corresponds to one transaction, described by 18 variables. Some of these measures characterize the customer, namely body mass index (BMI), age, collar size, weight, height. Other measures characterize the shirt, including collection, fabric, fit, collar, cuff, placket, pocket, white collar, white cuff, hem, and back yoke contrast. Finally, two variables characterize transactions, namely their country and the affiliate. An important market for Bivolino consists of obese customers. Therefore, the BMI variable was selected as the target variable.

Given that the CN2-SD algorithm expects either binary or categorical variables, it is necessary to transform continuous variables into categorical variables. Therefore, we performed a discretization following the categories defined by Bivolino.

Before applying the subgroup discovery algorithm, we carried out an exploratory analysis on the data, to gain a better understanding of its characteristics. For example, we observed that 96.6 % of the 8,056 orders belong to a group of five countries. In this sense, and because the point of view of *design* intend groups with good level of expression, we focused on these countries, namely Belgium, Germany, France, Netherlands, and the United Kingdom.

We also analyzed the orders in terms of gender and presence of promotional vouchers. Given that women make only 9.6 % of the orders and 80 % of these are made using promotional coupons, we decided to focus on male customers only. The reduced significance of women in Bivolino's business is due to it has only very recently started to produce woman shirts. The resulting database contains 7.066 orders.

## 4 Results

We used Rapid Miner's implementation of the CN2-SD algorithm. The model obtained consisted of 54 rules. Each of the obtained rules obtained describe a population subgroup whose distribution differs from the complete population distribution. To assess the unusualness of a rule, we calculated the percentual difference between the proportion of examples in the subgroup that belonged to the class in the consequent of that rule and in all the orders.

Additionally, to better interpret and evaluate the results in terms of usefulness for the *design* of new products, we proceeded with the interpretation and analysis of the subgroups found, classifying these subgroups according to the next criteria:

1. Uninteresting subgroups verify one of the following conditions:
    - Obvious subgroup from the standpoint of common sense;
    - Subgroup whose distribution has a small deviation in relation to the total distribution of orders;
    - Small subgroup, representing less than 0.5 % of the total of orders;
2. Interesting subgroup for marketing since provides useful information in this area, namely about the country, affiliate, and configurator where orders are made. This type of information is less interesting to the *design* because it contains no new information about the characteristics of the ordered shirts;
3. Interesting subgroups for design verify one of the following conditions:
    - Numerous subgroup, representing at least 30 % of the total orders);
    - Subgroup representing at least 5 % of the total orders, and presents relevant percentage deviations (high deviations) relative to the total distribution of orders.

**Table 1** Some rules obtained using the CN2-SD operator in RapidMiner

| Model (by CN2-SD algorithm) | Uninteresting subgroup | Interesting subgroup for *marketing* | Interesting subgroup for *design* |
|---|---|---|---|
| 1. if Country = uk then Obese | | Yes | |
| 2. if Fit = Regular then Obese | Obvious | | |
| 4. if Fit = Regular and Collar white = n and Cuff white = n then Normal weight | | | Population > 50 % |
| 7. if Affiliate = Retailer 1 and Cuff white = n and Country = uk then Morbidly Obese | | Yes | |
| 8. if Back Yoke contrast = y and Collar size = < 36 then Obese | | | Population > 43 % |
| 9. if Cuff = Round Single and Collar white = n and Cuff white = n then Overweight | Deviation < \|15 %\| | | |
| 14. if Hem = Curved Hem and Fabric = FabricID12186 then Obese | | | Population > 30 % |
| 15. if Age = 35/44 then Overweight | | Yes | |
| 21. if Placket = Real front and Affiliate = Bivolino then Obese | | Yes | |
| 22. if Weight = 45-75 then Overweight | Obvious | | |
| 23. if Fit = Super Slim Fit then Normal weight | Obvious | | |
| 33. if Fit = Regular and Weight = 95-115 and Collar white = n and Cuff white = n then Normal weight | | | Population > 10 %, Deviation > \|55 %\| |
| 36. if Weight = 115-135 then Morbidly Obese | Obvious | | |
| 39. if Hem = Straight Hem and Fit = Comfort fit and Collar white = n then Overweight Deviation > \|242 %\| | | | Population > 5 %, |
| 40. if collar = Italian Semi-Spread and Affiliate = Bivolino and Pocket = No Pocket and Collar white = n and Cuff white = n then Obese | | | Population > 5 %, Deviation < \|98 %\| |
| 46. if Height cm = 200/210 and Weight = 115-135 and Collar white = n then Overweight | Population < 0,5 % | | |
| 47. if collar = Classic Point and Heightcm = 190/200 and Pocket = Mitred and Weight = 115-135 and Placket = Real front and Cuff white = n then Overweight | Population < 0,5 % | | |
| 49. if Heightcm = 160/170 and Weight = 75-95 and Placket = Folded and Hem = Curved Hem then Obese | Population < 0,5 % | | |
| else Normal weight | | | |

Table 1 shows some of the rules of the model obtained with the CN2-SD algorithm, when applied to 7.066 orders characterized by 19 variables where the target variable is the BMI variable.

Although the rules found describe unusual distributions, as would be expected, not all provide interesting and useful knowledge. Some rules represent obvious subgroups, as is the example of a subgroup of individuals who are overweight that choose the regular fit shirts (rule 2); or the subgroup in which the shirts are of type Super Slim Fit, tend to be bought by customers with normal weight (rule 23).

However, there is also important knowledge for marketing, such as a subgroup which suggests that the United Kingdom population tends to be more obese (rule 1); additionally, if UK customers make their purchases at Retailer 1, then they tend to be morbidly obese (rule 7); or customers whose age stands between 35 and 44 years old tend to have overweight.

Finally some rules provide very interesting knowledge to the design of new products: the subgroup of individuals with collar size less than 36 cm and that choose back yoke contrast tend to be obese (rule 8). This is therefore a very specific and interesting subgroup enjoying the contrast of the same line. Another interesting subgroup chooses curved hems with a particular fabric, FabricID12186 (rule 14). This group of customers tends to be obese. In this sense, perhaps this is the subgroup of greatest interest to the design due to its size, deviations, and detail of the presented information.

## 5 Conclusions

The present study investigates the use of subgroup discovery algorithms to obtain models that suitable for supporting the design processes in the textile industry, in particular for companies producing highly-customizable garments. Additionally, the use of the same models for marketing purposes was also studied.

The aim is to find subgroups that present unusual choices and unusual characteristics in the orders made and that differentiate them from the global distribution of orders. In practical terms, we aimed to find subgroups whose distribution around the target variable Body mass index (BMI) significantly differs from the distribution in which all orders are considered. The models were obtained with the CN2-SD implementation in Rapid Miner on data provided by Bivolino, a company that manufactures customized shirts.

The results clearly show the usefulness of subgroup discovery to support design in the textile industry. Although not the main objective of this study, the results also illustrate the possibility of using the same approach to obtain useful knowledge for marketing.

This study also demonstrates the importance of carefully perform two steps from the knowledge extraction process when using databases. These steps are data preparation and the evaluation of results.

In terms of further work, we present three suggestions. The first is to further explore this case study with other parameters of the CN2-SD algorithm. The second is to apply other subgroup discovery algorithms. Finally, we aim to validate the obtained results with the designers of Bivolino.

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## References

1. Thomassey S (2010) Sales forecasts in clothing industry: The key success factor of the supply chain management. Int J Prod Econ 128:470–483
2. Delmater R, Hancok M (2001) Data mining explained: a manager's guide to customer-centric business intelligence. Digital Press
3. Fayyad U, Piatetsky-Shapiro G, Smyth P (1996) data mining to knowledge discovery in databases. Am Assoc Artif Intell: AI Mag 17(3):37–51
4. Gamberger D, Lavrac N (2002) Generating actionable knowledge by expert-guided subgroup discovery. In: Proceedings of the 6th European conference on principles and practice of knowledge discovery in Databases, vol 2431, pp 163–174
5. Lavrac N, Cestnik B, Gamberger D, Flach P (2004) Decision support through subgroup discovery: three case studies and the lessons learned. Mach Learn 57(1–2):115–143
6. Kloesgen W (1996) Explora: a multipattern and multistrategy discovery assistant. Advances in knowledge discovery and data mining. American Association for Artificial Intelligence, pp 249–271
7. Wrobel S (1997) An algorithm for multi-relational discovery of subgroups. In: Proceedings of the 1st European symposium on principles of Data Mining and knowledge discovery, vol 1263, pp 78–87
8. Trajkovski I, Zelezny F, Tolar J, Lavrac N (2006) Relational descriptive analysis of gene expression Data. In: Proceedings of the 3rd starting artificial intelligence researchers, pp 184–195
9. Trajkovski I, Zelezny F, Tolar J, Lavrac N (2008) Learning relational descriptions of differentially expressed gene groups. IEEE Trans Syst Man Cybern B Cybern 38(1):16–25
10. Zelezny F, Tolar J, Lavrac N, Stepankova O (2005) Relational subgroup discovery for gene expression data mining. In: Proceedings of the 3rd European medical and biological engineering conference
11. Wrobel S (2001) Relational data mining. Springer, Berlin
12. Lavrac N (2005) Subgroup discovery techniques and applications. In: Proceedings of the 9th Pacific-Asia conference on knowledge discovery and Data Mining, vol 3518, pp 2–14
13. Gamberger D, Lavrac N (2002) Expert-guided subgroup discovery: methodology and application. J Artif Intell 17:501–527
14. Herrera F, Carmona CJ, González P, del Jesus MJ (2011) An overview on subgroup discovery: foundations and applications. Knowl Inf Syst 29(3):495–525
15. Kloesgen W (1999) Applications and research problems of subgroup mining. In: Proceedings of the 11th international symposium on foundations of intelligent systems, pp 1–15
16. Flach P, Gamberger D (2001) Subgroup evaluation and decision support for a direct mailing marketing problem. In: Proceedings of the 12th European conference on machine learning

and 5th European conference on principles and practice of knowledge discovery in Databases, pp 45–56
17. Kavsek B, Lavrac N (2004) Analysis of example weighting in subgroup discovery by comparison of three algorithms on a real-life Data set. In: Proceedings of the 15th European conference on machine learning and 8th European conference on principles and practice of knowledge discovery in Databases, pp 64–76
18. Kavsek B, Lavrac N (2004) Using subgroup discovery to analyze the UK traffic Data. Metodoloski Zvezki 1(1):249–264
19. Zelezny F, Lavrac N, Dzeroski S (2003) Constraint-based relational subgroup discovery. In: Proceedings of the 2nd workshop on multi-relational Data Mining, pp 135–150
20. Barrera V, López B, Meléndez J, Sánchez J (2008) Voltage sag source location from extracted rules using subgroup discovery. Front Artif Intell Appl 184:225–235
21. Clark P, Boswell R, (1991) Rule induction with CN2: some recent improvements. In: Proceedings of the fifth European working session on learning pp 151–163, Springer
22. Clark P, Niblett T (1989) The CN2 induction algorithm. Mach Learn 3(4):261–283
23. Lavrac N, Kansek B, Flach D, Todorovski L (2004) Subgroup Discovery with CN2-SD. J Mach Learn Res 5:153–188
24. Lavrac N, Flach P, Kavsek B, and Todorovski L (2002) Adapting classification rule induction to subgroup discovery. In: Proceedings of the second IEEE international conference on data mining, vol 3518, pp 266–273

# Statistical Process Control Methods as an Essential Tool for Modeling and Improvement of Diagnostic Processes

**Martina Winkelhoferova, Veronika Marikova and Jiri Tupa**

**Abstract** The paper deals with modeling and improvement of diagnostic processes. The aim is to develop a new methodology which could be used as a tool for modeling and improvement of diagnostic processes. This paper is firstly focused on evaluation of SPC methods and their possible usage for modeling, measurement, controlling, and following improvement of diagnostic processes. Seven basic methods were evaluated according to few basic criteria which are important in the field of diagnostics. The Ishikawa diagram was chosen as one of the suitable tool and was used for setting of Key Performance Indicators. Then, the results were applied on specific diagnostic process and their behavior was analyzed and evaluated. The research was mainly focused on time and quality measurement because they play very important role in the final product evaluation and tell us which parts has to be optimized.

## 1 Introduction

Enterprises in electronics manufacturing have to use diagnostics systems for preventive and maintenance management. The diagnostics system is an important tool for management set correction and improvement processes. Diagnostics management covers planning, realization, execution, and improvement of diagnostics processes. The objective of diagnostics process management is to achieve as well as guarantee quality assurance [1].

Recent research has methodologies for application of the process management in manufacturing, information, and administrative processes. Most of the scientists were focused on modeling of process and quality process management in these

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fields. For example, Pengelly et al. [2] solved the question of quality planning. They said that the critical point in quality process management is planning. They developed a frame for quality measurement which is based on process modeling and applied on administrative process.

Aversano et al. [3] also worked on quality measurement for administrative processes. They set up a model which is based on Goal Quality Management which is focused on process analysis.

Other scientists Pidun and Felden [4] prepared the process analysis focused on setting of KPI's. They summarized different methods for process measurement and then set the KPI's. The aim of their work was to create an overview of methods for process analysis and then specify it for measurement.

There are as well many different methods for modeling of processes. For example, Heavey and Ryan [5] summarized modeling methods in their article. According to their survey, there are a large number of these methods and each has its advantages and disadvantages. According to their conclusion there is no method that would be itself sufficient for complete process support and process modeling in enterprise. They focused their research on administrative processes.

According to the research there are many authors who worked with processes and their measurement. But they are focused on administrative processes.

There is no evidence in the literature of a suitable process management tool for diagnostic purposes in the product/process life cycle which would be focused on diagnostic process modeling and measurement [6, 7]. There is a need to design a methodology for process diagnostics management. From many reasons is essential and useful to measure, control, and optimize processes also in this field.

The aim of this paper is to find a suitable process management tool which would be useful for modeling and measurement and following improvement of diagnostic processes. If we want to improve processes, we have to be able to model and measure them. So, this paper mainly covers the measurement of the processes. Measurement shows to us narrow points of the process—it means parts which have to be improved. It is the reason why it is necessary to be firstly focused on modeling and measurement of diagnostic processes because without these two steps we are not able to improve them because we do not know what to improve.

We decided to use Statistical Process Control methods [7, 8]. Statistical Process Control is connected to Statistical Quality Control. Statistical Quality Control includes seven basic tools—tables, flow charts, Ishikawa diagram, histograms, regulation diagrams, scatter diagrams, and Paret analysis. Statistical Process Control uses regulation diagrams as a basic tool to ensure stability of the process [6–8]. So, firstly we decided to make an analysis of these seven basic tools to see if these methods could be helpful in improvement of diagnostic processes.

If these methods could be useful for working with diagnostic process, it could bring many benefits as better understanding of processes, better transparency, faster work with processes, and many others.

So, this paper is mainly focused on analysis of seven basic tools and their possible usage for working with diagnostic process.

At first, KPI’s have to be set, criteria for analysis have to be determined and analysis has to be done. Then the results will be verified on specific process.

## 2 Diagnostic Processes and Setting of Their KPI’s

The diagnostic process is a planned sequence of activities that make possible to identify the structure or behavior of the object by using information, knowledge, financial, human, and material resources in accordance with customer requirements [2].

The diagnostic processes are different from manufacturing and administration processes. One difference is usage of output of one diagnostic process as an input for other diagnostic process. These outputs can be measured data or obtained knowledge or experience. For the other difference can be considered that the mentioned data, knowledge/experience, and information are the integral part of this process. The knowledge and experience are ignored in conventional processes because they do not play such important role as in the diagnostic processes. In the field of research and development these processes are more complicated, therefore knowledge and experience are so important and significant [2].

The diagnostic processes occur in the whole life cycle of the product—from the research and development to the liquidation. Therefore, it increases their importance and also the effort to their control and following optimization. This importance is rising mainly thanks to the research and development of new technologies, the high emphasis which is put on knowledge, experience, reliability, accuracy, and safety.

The aim of many companies and institutions is to be able control the processes. The controlling of the processes is possible only when we are able to model and measure them. Modeling is an essential method for visualization of processes and plays a very important role. It is important to know how processes run, how they work, and know some basic metrics.

Each diagnostic process involves four main steps—specification of what have to diagnose, preparation of measurement, own measurement, and evaluation of measurement. Also, setting of key performance indicators (KPI) is very important for process performance measurement and improvement.

Key performance indicators, in practical terms and for strategic development, are objectives to be targeted that will add the most value to the business. These are also referred to as key success indicators [2].

At first it is necessary to set general KPI’s for diagnostic process. These KPI’s then help us to see what is important in diagnostic processes and what has to be measured and improved. Next the criteria for analysis have to be determined and evaluated.

**General KPI's for Diagnostic Processes**

1. Knowledge and experience of research workers
2. Transparency of the process
3. Time measurement of the process
4. Quality measurement of the process
5. Costs measurement of the process.

These KPI's are important for diagnostic process. If we ignore some of these indicators, the process would not be measurable or it would not be possible to work with the process.

The KPI's which are connected to time, quality, and costs measurements have to be specified for different fields of diagnostics measurement. For example, in electronics these KPI's have be little bit different from KPI's in partial discharge activity. So, it is necessary to specify in detail KPI's for different processes. The KPI's mentioned above are general KPI's for all diagnostic processes.

## 3 Analysis of the Methods

As I mentioned above, there is seven basic tools for statistical quality control which were analyzed according to criteria which are important for work with processes. Then the individual methods were evaluated.
**These Criteria are:**

a. Suitability for KPI's evaluation
b. Requirements for knowledge and experience of workers
c. Does it make possible to better understanding of processes?
d. Is it possible to use it for modeling or measurement and following improvement of processes?
e. Simplicity of processing and evaluation
f. Speed of evaluation
g. Representation of results.

The analysis said to us that there is a possibility of using SPC methods for modeling and measurement of diagnostic processes. It is obvious from this analysis, that the flow charts, Ishikawa diagram, and histograms are the most suitable for us.

Tables or database are complicated for processing of data because if there are much data, they are little bit confused. They cannot be used for measurement as well as flow charts. Tables or database can be useful for data collection or representation of results.

The flow charts are very useful for illustration of process flow and for preparation of process analysis. Flow charts will be used for design of methodology for modeling of diagnostic process. They cannot be used for measuring of diagnostic processes because there is no possibility of measurement. But it is necessary to mention that they can be very useful as layout for measurement.

The Ishikawa diagram was evaluated as a good tool for setting of KPI's for measuring of diagnostic processes and for avoiding of forgotten steps and risks of the process. The diagram is well understandable and readable and the requirements for knowledge are not as high. This tool can help us to see which steps are important in the process in the connection to specific measurement of the process, what has to be carried out and which risks can influence the process.

The histograms are good tool for working with diagnostic processes according to analysis showed above. The histograms represent exact results, they are quickly evaluated and there are no high requirements for knowledge. They show narrow points of the process.

Paret analysis could be useful for searching and replacing mistakes but it is also knowledge-intensive and time consuming. But the results are well readable from Paret analysis.

Regulation diagrams can be helpful in identifying if the process is in a level which we need and with the help of this tool, the process can be stabilized. But it is necessary to have some knowledge about this tool—it means that work with it can be more complicated. On the other hand, it can provide us nice representation and well understandable results.

Scatter diagrams could be helpful as well in identifying if the process is in a level which we need but there are great demands on knowledge of workers and work with them is longer and more complicated.

## 4 Design of Methodology

According to the analysis results the methodology for modeling and improvement of diagnostic processes were proposed.

The methodology was designed in following steps:

1. **KPI's setting**—KPI's for specific diagnostic process has to be set
2. **Using of Statistical Quality Control Methods and Statistical Process Control Methods**—Flow charts, Ishikawa diagram, and histograms are the most suitable for us on the base of the analysis which was done. This analysis is presented in Table 1. As well the SPC method—Regulation diagrams—was found out as a good tool for improvement of diagnostic processes.
3. **Verification of results**
    a. Modeling of diagnostic processes—flow charts were evaluated as one of the possible tool for modeling of diagnostic process. They help us to see individual steps of the process and make the process more transparent and understandable.

**Table 1** SQC methods analysis

| SQC methods | a. | b. | c. | d. | e. | f. | g. |
|---|---|---|---|---|---|---|---|
| Tables/database | √ | √ | √ | X | X | X | √ |
| Flow charts | √ | √ | √ | √ | √ | √ | √ |
| Ishikawa diagram | √ | √ | √ | √ | √ | √ | √ |
| Histograms | √ | √ | √ | √ | √ | √ | √ |
| Paret analysis | √ | X | √ | √ | X | X | √ |
| Regulation diagram | √ | √ | √ | √ | X | √ | √ |
| Scatter diagram | √ | X | √ | √ | X | X | √ |

b. Measurement of diagnostic processes—Ishikawa diagram was found out as a good tool for determination of critical steps in the process in connection with measurement of process—for time measurement.
c. Improvement of diagnostic processes—Histograms help us to see narrow points of the process and tell us what has to be improved. Here, it is time to use as well SPC method—Regulation diagrams to define why the process is variable and try to stabilize it.

## 5 Case Study

The designed methodology was applied on the diagnostic process—partial discharge activity. In this case, we used SPC methods for specification of steps in this process, modeling and following measurement and improvement.

At first, we had to set KPI's for our measurement. We set time as one of the key indicator for diagnostic processes. We divided time into three main parts—time of measurement preparation, time of measurement, and time of measurement evaluation.

Then, flow chart was used for representation of individual steps of the process which help us to see sequence of activities and how the process runs. Part of the process of partial discharge measurement is shown in Fig. 1. For preparation of flow charts it is necessary to know some basic analysis techniques.

Then, the Ishikawa was prepared. We used Ishikawa diagram for determination of KPI's focused on time. With the help of this tool, it is possible to see parts of process which can influence running time of the whole process which is critical for final product quality and costs. It is necessary to find optimal time of duration of these processes because it has an influence to quality and costs as well. Ishikawa diagram is shown in Fig. 2.

The Ishikawa tool represents detailed steps of the process which can influence the running time of whole process. There are figured all activities which have an impact on the time and then of course as well on quality and costs.

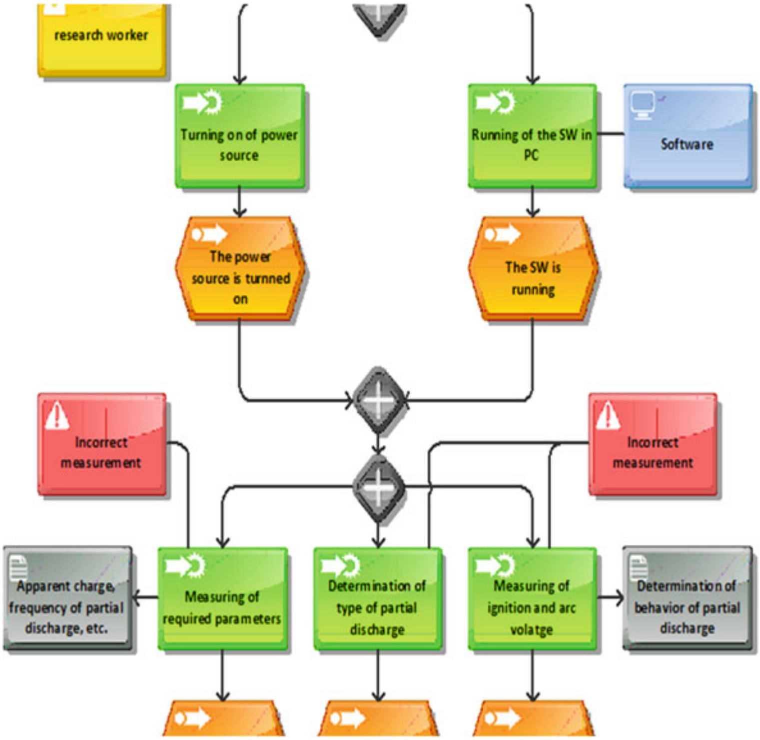


**Fig. 1** Part of partial discharge process

If this time is very short, it would have significant impact on quality. The cost would be reduces but the quality would be poor. On the other hand, if this time is very long, the costs would be higher and there is a question, if the quality is better or not. It is suitable to find optimal time—the shortest possible—in which the quality will be hold on high level and the costs will be the lowest.

Based on the Ishikawa diagram we studied this process and we watched the problems which can occur. With the help of experienced research worker we set the most common problems. We analyzed ten measurements and we measured the most common problems. According to this measurement, we counted the percentage of the influence on the whole process. This was established in connection with time—influence on the duration of the process. It is presented in the Table 2.

Here, we can see how knowledge and experience are important in the diagnostic processes because the non-experienced worker could not provide this process.

From the Ishikawa, the percentages of possible delays of the process were counted, put in the table and the histogram was prepared. According to this statement, we found out which part of the process is critical for us and which part has to be optimized and improved.

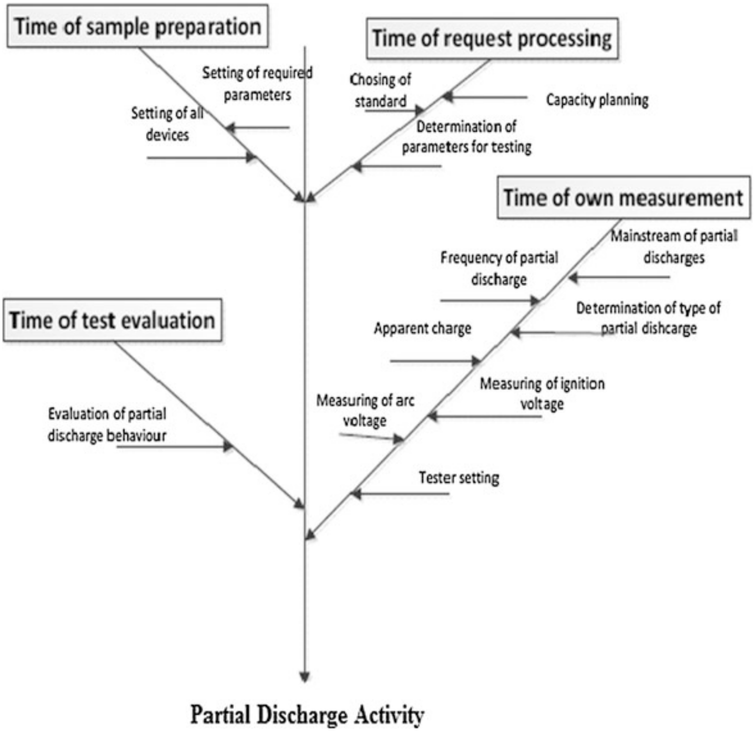


**Fig. 2** Ishikawa diagram

**Table 2** Problems which occur in this process and their influence on duration of the process

| | The most common problems | Influence on duration of the whole process in % |
|---|---|---|
| Time of request processing | • Inaccurate specification from customer—additional communication<br>• Inexperienced worker<br>• Lack of workers<br>• Incorrect specification of test parameters—repeated specification<br>• Late delivery of samples | 45 |
| Time of sample preparation | • Complexity of preparation<br>• Inexperienced worker—slow work<br>• Incorrect setting of one/all devices<br>• Incorrect setting of required parameters (voltage,…) | 40 |
| Time of test setting and testing | • Failure of measurement device or software<br>• Inexperienced worker—incorrect test setting | 5 |
| Time of test evaluation | • Incorrect evaluation of partial discharge behavior—inexperienced worker | 10 |

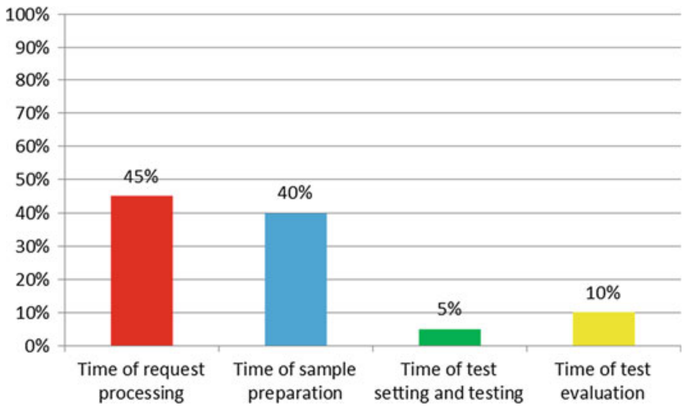


**Fig. 3** Possible delay of the process in % according to frequency of problems occurrence

The histogram is shown in Fig. 3 and represents the influence of individual parts of this process on the duration of the process.

The graph displays the possible delay of this process in % according to amount of the possible delays—according to frequency of problems occurrence.

From the histogram is obvious those time requests processing and time of sample preparation are the most important part for us because there are many things which can delay the whole process.

From this point of view, we can see that knowledge and experience are critical mainly during these two parts but they are very important for good running of the whole process because a research worker has to know how chose the correct standard, specify the parameters for testing and mainly how to set all devices. For this reason, these two parts are very important and incorrect preparation would have an impact on quality, costs, and as well on delay of the whole process.

We made as well the test how the process will be delayed if the process is done by inexperienced worker. The results were such as we expected—experienced workers were faster and more reliable than inexperienced workers. The test was carried out with three experienced and three inexperienced workers. Experienced workers worked calm, reliably and the process ran well—devices were set immediately, the results were well evaluated. Inexperienced workers were very nervous, worked slowly, and made mistakes—for example two from three inexperienced workers had to set devices three times and it caused big delay of the process. So, from this small test is evident that experienced workers are here, in the field of diagnostics, more important than in other fields, for example more than in administrative field.

From this case study is evident that tools mentioned above are helpful during process analysis, setting of the KPI's and finding narrow points of the process. It is also obvious that KPI parameters can be influenced by many causes. So, now we want to focus our research on statistical process control of KPI's. It means to evaluate changes which influence KPI's and the whole process. We can achieve it by using Regulation diagrams and trying to eliminate causes which influence it.

## 6 Conclusion

The methodology for modeling and improvement of diagnostic processes was designed and verified on specific process. It is possible to see from the results that statistical quality control methods are useful and helpful for modeling, measuring, and improvement of diagnostic processes. We verified that flow charts are good for modeling of diagnostic processes because they make these processes more transparent and better understandable.

Then, Ishikawa diagram is very useful for setting of KPI's for time measurement which is closely connected as well with quality. The big impact on quality and time as well, has knowledge and experience of workers. We can say that they are critical for achieving of required quality, so it is necessary to keep in mind that knowledge and experience of workers are one of the most significant things which have to be ensured in field of diagnostics.

At last, histograms showed to us narrow points of the process which means, parts that have to be improved. Thanks to this we can focus on these critical parts and try to improve them. There are some possibilities how to shorter the time and ensure the required quality of the final product.

The last step is to ensure the continuous improvement of diagnostic processes. To achieve it, it is necessary to permanently monitor the behavior of the process and try to stabilize it.

The further research will be dedicated to finding all causes which can influence diagnostic processes and by using regulation diagrams try to stabilize them.

Then we would like to focus on extension of proposed methodology for more measurements and mainly we would like to focus our work for developing of method or technique to ensure knowledge and experience of workers. We would like to prepare some useful tool because, as is evident from this paper, knowledge and experience are very important in diagnostic processes.

In addition, we found out that this process is repeatable and so can be standardized. This methodology can be used for modeling, measurement, and improvement of this process and will be applied on other processes to find out if it is applicable for other type of processes.

This research showed to us that using of these methods for working with diagnostic process can safe time, costs, and ensure the quality of results because the problems and inaccuracies can be disclosed early. And nowadays it is put a big emphasis on quality and reliability of used machines and technologies. So, controlling and improvement of processes, not only in diagnostics, become very important.

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## References


1. Taiichi O (1998) Toyota production system: beyond large-scale production. Productivity Press
2. Pengelly A, Norris M, Higham R (1993) Software process modeling and measurement: AQMS case study, vol 35, No 6/7. Butterworth-heinemann Ltd. ISSN 0950- 849/93/060375-06
3. Aversano L, Bodhuin T, Canfora G, Tortorella M (2004) A framework for measuring business processes based on GQM. In: Proceedings of the 37th Hawaii international conference on system sciences. ISSN 0-7695-2056-1/04
4. Pidun T, Felden C (2010) An overview of models of business process analysis: be tone performance measurement with KPIs. In: 14th international enterprise distributed object computing conference workshops. ISSN 978-0-7695-4164- 8/10. doi:10.1109/EDOCW.2010.48
5. Heavey C, Ryan J (2006) Process modeling support for the conceptual modeling phase of a simulation project. In: Proceedings of the 2006 winter simulation conference. ISSN 1-4244-0501-7/06
6. Winkelhöferová M (2011) Measuring and evaluating of diagnostic processes. Written work for the state doctoral examination. University of West Bohemia, Pilsen
7. Griffith G (1996) Statistical process control methods for long and short runs, 2nd edn. ASQC Quality Press, USA. ISBN 0-87389-345-X
8. Does RJMM, Roes KCB, Trip A (1999) Statistical process control in industry, implementation and assurance of SPC. Kluwer Academic Publisher, The Netherlands. ISBN 0-7923-5570-9

# Rough Cut Machining for Impellers with 3-Axis and 5-Axis NC Machines

**Dong-Won Kim, M. A. Suhaimi, Byung-Mun Kim, Min-Ho Cho and F. Frank Chen**

**Abstract** In recent times, impeller machining has posed a new challenge to engineers due to demand from aerospace, automobiles, and ship building industries. Various methods are introduced by researchers in machining impellers by using 5-axis milling machine; this is because the 5-axis method has the flexibility of tool orientation to machine the extremely twisted surfaces between the blades of impellers. When impellers are machined by a 5-axis machine, the time consumed is very long and the process creates a bottleneck in the manufacturing line. The problem causes increase in the manufacturing lead time and manufacturing cost. To overcome the problem, this paper introduces a new method of machining impellers by integrating 3-axis and 5-axis machine. This paper opens up a new field in impeller machining with the aim to reduce rough-cut time. The results show that by applying this strategy, total machining time of an impeller can be reduced significantly up to 17 %.

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## 1 Introduction

Impellers are widely used in the areas of aerospace, automobiles and ships' component parts. Machining an impeller is the most complicated process because it consists of blades with twisted ruled surfaces. In order to perform machining operations, a 5-axis machine is selected due to its flexibility in tool orientation to machine the extremely twisted surfaces between the blades of an impeller [1–3]. Unlike conventional 3-axis machining, serious tool collisions can occur while machining an impeller blade because the tool direction of machine is fixed to the z-axis and cannot be changed freely to avoid collisions.

Thus, researchers took advantage of the flexibility and capability of 5-axis machines. In recent times, several papers have been reported by applying 5-axis machining strategy for machining impellers with aims to improve the machining time. So et al. [4] tried to optimize impeller NC data for 5-axis machining through step length adjustment, and Quan et al. [5] developed a software in order to generate cutting tool-paths based on the rules surface of impeller blades.

However, both machining systems, either 3-axis or 5-axis machine, have their own pros and cons. Although 5-axis machine offers flexibility and capability of avoiding tool collisions, the time required to produce a single product is still very long [6, 7]. Such time lag decreases the productivity and can cause bottlenecks in the manufacturing streams. The main objective of this study is to improve machining time by dividing roughing machining process into two different machining processes with the use of a 3-axis machine and a 5-axis machine, respectively.

For this purpose, two types of tool-path strategies will be generated accordingly; 3-axis and 5-axis. Both machining strategies approach will be conducted in the same 5-axis machine and the total roughing machining time will be recorded. Then, the total machining time is compared with the time taken by using a full 5-axis machine alone; rough machining the impeller with fully 5-axis function. Two types of impellers are used for the purpose of comparing the total machining time, the details of which are discussed in this paper.

## 2 The Features of an Impeller

Figure 1 shows two different types of typical centrifugal impellers, which are splitter type and non-splitter type. The main difference between these two impellers is the design of impeller blades. The non-splitter type impeller has identical design for all blades; the splitter type impeller has splitter blades of different design alternating with main blades. Despite the difference in design, the main parts and the main functions of the impeller remain the same. A typical impeller comprises 16 identical twisted ruled blades and a hub. The geometrical model of blades consists of suction surface, pressure surface, leading edge, and trailing edge. The outer boundary of a blade is known as shroud surface, as shown in detail in Fig. 1.

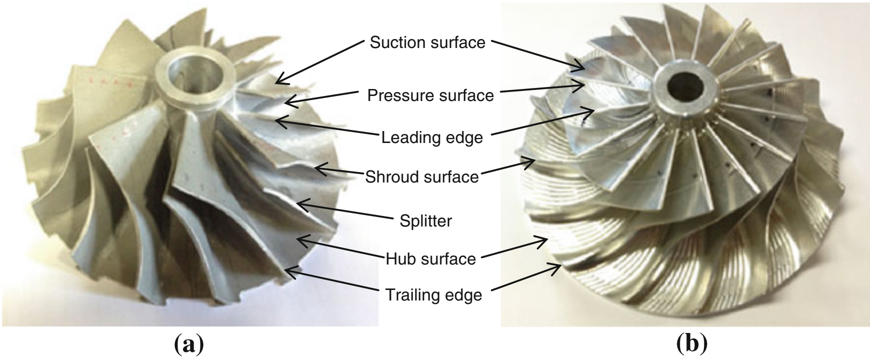


**Fig. 1** Types of a typical centrifugal impeller. **a** Splitter type. **b** Non-splitter type

There are a few studies related to machining of centrifugal impellers. Young et al. [2] focused on generating CL data based on the geometry model of blades and hub of impeller; his aim was to reduce the roughing machining time by using only five-axis CNC machine. Qi et al. [1] also focused on the rough machining of an impeller by dividing the space between blades in generating the CC points that could eliminate global interference between the tool and the blades. Heo et al. [7] studied the roughing strategies of an impeller by dividing the machining area into several regions based on shroud and hub surfaces. They proposed a 3-axis tool path generation method to generate CL data for rough machining.

However, existing researches did not account for integrating different types of machining strategies such as 3-axis and 5-axis machining together for a roughing process. From this aspect, this paper opens up a new field in impeller machining, which improves machining time.

## 3 Process Planning for Roughing Strategies

Roughing is the most important process in machining any kind of material which removes the major part of the stock material to form a semi-finished product. In order to improve machining time, material should be removed as much as possible. It is a very important phase as it affects the accuracy of machining an impeller in the finishing process. In order to improve machining time, this study applies a different method of machining strategies, which divides roughing strategies by using 3-axis and 5-axis approach.

In this approach, all roughing processes are done in a single 5-axis machine. The main idea of dividing the roughing process into 3-axis and 5-axis method is based on the following procedure. In the first step of roughing, the table of the 5-axis machine is fixed and the impeller is machined only by using 3-axis machining strategy, the tool-paths for the 3-axis machining strategy is shown in Fig. 2.

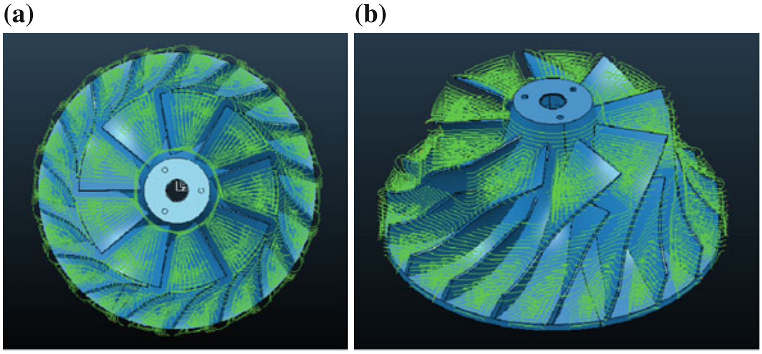

Fig. 2 3-axis roughing process. a Top view. b Isometric view

After the first stage of roughing process is completed, the second stage of roughing process starts by using full 5-axis machining to remove the rest of the uncut material between the blades. This process will take shorter time because the amount of uncut materials left is smaller.

## 4 Machining Simulation and Verification

Figure 3 shows the stock for the impeller machining, which was prepared from turning process with 45 mm inner radius, 175 mm outer radius, and 190 mm in height. The impeller design as shown in Fig. 2 has a total of 18 blades including 9 splitter blades. The angle between two blades is 40°. The cutter is a ball-mill with a diameter of 16 mm and a shank length of 80 mm. The selected step-over tool path is 5 mm, the cutting depth is 5 mm, and the machining allowance is 3 mm for 3-axis (first stage) and 1 mm for 5-axis (second stage). The following machining simulation is carried out by the software package PowerMILL Pro 2012 [8]. The rough machining output of the 3-axis machining simulation is shown in Fig. 4. The cutting simulation continues with the 5-axis roughing stage (second stage) shown in Fig. 5.

Based on the simulation results, the total machining time taken is compared with the machining time of roughing strategy by using full 5-axis machining mode. Table 1 shows the comparison between the total machining time, total tool-path length, total weight, and amount of material removed.

As shown by the simulation results, the machining time of two-stage roughing strategy is 17 % less than that of 5-axis only roughing strategy. This time usage comparison is based on the removal of the same weight of material from the stock of a splitter type impeller. The results shown are based on removing 50 % of weight volume between the blades for the splitter type impeller.

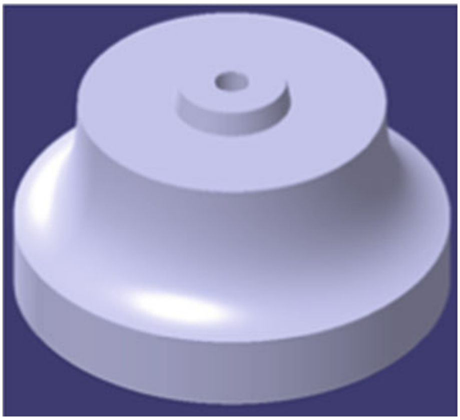

**Fig. 3** Stock design

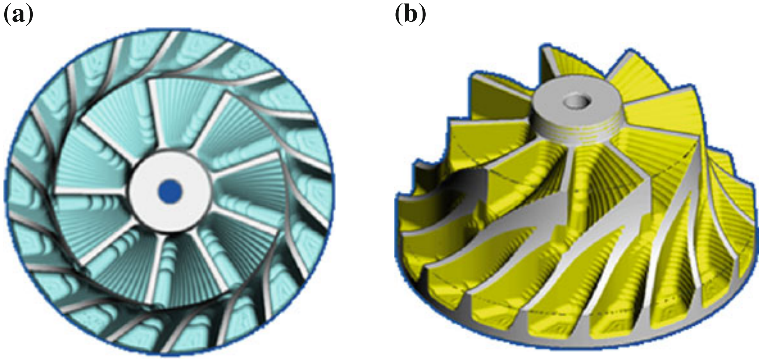


**Fig. 4** 3-axis rough machining (*first stage*). **a** Top view. **b** Isometric view

## *4.1 Verification of the Simulation Results*

To verify the simulation results, a non-splitter type impeller is simulated with the same two roughing strategies: two-stage roughing strategy and 5-axis only roughing strategy. Figure 6 shows the non-splitter type impeller used for this purpose. The non-splitter type impeller consists of 9 blades with 40° angle between the blades. By following the same machining procedures, the results of the machining simulations are shown in Table 2.

As shown by the simulation results, the machining time of two-stage roughing strategy is 11 % less than that of 5-axis only roughing strategy. This time usage comparison is based on the removal of the same weight of material from the stock of a non-splitter type impeller. The results shown are based on removing 52 % of weight volume between the blades for the non-splitter type impeller.

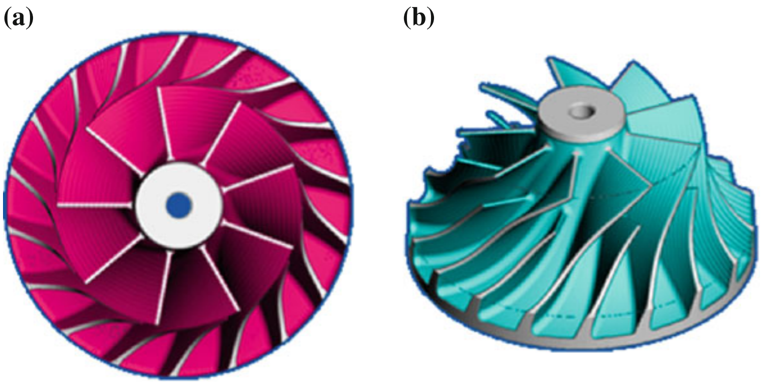


**Fig. 5** 5-axis rough machining (*second stage*). **a** Top view. **b** Isometric view

**Table 1** Simulation results of a splitter type impeller

| | | Tool-path length (mm) | Machining time (h/m/s) | Weight (kg) | Material removed (kg) |
|---|---|---|---|---|---|
| Stock | | – | – | 11.903 | – |
| 1st stage | Rough-cut with 3-axis | 138,632.13 | 2:06:48 | 9.233 | 2.67 |
| 2nd stage | Rough-cut with 5-axis | 337,627.89 | 4:43:03 | 6.486 | 2.747 |
| Total | | 476,260.02 | 6:49:51 | 6.486 | 5.417 |
| Only 5-axis (existing method) | | 547,552.32 | 8:13:32 | 6.486 | 5.417 |

**Fig. 6** Non-splitter type impeller

**Table 2** Simulation results of a non-splitter type impeller

| | | Tool-path Length (mm) | Machining time (h/m/s) | Weight (kg) | Material removed (kg) |
|---|---|---|---|---|---|
| Stock | | – | – | 11.903 | – |
| 1st stage | Rough-cut with 3-axis | 156,607.82 | 2:22:05 | 8.999 | 2.904 |
| 2nd stage | Rough-cut with 5-axis | 281,959.29 | 3:31:39 | 6.368 | 2.631 |
| Total | | 438,567.11 | 5:53:44 | 6.368 | 5.535 |
| Only 5-axis (existing method) | | 463,000.84 | 6:36:59 | 6.368 | 5.535 |

## 5 Conclusions

The objective of this study is to propose a method which can effectively reduce the roughing machining time of impeller by integrating the 3-axis and 5-axis machining methods. Two types of impellers, which are splitter and non-splitter types, are simulated. Based on the results, it can be seen that by integrating the machining methods, the total machining time can be reduced by up to 17 %. Note that the effect of the reduction of machining time could be varied according to the complex geometric shapes of impeller blades. Thus, the introduction of this new method paves the way for a new technique to produce impellers, which can shorten the lead time of manufacturing and reduce the total manufacturing cost.

The method introduced in this study can be applied to machining impellers of other designs in order to reduce machining time. Finally, the results are verified by the simulation of impellers of different types, which prove that the integrated 3-axis and 5-axis rough machining is successful in reducing the machining time of an impeller. The proposed method is even useful when a (3 + 2) axis NC machine is available in a shop floor. Further study will be carried out in order to prove the results of the simulation works.

**Acknowledgments** This research was partly supported Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0022044).

## References

1. Qi R, Liu W, Bian H, Li L (2009) Five-axis rough machining for impellers. Front Mech Eng China 4(1):71–76
2. Young H-T, Chuang L-C, Gerschwiler K, Kamps S (2004) A five-axis rough machining approach for a centrifugal impeller. Int J Adv Manufact Tech 23:233–239
3. Huran L (2012) Computer aided simulation machining programming in 5-axis NC milling of impeller leaf. Int Conf Solid State Devices Mater Sci Phys Procedia 25:1457–1462

4. So B-S, Jung Y-H, Kurfess T-R, Hwang S-M (2007) 5-axis machining speed enhancement by step length optimization. J Mater Process Technol 187–188:2–5
5. Quan L, Yongzhang W, Hongya F, Zhenyu H (2008) Cutting path planning for ruled surface impellers. Chin J Aeronaut 21:462–471
6. Marciniak K (1987) Influence of surface shape on admissible tool positions in 5-axis face milling. J Comput Aided Des 19(5)
7. Heo E-Y, Kim D-W, Kim B-H, Jang D-K, Chen FF (2008) Efficient rough-cut plan for machining an impeller with a 5-axis NC machine. Int J Comput Integr Manuf 21(8):971–983
8. PowerMILL Pro 2012 R2 SP9. Version 14.0.07.32.1148634. Copyright (c) 1995–2012 Delcam plc

# Discharge Parameters for Pass-Through Holes in EDM-Drilling

**Cheol-Soo Lee, Jong-Min Kim, Yong-Chan Choi, Eun-Young Heo and Dong-Won Kim**

**Abstract** Electrical discharge machining (EDM) drill is a kind of EDM processes to machine deep, micro sized holes of hard machining material. Since it works regardless of materials strength or stiffness, it is known that EDM drilling is effective than conventional drilling for the micro-drilling. The accuracy of a machined surface is determined by electric discharge parameters. Thus, in this study a EDM-drilling plan with the experiment of design (DOE) is set up to analyze the characteristics of Pass-Through Holes in EDM-drill and then the relationship between the four major discharge parameters and machined hole accuracy is addressed in terms of hole diameter and surface roughness. Finally, the tendency in each parameters of EDM-drilling is studied with average response value (ARV).

## 1 Introduction

EDM (electric discharge machining) drilling is one of the unconventional machining processes for micro-sized hole machining. It works regardless of the strength and stiffness of materials if a workpiece is electrically conductible. EDM-drilling can tunnel deep-micro holes by the rotation of a hollowed electrode spouting out dielectric material as shown in Fig. 1. Like other machining processes, EDM drilling generates debris that is the scrap from a machined workpiece

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A. Azevedo (ed.), *Advances in Sustainable and Competitive Manufacturing Systems*, Lecture Notes in Mechanical Engineering, DOI: 10.1007/978-3-319-00557-7_51,

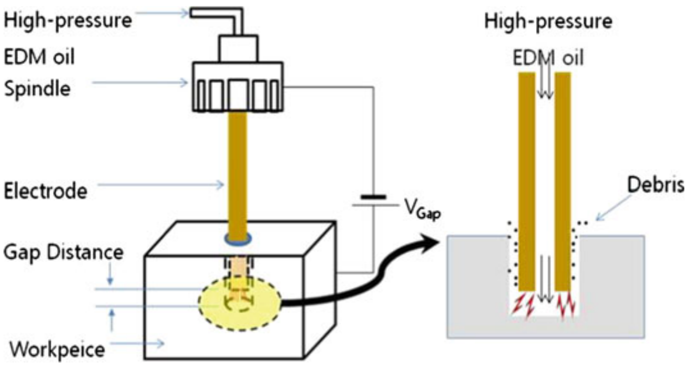



**Fig. 1** EDM-drill illustration

and an electrode. It disturbs the normal flow of dielectric, degrading the discharge efficiency, and furthermore, increasing the wear amount of the electrode. Thus, the high pressured dielectric from an EDM electrode is essential in blowing out the debris successfully.

An EDM-drilling process is composed of three phases. The first entering phase starts when a discharging electrode touches the top surface of a workpiece, then, the discharge spark occurs. The second phase means a main machining, namely discharging process where a target hole is being machined. The hole pass-through occurs in the third phase, then, the electrode comes out of the backside of the workpiece. Thus, machining quality of EDM drilling is mainly determined by the discharge parameters both in the first entering phase and in the final pass-through phase.

In this paper, a EDM-drilling plan with the experiment of design (DOE) is set up to analyze the characteristics of Pass-Through Holes in EDM-drill. The four major parameters in the EDM-drilling are $T_{on\text{-}time}$ and, $T_{off\text{-}time}$ accounting for discharge duty ratio, a peak current $I_p$, and a discharge voltage $V_{gap}$. The experimental data shows what influence can be shown after the change of the variable factors in diameter accuracy and surface roughness. The tendency in each condition of EDM-drilling is studied with average response value (ARV).

## 2 EDM-Drilling for Pass-Through Hole Process

### *2.1 EDM-Drilling*

EDM drilling to machining deep and narrow holes has different fitting features from die-sinking EDM or wire EDM. The electrode has hollow, uses this path to spray high pressure dielectric and utilizes rotation of the spindle to fast remove debris created during machining. Because debris generated during the first EDM

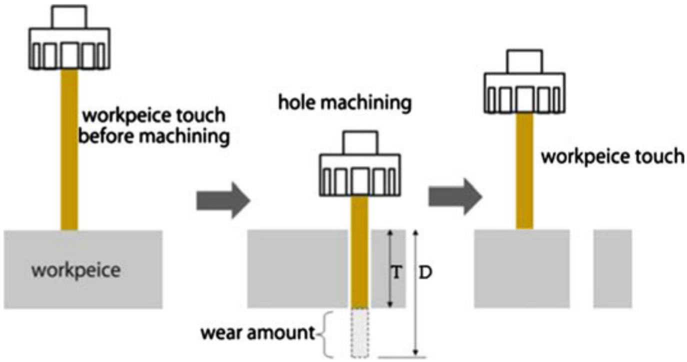



**Fig. 2** Electrode wear out calculation

machining constrain gap distance with the workpiece and interfere circulation of dielectric to generate the second discharge, increasing consumption of electrode as well as lowering machining quality. Removal of debris during hole drilling plays a very important role for hole appearance precision and surface roughness.

## *2.2 Through Hole Prediction Using Electrode Wear Ratio*

EDM drilling consumes the tool, electrode differently from cutting machining such as milling or drilling. Hole drilling using EDM drill should feed the electrode considering consumed electrode to the drilling depth so that it is able to create a hole. Electrode consumption can not be measured in real time but calculated through preliminary penetrating test. Figure 2 shows a method to calculate electrode consumption on EDM drill.

General electrode consumption is calculated using electrode difference on the reference plane before/after drilling a hole. Electrode consuming ratio (W′) can be expressed as electrode wear amount (D − T) consumed at a time of penetration divided by hole thickness (T).

$$W' = ((D - T) / T) \times 100\,[\%] \quad (1)$$

## *2.3 Experimental System*

An EDB-435f EDM drill (Fig. 3) from KTC Corporation is used in the experiment to find the relationship between the discharge parameters and the machining quality. Especially, as EDB-435f EDM drill carries out using digital circuit to control charging/discharging time ($T_{on\text{-}time}$, $T_{off\text{-}time}$) differently from those using

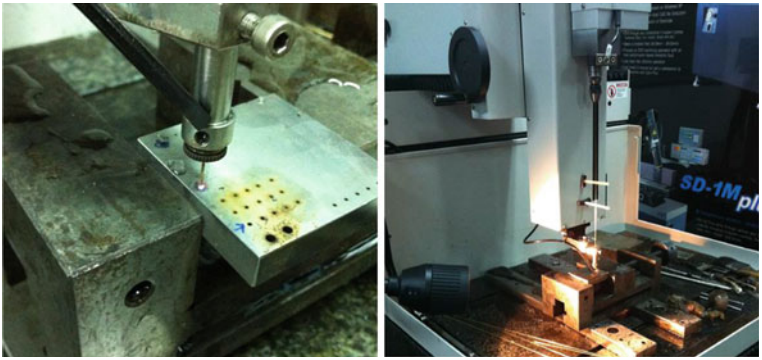
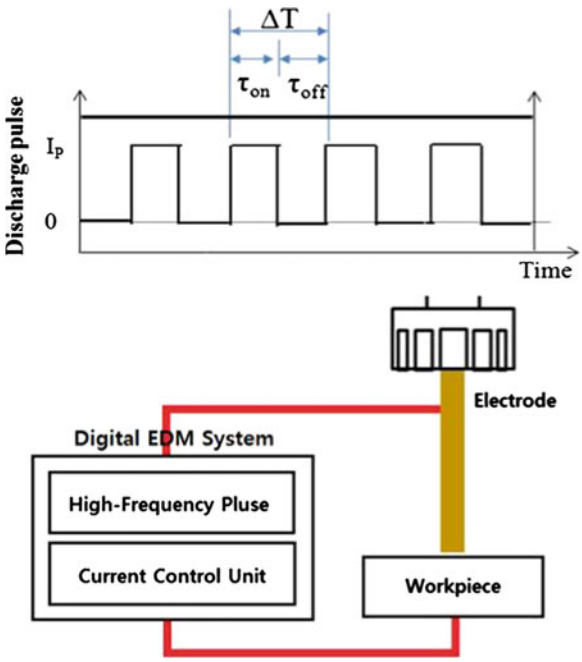


**Fig. 3** EDM-drill machine (EBD-435f)

the existing analog RC discharging circuit, it has a feature to allow well machined surface shape as well as machining time (Fig. 4).

The EDM drill equips an electrode guide preventing the eccentric rotation of the electrode, using water, graphite, and discharge oil for the dielectric. For an electrode, brass is used, while SKD-11 tool steel for an experimental workpiece. An OLS 3000 con-focal laser scanning microscope is used to observe the machined surface (see Fig. 5). The experiment repeats three times by using the same condition.

**Fig. 4** Digital EDM-drill discharging process



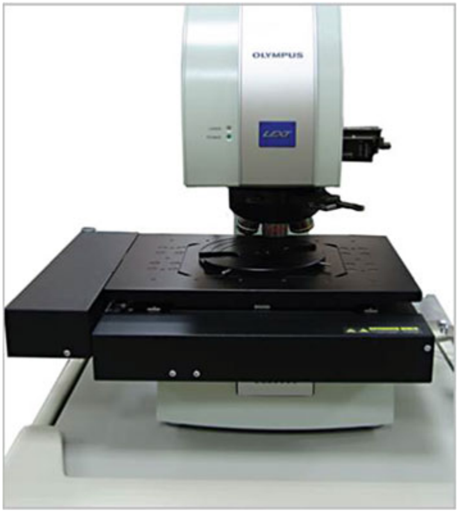



**Fig. 5** Con-focal laser scanning micro-scope (OLS-300)

# 3 Experimental Preparations

## *3.1 Experiment Design*

This study prepares $3^n$ factorial experimental design while individual factor level, n, is 3: −1(down), 0(mid) and 1(up). Supposing the reciprocal act is ignored, the characteristic of EDM-drilling is analyzed through 9 experiments according to 4 factors. Current $T_{on\text{-}time}$ level is 20, 28, and 35 μs. Current $T_{off\text{-}time}$ level is 2, 5 and 10 μs, peak current level is 14.15, 18.2 and 22.93 A. Finally, discharge voltage level is 20.7 and 26.2 V. Table 1 shows the factors and its levels. As static parameters of EDM condition, electrode wear ratio is 50 %, objective through hole depth is 11 mm, dielectric is water, dielectric pressure is 40 kg/cm$^2$. The electrode is brass of Ø0.7 (inner diameter Ø0.25), workpiece depth is 10 mm and material type is SKD-11.

**Table 1** EDM-drilling parameters

| Experiment factors | 1(−1) | 2(0) | 3(1) |
|---|---|---|---|
| $T_{on\text{-}time}$ (μs) | 20 | 28 | 35 |
| $T_{off\text{-}time}$ (μs) | 2 | 5 | 10 |
| $I_p$ (A) | 14.15 | 18.2 | 22.93 |
| $V_{gap}$ (V) | 20.7 | 26.2 | – |

**Table 2** Experimental result of pass-through holes in EDM-drilling

| No | $I_{on\text{-}time}$ | $I_{off\text{-}time}$ | $I_p$ | $V_{gap}$ | $D_u$ | $D_d$ | $R_u$ | $R_d$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 5 | 18.2 | 20.7 | 814.79 | 502.22 | 30.47 | 23.78 |
| 2 | 20 | 5 | 22.93 | 26.2 | 873.93 | 554.5 | 24.96 | 29.90 |
| 3 | 28 | 2 | 18.2 | 20.7 | 820.21 | 544.37 | 31.28 | 28.99 |
| 4 | 28 | 5 | 14.5 | 20.7 | 850.06 | 481.15 | 26.64 | 25.02 |
| 5 | 28 | 5 | 18.2 | 20.7 | 861.37 | 526.77 | 27.61 | 26.87 |
| 6(3) | 28 | 5 | 18.2 | 26.2 | 838.07 | 515.35 | 23.06 | 19.19 |
| 7(2) | 28 | 10 | 18.2 | 20.7 | 851.06 | 505.54 | 25.00 | 22.05 |
| 8(1) | 35 | 5 | 18.2 | 20.7 | 904.24 | 532.82 | 27.53 | 16.84 |

*Note* $D_u$: Diameter of upside machined hole (mm), $D_d$: Diameter of downside machined hole (mm)
$R_u$: upside surface roughness (μm), $R_d$: Downside surface roughness (μm)

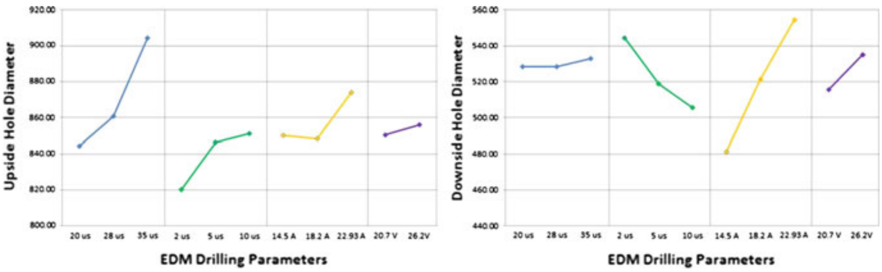
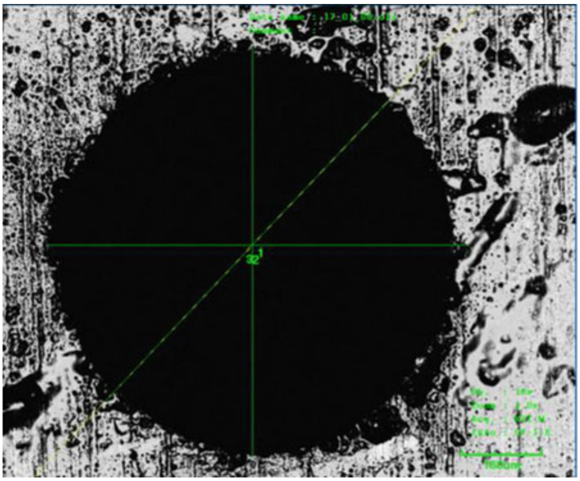



**Fig. 6** Average response value (ARV) of hole diameters by EDM-drilling parameters (*upside, downside*)

**Fig. 7** Diameter measurement by laser scanning (OLS-300)



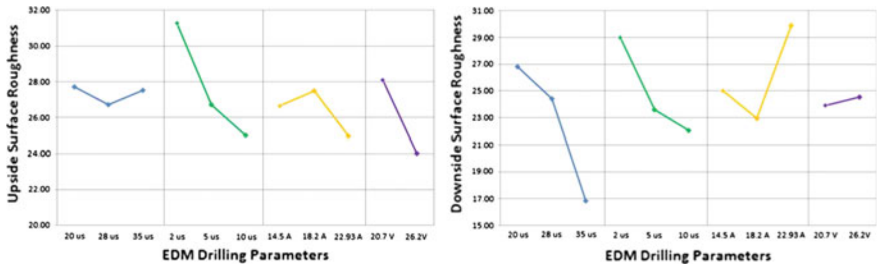



**Fig. 8** Average response value (ARV) of surface roughness by EDM-drilling parameters (*upside, downside*)

**Table 3** Experimental results on diameter accuracy (mid-term factor analysis)

| Experimental values | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Comparison factor | On-time | Off-time | Vgap | Ip | Standard | On-time | Off-time | Ip |
| Initial criterion (mid value) | 28 | 5 | 20.7 | 18.2 | | 28 | 5 | 18.2 |
| Factor increment (%) | +25 | +100 | +27 | +26 | | −29 | −60 | −22 |
| Diameter increment: entering surface (%) | +4.98 | −1.20 | −2.70 | +1.46 | | −5.41 | −4.78 | −1.31 |
| Diameter increment: passed-through surface (%) | +1.15 | −4.03 | −2.17 | +5.26 | | −4.66 | +3.34 | −8.66 |

**Fig. 9** Measurement of surface roughness by laser scanning (OLS-300)

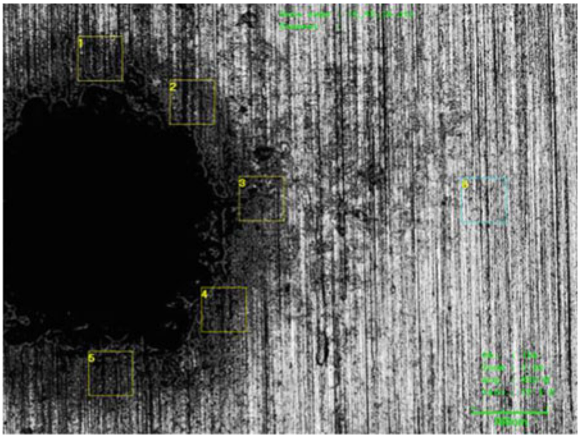


**Table 4** Experimental results on surface roughness (mid-term factor analysis)

| Experimental values | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Comparison factor | On-time | Off-time | Vgap | Ip | Standard | On-time | Off-time | Ip |
| Initial criterion (mid value) | 28 | 5 | 20.7 | 18.2 | | 28 | 5 | 18.2 |
| Ratio of factor increment (%) | +25 | +100 | +27 | +26 | | −29 | −60 | −22 |
| Roughness increment: entering surface (%) | −0.30 | −9.46 | −16.50 | −9.59 | | +10.35 | +13.28 | −3.537 |
| Roughness increment: pass-through surface (%) | −37.34 | −17.94 | −28.57 | +11.27 | | −11.50 | +7.89 | −6.89 |

### 3.2 Machining Experiments and Results Using Experiment Design

The experiment repeats 3 times with the same design to reduce the error and to increase the confidence. As shown in Table 2, three measurements are evaluated: are $T_{on\text{-}time}$ and, $T_{off\text{-}time}$ accounting for discharge duty ratio, a peak current $I_p$, and a discharge voltage $V_{gap}$ according to the EDM-drilling parameter combination (Fig. 6).

### 3.3 Diameter of Machined Holes

The diameters of a entering and a pass-through surface were measured as shown in Table 2. The measurement values were obtained by the average of vertical, horizontal and diagonal diameters (see Fig. 7). The diameters of an entering surface and a pass-through surface were proportional to the increase of $T_{on\text{-}time}$ and $I_p$. The diameters of a top entering surface and a bottom pass-through surface were inversely proportional to the increase of $T_{off\text{-}time}$ (Fig. 8).

### 3.4 Roughness of Machined Holes

The surface roughness of an entering surface and a pass-through surface was measured as shown in Table 3. The surface roughness values for 5 different spots of 100 × 100 (μs) surrounding the machined hole were measured and their average values were compared to the un-machined surface's roughness (see Fig. 9). The roughness of an entering surface was improved as $T_{on\text{-}time}$ and $T_{off\text{-}time}$ decreased, while that of a pass-through surface was improved as Ip increased (Table 4).

## 4 Conclusion

In this study, the influence on the machining accuracy by the four major EDM discharge parameters, namely $T_{on\text{-}time}$, $T_{off\text{-}time}$, $V_{gap}$, and $I_p$, has been addressed, where the accuracy was measured in terms of the diameter of the machined hole and the surface roughness surrounding the machined hole. From the experimental results, the major influential factor on an entering surface diameter is $T_{on\text{-}time}$, while the major influential factor on a pass-through surface diameter is $I_p$. As for the surface roughness, the major influential factor on an entering surface is $V_{gap}$, while the major factor on a pass-through surface is $T_{on\text{-}time}$. From these findings, this study can be a cornerstone for the further study to optimally determine the discharging parameters of EDM drilling.

**Acknowledgments** This research was supported by the Converging Research Center Program through the Korean Ministry of Education, Science and Technology (Grant Number: 2012K001051).

## References

1. Lee CS, Choi YC (2012) Modeling of elect ride wear for the pass-through hole machining by EDM-drill. In: Proceedings of the society of CAD/CAM engineers conference, pp 684–688
2. Jawaid A, Cje-haron CH, Abdulah A (2000) Tool wear characteristics in turning of titanium alloy Ti-6246. J Mater Process Technol 92–93:329–334
3. Maeng HY, Park K, Shin SH (2007) Improvement of electro discharge machining process using side flushing devices, vol 15(1). Transactions of the Korean Society of Manufacturing Technology Engineers, pp 23–31
4. Oh SH (2003) Machining technique and researching trend of hard machining material. J Korean Soc Mach Tool Eng 12(1):25–31
5. Snoeys R, Staelens F, Dekeyser W (1986) Current trends in non-conventional material removal processes. Annals CIRP 35:467–480
6. Masuzawa T (2000) State of the art micromachining. Annals CIRP 49:473–488

# Graph-Based Analysis of Metal Cutting Parameters

**Sampsa Laakso, Jaakko Peltokorpi, Juho Ratava, Mika Lohtander and Juha Varis**

**Abstract** In this work, the interdependencies of different metal cutting parameters are examined. In order to ensure competitiveness in the field of manufacturing, the quality, productivity and costs of the work must be in optimal balance. The parameters affecting the end result of a metal cutting process form a complex web of interdependencies. In this work, graph-based modularity analysis is applied in order to impose a structure on the network of parameters. This allows the identification of the parameters that are to be used in more thorough examination of the individual cases. Combined with an understanding of the graph topology such as parameterized relationships between different factors, this enables powerful heuristic tools such as expert systems to be created.

## 1 Introduction

This study makes a proposal and then presents the information required to describe the machine and device resources in a machining environment. This information is needed for the development of an analytical method for automated and highly productive production. The description of the product and device resources and their interconnectedness is the starting point for method comparison [1], the development of expenses [2], production planning [3, 4] and performing optimization [5]. According to Newness et al. [2], budgeting during the design phase requires the presentation of factors relating to production and the product itself, as

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does process optimization. The manufacturing methods cannot be optimized unless the environmental variables and their interdependences are known. Furthermore, it is impossible to create an optimal technological design, as indicated by Wang and Xie [6], unless the characteristics of the processes are known.

There are at least two points of view on cost-effectiveness in the manufacturing context, namely a cost-effective total product and cost-effective manufacturing. The concept of a cost-effective total product contains the idea of the financial control of the product's life cycle, including the main levels of this cycle: design, manufacture, marketing, use, maintenance, service and recycling, or materials recovery [7]. When examining the concept of cost-effective manufacturing, we have to note that economically efficient manufacturing costs form a part of life cycle management and thus of the product's all-in price, but they do not influence the product directly as much as they do the actual manufacturer. The manufacturer must receive a yield from the manufacturing activities, making their chances of profitable operations smaller than those of the bearer of the actual product or product rights. A product is made more cost-effective when as little energy as possible is used in its production. In addition to this, the product's cycle in production must be organized in such a way that no energy is wasted on unnecessary stages of operation, warehousing or transport [7].

The product and its production should be ecological, regardless of the point of view of cost-effectiveness. Therefore it is required to commit to an ever-increasing degree to manufacturability, as well as all other activities and events during a product's life cycle. In order for this to be possible, the informational parts of each process related to the product should be under control and the relationships of the factors affecting them should be understood [7].

One technical development trend which research and development is currently turning towards may be the integration of master production scheduling and detailed capacity planning of separate design functions, such as drafting, operation, mechanics, or production design, under one overall system in order to improve future profitability. However, whatever the development trend, it is almost certain that the portion of automatic and semi-intelligent systems will inevitably grow. The development of smarter systems requires several separate functions, practices and disciplines to be gone through in order to prepare systems that are able to present the information people need at the right time and with suitable accuracy.

When a product is designed in such a way that the capabilities and machine properties of production are taken into account throughout, a significantly higher degree of value added can be produced in a product than by acting in a traditional way, where the focus is first on functional structure and only then are the manufacturing possibilities charted [7]. Today, manufacturing companies must be agile under conditions of global competition in order to do business successfully. In western countries, one typical response to decreasing cost-effectiveness is to transfer or outsource the non-core-competence actions to a lower-cost location and concentrate on the most-value-adding actions, in which production efficiency also plays a major role. Such a contrast could be discerned between manufacturing bulk products and assembling low-volume mass-customized products.

## 2 Methods

Cutting is one of the most complex physical problems in industry. In order to improve the performance of a cutting system, changes must be made to the cutting parameters. However, changing one parameter has multiple outcomes; for example, increasing the cutting speed leads to a higher output of products but it can lead to lower profit as a result of an increased rate of tool wear. This makes optimizing cutting parameters difficult. Optimizing cutting on the basis of a limited set of parameters can achieve good results, but may have unexpected side-effects. Optimizing the cutting speed and tool wear on the basis of income can lead to bad product quality and therefore loss of profit as a result of rejected products. Understanding a cutting system requires an advanced level of expertise in the subject, which is a relatively rare and thus expensive commodity in the industry. In this paper, the proposal is to build a knowledge base with a network analysis tool in order to empower decision makers to analyze different outcomes of parameter adjustment.

The data for this research are collected from multiple research papers considering machining problems. The data are simplified into the form of a binary matrix that indicates the relationships between different parameters. The Gephi network analysis software[1] is used to automatically rearrange the network of parameters to visualize the weight of different parameters and to group the parameters [8]. Data for Gephi are prepared in human-readable form in Microsoft Excel using the NodeXL extension[2] [9]. Both pieces of software are published with an open source license and are freely available. Modularity analysis conducted with Gephi demonstrates how different parameters are connected and what kind of groups they form. This makes it possible to measure how well a network decomposes into modular communities [10].

Several approaches have been used for the optimal cutting parameter value selection problem in cutting. If the model is known, there are several solvers that are available commercially, such as LINGO for linear programming problems. Well-known algorithms can be implemented for a customized solution. In addition, there are expert systems that were developed to find a suitable tool and cutting parameters [11–13]. For black-box models (where the objective space surface is not known) genetic algorithms and neural networks are very popular, such as in Peng [14], though particle swarm optimization (PSO) methods have also

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1 Available from https://gephi.org/.

2 Available from http://nodex1.codeplex.com/.

been used [15]. Some cutting parameters may also be adjusted while the machining process is under way [16–19]. The methods applied prior to machining may take considerable amounts of time, depending on the complexity of the problem or the exact configuration of the solver, but the methods used while the machining is under way must understandably be very computationally cheap. However, in order to achieve the required accuracy for the model to be optimized, it is crucial that the effects between different factors are understood and the most relevant parameters are identified.

## 3 Research

The cutting speed is the relative motion between the cutting tool and the workpiece. The cutting speed affects the magnitude of the cutting force, as well as the cutting temperature. The cutting temperature has been widely studied but because the connection between the cutting speed and temperature is highly case-sensitive, no generic models exist [20]. The effect of the cutting speed on tool wear rate is one of the most traditional research topics in machining. Usually, tool wear rate increases with increasing cutting speed. Though the field is well established, there are many new studies considering wear because nearly all tool-workpiece material couples require tool life testing since no universal model exists [21]. The cutting speed affects the power consumption of a machine tool; generally, at higher speeds power consumption is higher. In addition, higher cutting speeds lead to a better surface quality, except some examples such as specific stainless steels [22, 23]. The effect of the cutting speed on the cutting time is obvious but the effects on residual stresses and tolerances are more difficult to determine. In some cases there is a clear effect on tolerances, for example when the velocity of mass deforms a workpiece moving at high speed, causing inaccuracies in the intended geometry. The cutting speed has a clear effect on residual stresses, as demonstrated by numerous studies, but the trends are highly case-sensitive [24].

The cutting feed is the speed at which the cutting tool advances through the workpiece. The cutting feed has an almost linear effect on the cutting force, as the area of the tool-chip contact area increases with increasing feed. This has been concluded in numerous studies, such as Kienzle and Victor's [25] commonly referenced study. The cutting feed has an impact on the cutting temperature, as presented in Bacci and Wallbank's review [26]. The impact of the cutting feed on tool wear and the tool wear rate has been investigated by researchers such as Astakhov [27]; it is concluded that the effect of the feed is dependent on other variables, such as the cutting temperature and cutting speed. The cutting feed has only a minor effect on the power consumption [10, 28]. The effect of the cutting feed on surface roughness is case-sensitive but clearly exists [10, 29, 30]. The cutting feed has an inverse linear relation to the cutting time. The feed has an effect on residual stresses, as reported in Cui et al. [21] and affects tolerances, at least through increased amounts of tool deflection at high feeds [31].

The cutting depth is a set value that defines the depth of the cut. Since the tool-chip contact area is determined by the cutting depth and feed, the cutting depth has a similar nearly linear relation to cutting forces as the cutting feed [32]. The temperature of the tool-chip contact surface increases slightly with an increase in the depth of the cut [33]. The cutting depth is linear to the cutting volume, which directly increases tool wear, but if the machining is carried out under the optimum cutting regime an increase in the depth of the cut should not change the tool wear rate [9, 24]. The power consumption increases with an increase in the depth of the cut [25]. The cutting depth affects the number of passes needed to finish a workpiece, and therefore the cutting time decreases with an increase in the depth of the cut. Tensile residual stresses are increased with increasing tool-chip contact surface; when low tensile stress values at the surface of the workpiece are desired, the cutting depth should be small [21]. The depth of the cut affects the forces acting on the tool and therefore the tool deflection; this has an effect on the tolerances of the workpiece [27].

The cutting force is the reaction to the cutting action. The force equals the energy required to remove material from the workpiece. The cutting force acts on the cutting tool. It can be viewed as resulting from three force components. These components point in the radial and tangential directions in relation to the machined surface and the opposite direction to the feed. Therefore, the cutting force directly affects the choice of tool. The cutting force also affects the tool wear mechanism and tool wear rate [34]. The cutting force is the primary contributor to power consumption. The cutting force can affect surface quality by changing the contact conditions at the tool-chip interface but no general trends have been discovered [27, 35]. The cutting force indicates the amount of friction and plastic deformation in the cutting zone and therefore the level of residual stresses generated.

The power consumption of a machine tool is the amount of energy the machine needs to perform cutting operations. The maximum power of a machine tool is a limiting criterion when selecting the cutting speed, feed and depth; therefore, its also affects the maximum allowable cutting force. Electricity is getting more expensive and the excessive use of power is seen as bad PR in view of the prevailing green philosophy policies. A simplified equation for calculating power requirements is

$$P = Rv \tag{1}$$

where P is the power consumption, R is the resultant cutting force and v is the cutting speed.

Tolerances are the accepted range of dimensions of the ready workpiece. Machine tools and the tolerances achievable by them must be considered when choosing requirements for tolerance and quality in the design phase. As already noted, the tolerances of the workpiece are affected by the cutting force through tool and workpiece deflection.

A cutting tool is a geometrically defined shape that is strong and hard enough to mechanically remove material from a workpiece. A cutting tool has a major effect on the maximum applicable cutting speed, feed and depth. These values are provided by the tool manufacturers for each type of workpiece material. The recommended optimal cutting parameters for a 15 min tool life are usually found in the catalogs of the tool manufacturers. Cutting tool performance is determined by the mechanical, tribological and thermal properties of the tool material. The performance is often measured by the tool life, maximum achievable material removal rate and cost of the tool. The geometry of the cutting tool has a major impact on cutting forces, cutting temperature, surface quality, and tolerances [10, 20, 21].

Tool wear is the flow of material away from the cutting tool as a result of adhesion, abrasion, plastic deformation, and electrochemical phenomena. Tool wear obviously affects the cutting tool and its costs and performance, which is reflected in increased cutting forces [36]. Tool wear has an effect on the surface quality; the flank wear profile in particular is seen on the surface of the workpiece [37]. Tool wear and the cutting temperature have a strong omnidirectional effect on each other and the cause-effect relationship should be investigated experimentally more thoroughly [38]. The tool wear rate is the speed at which the tool wears. The wear rate affects how long one tool can be used continuously and therefore the cutting time is affected. Tolerances are critical with regard to tool wear rate because if the wear is fast, then the tool compensation changes quickly and is inaccurate, therefore leading to poor tolerances.

Cutting fluid is a lubricant and its major functions are removing cutting waste and chips, cooling the tool and workpiece, and lubrication. The lubricating properties of cutting fluids have been questioned because there are indicators that the cutting fluid cannot access the tool-chip contact surface as a result of the high pressure in that area. The cutting fluid has an effect on surface quality and tool wear, as presented, for example, in Xavior and Adithan's [39] work. The cooling properties of cutting fluids are evident and strongly correlated by the thermal properties of the fluid [40].

The cutting temperature is generated from the friction and adhesion between the tool and the workpiece and from the plastic deformation of the workpiece material. The cutting temperature has a significant effect on the cutting tool wear rate [41]. Thermal softening and thermal elongation of the workpiece and tool also affect the cutting forces and tolerances. Residual stresses are caused by the joint effect of elastic and plastic deformation and changes in temperature [42].

The cutting time is the time needed for the cutting action. The cutting time affects the choice of cutting tool and the cumulative temperature generated and conducted to the workpiece and tool. The cutting time is the primary measurement for tool life and therefore tool wear should be considered. The cutting time affects the total power consumption of the process, labor costs and machine costs.

The surface quality is the topology of the already-machined surface layer of the workpiece. The surface quality affects the tolerances if the surface average roughness value Ra is high. The quality and tolerance requirements are also affected by a bad surface or very high costs of reaching good surface quality. Residual stresses are the remaining stresses in the workpiece after the cutting is done. The surface quality and tolerances can change if the residual stresses are released and therefore distort the workpiece. Quality and tolerance requirements are engineering-driven qualities that are critical for the workpiece to function properly in its intended surroundings. The requirements for the product also have a major impact on product costs, because if the requirements are unnecessarily high, then producing over quality in the sense of surface roughness, and the tolerances, tool, labor and machine costs are higher. Additionally, if the tolerance requirements are high, this requires the surface roughness requirements to be high too.

Tool costs mainly comprise the retail price of tool bits. If tool costs are critical in the cost structure of the product, this can affect the choice of cutting tool. Labor costs are calculated from the time the machinist must attend to the machine tool for each workpiece. Machine costs include maintenance and down payments.

Table 1 and Fig. 1 present the relationships between different variables in the cutting process.

**Table 1** Connections between different cutting variables

| | Cutting Speed | Cutting Feed | Cutting Depth | Cutting Fluid | Cutting Tool | Cutting Force | Cutting Temperature | Tool Wear | Tool Wear Rate | Power Consumption | Surface Quality | Cutting Time | Residual Stresses | Tolerances | Tool Costs | Labor Costs | Machine Costs | Quality Requirements | Tolerance Requirements |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cutting Speed | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Cutting Feed | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Cutting Depth | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Cutting Fluid | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cutting Tool | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Cutting Force | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Cutting Temperature | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Tool Wear | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Tool Wear Rate | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Power Consumption | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Surface Quality | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| Cutting Time | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| Residual Stresses | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Tolerances | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Tool Costs | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Labor Costs | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Machine Costs | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Quality Requirements | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| Tolerance Requirements | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |

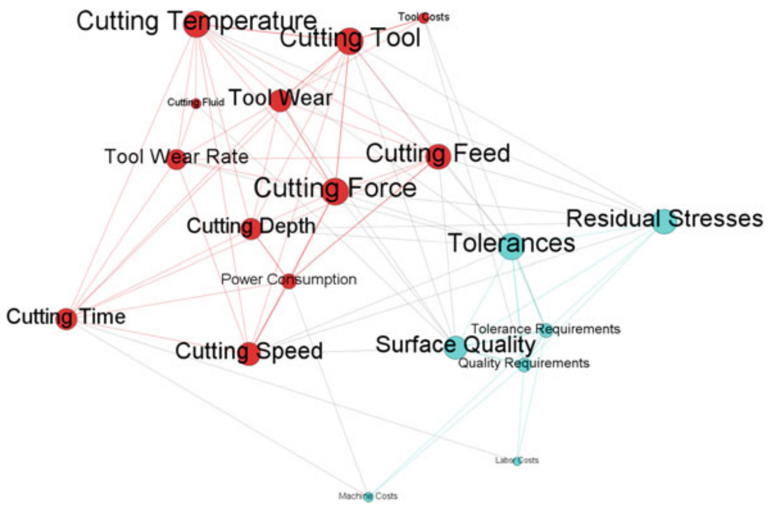


**Fig. 1** Relationships between factors affecting the metal cutting process

## 4 Conclusions

Optimizing workpiece quality, machining costs, and productivity is essential for competitive manufacturing. In order to optimize cutting processes, different parameters are adjusted to achieve desirable outcomes. However, as a result of the complex nature of the cutting process and the various coupled effects of different parameters, it is difficult to predict different outcomes resulting from a parameter change. This research was conducted to inspect a graph-based approach to the creation of an expert system for assessing the outcomes of different cutting parameter changes. This is done by applying a simplified model based solely on known relationships between different parameters in cutting.

The analysis shows that cutting parameters are divided into two groups, namely "machine parameters" and "design parameters". The division is based on Gephi modularity analysis. First, it is interesting to note that the modularity analysis led to sensible groups. Additionally, it seems to be sensible to use the network approach in order to visualize such a practical problem. Depending on the case to be optimized, different parameter loops can be identified and thus taken into account during the design of the machining routine. This approach does not give automatic optimization solutions for these cases, but helps to identify the parameters that are to be used in more thorough analysis. This kind of an expert system can be upgraded by inducing topology in the form of functions between different parameters. However, because of the high level of variation in the materials used for tools and workpieces, universal models of cutting parameters have not been created. This makes it difficult to formulate such functions.

Regardless of this, the observation of two distinctive parameter groups (design and machine parameters) eases the design of the machining process through the creation of a clearer distinction between objectives and means.

## References


1. Lutters D, ten Brinke E, Streppel AH, Kals HJJ (2000) Computer aided process planning for sheet metal based on information management. J Mater Process Technol 103:120–127
2. Newness LB, Mileham AR, Hosseini-Nasab H (2007) On-screen real-time cost estimating. Int J Prod Res 45(7):1577–1594
3. Cuirana J, Ferrer I, Gao JX (2006) Activity model and computer aided system for defining sheet metal process planning. J Mater Process Technol 173:213–222
4. Hayes C (1996) P3: a process planner for manufacturability analysis. IEEE Trans Robot Autom 12(2)
5. Singh DKJ, Jebara C (2005) Feature-based design for process planning of machining processes with optimisation using genetic algorithms. Int J Prod Res 43(18):3855–3887
6. Wang GG, Xie SQ (2005) Optimal process planning for a combined punch-and-laser cutting machine using ant colony optimization. Int J Prod Res 43(11):2195–2216
7. Lohtander M (2010) On the development of object functions and restrictions for shapes made with a turret punch press, Lappeenranta University of Technology
8. Bastian M, Heymann S, Jacomy M (2009) Gephi: an open source software for exploring and manipulating networks. In: 3rd international AAAI conference on weblogs and social media, San Jose, CA, USA
9. Smith M, Schneiderman B, Milic-Frayling N, Rodrigues EM, Barash V, Dunne C, Capone T, Perer A, Gleave E (2009) Analyzing (social media) networks with Node XL. In: Proceedings of the 4th international conference on communities and technologies, State College, PA, USA
10. Blondel VD, Guillaume J-L, Lambiotte R, Lefebvre E (2008) Fast unfolding of communities in large networks. J Stat Mech Theory Exp 10:1000
11. Abburi NR, Dixit US (2006) A knowledge-based system for the prediction of surface roughness in turning process. Robot Comput Integr Manuf 22(4):363–372
12. Huh K, Pak C (2003) Unmanned turning force control with selecting cutting conditions. In: IEEE American control conference, Denver, CO, USA
13. Karayel D (2009) Prediction and control of surface roughness in CNC lathe using artificial neural network. J Mater Process Technol 209:3125–3137
14. Peng YH (2004) On the performance enhancement of self-tuning adaptive control for time-varying machining processes. Int J Adv Manuf Technol 24:395–403
15. Srinivas J, Giri R, Yang S-H (2009) Optimization of multi-pass turning using particle swarm intelligence. Int J Adv Manuf Technol 40:56–66
16. Ratava J, Rikkonen M, Ryynänen V, Leppänen J, Lindh T, Varis J, Sihvo I (2012) An adaptive fuzzy control system to maximize rough turning productivity and avoid the onset of instability. Int J Adv Manuf Technol 53(1):71–79
17. Ryynänen V, Ratava J, Lindh T, Rikkonen M, Sihvo I, Leppänen J, Varis J (2009) Chip control system for monitoring the breaking of chips and elimination of continuous chips in rough turning. Mechanika 4(78):57–62
18. Sharma VS, Sharma SK, Sharma AK (2006) Cutting tool wear estimation for turning. J Intell Manuf 19(1):99–108
19. Yilmaz O, Görür G, Dereli T (2001) Computer aided selection of cutting parameters by using fuzzy logic. In: Proceedings of the international conference, 7th fuzzy days on computational intelligence, theory and applications, Dortmund, Germany

20. Saglam H, Yaldiz S, Unsacar F (2007) The effect of tool geometry and cutting speed on main cutting force and tool tip temperature. Mater Des 28(1):101–111
21. Cui X, Zhao J, Dong Y (2012) The effects of cutting parameters on tool life and wear mechanisms of CBN tool in high-speed face milling of hardened steel. Int J Adv Manuf Technol
22. Bhattacharya A, Das S, Majumder P, Batish A (2009) Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. Prod Eng 3(1):31–40
23. Hamdan A, Sarhan AAD, Hamdi M (2012) An optimization method of the machining parameters in high-speed machining of stainless steel using coated carbide tool for best surface finish. Int J Adv Manuf Technol 58(1–4):81–91
24. Navas VG, Gonzalo O, Bengoetxea I (2012) Effect of cutting parameters in the surface residual stresses generated by turning in AISI 4340 steel. Int J Mach Tools Manuf 61:48–57
25. Kienzle O, Victor H (1952) Die Bestimmung von Kräften und Leistungen an spanenden Werkzeugmaschinen. VDI-Z 94(11–12):155–171
26. da Silva MB, Wallbank J (1999) Cutting temperature: prediction and measurement methods—a review. J Mater Process Technol 88(1–3):195–202
27. Astakhov VP (2007) Effects of the cutting feed, depth of cut, and workpiece (bore) diameter on the tool wear rate. Int J Adv Manuf Technol 34(7–8):631–640
28. Bhushan RK (2013) Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites. J Cleaner Prod 39:242–254
29. Kumar NS, Shetty A, Shetty A, Ananth K, Shetty H (2012) Effect of spindle speed and feed rate on surface roughness of carbon steels in CNC turning. Procedia Eng 38:691–697
30. Aouici H, Yallese MA, Chaoui K, Mabrouki T, Rigal J-F (2012) Analysis of surface roughness and cutting force components in hard turning with CBN tool: prediction model and cutting conditions optimization. Measurement 45(3):344–353
31. Ong TS, Hinds BK (2003) The application of tool deflection knowledge in process planning to meet geometric tolerances. Int J Mach Tools Manuf 43(7):731–737
32. Sivaraman V, Sankaran S, Vijayaraghavan L (2012) The effect of cutting parameters on cutting force during turning multiphase micro alloyed steel. Procedia CIRP 4:157–160
33. Abhang LB, Hameedullah M (2010) Chip-tool interface temperature prediction model for turning process. Int J Eng Sci Technol 2(4):382–393
34. Choudhury SK, Kishore KK (2000) Tool wear measurement in turning using force ratio. Int J Mach Tools Manuf 40(6):899–909
35. Bartarya G, Choudhury SK (2012) Effect of cutting parameters on cutting force and surface roughness during finish hard turning AISI52100 grade steel. Procedia CIRP 1:651–656
36. Li K-M, Liang SY (2007) Modeling of cutting forces in near dry machining under tool wear effect. Int J Mach Tools Manuf 47(7–8):1292–1301
37. Pavel R, Marinescu I, Deis M, Pillar J (2005) Effect of tool wear on surface finish for a case of continuous and interrupted hard turning. J Mater Process Technol 170(1–2):341–349
38. Ghani MU, Abukhshim NA, Sheikh MA (2008) An investigation of heat partition and tool wear in hard turning of H13 tool steel with CBN cutting tools. Int J Adv Manuf Technol 39(9–10):874–888
39. Xavior MA, Adithan M (2009) Determining the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel. J Mater Process Technol 209(2):900–909
40. Vieira JM, Machado AR, Ezugwu EO (2001) Performance of cutting fluids during face milling of steels. J Mater Process Technol 116(2–3):244–251
41. Jianxin D, Hui Z, Ze W, Yunsong L, Youqiang X, Shipeng L (2012) Unlubricated friction and wear behaviors of $Al_2O_3$/TiC ceramic cutting tool materials from high temperature tribological tests. Int J Refract Metal Hard Mater 35:17–26
42. Guillemot N, Winter M, Souto-Lebel A, Lartigue C, Billardon R (2011) 3D heat transfer analysis for a hybrid approach to predict residual stresses after ball-end milling. Procedia Eng 19:125–131

# A Surface Roughness and Power Consumption Analysis When Slot Milling Austenitic Stainless Steel in a Dry Cutting Environment

**Patricia Muñoz-Escalona, Alborz Shokrani, Vimal Dhokia, Reza Imani-Asrai and Stephen T. Newman**

**Abstract** Engineered components must satisfy the surface texture requirements and traditionally surface roughness (arithmetic average, Ra) has been used as one of the principles methods to assess quality. Surface roughness is a result of the cutting parameters such as: cutting speed, feed per tooth and the axial depth of cut, also the tool's geometry, tool wear vibrations, etc. Moreover, the surface finish influences the mechanical properties such as fatigue behavior, wear, corrosion, lubrication, and electrical conductivity. The research reported herein is focused mainly on surface roughness and power consumption analysis of an austenitic stainless steel milled in a dry cutting environment. The experiments were conducted on a Siemens 840D Bridgeport Vertical Machining center 610XP2. The selection of this workpiece material was based on it's widely applications in cutlery, hardware, surgical instruments, industrial equipment and in the automotive and aerospace industry due to its high corrosion resistance and high strength characteristics. The results show that selection of a careful combination of cutting parameters can achieve low values of surface roughness and power consumption instead of changing the cutting parameters individually.

## 1 Introduction

In machining processes, surface roughness is an important quality characteristic. The combination of cutting parameters of tool wear, machine-tool vibrations, etc., is a few of the variables that affect the roughness of a machined surface. The lack

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of any specified surface finish in engineer drawings or the lack of achieving an inadequate roughness can be the source of a major problem. Most decisions about which roughness should a material have depends on a combination of different factors such as: environment, temperature of operation, strength required, etc.

During the past years there has been extensive research and development regarding tool wear, tool life, surface roughness, etc. and the results have provided lots of knowledge [1–4]. However, many gaps still need to be filled since depending on the material workpiece-tool combination a different result can be obtained.

In 2001 Rao and Shin [5] conducted a surface integrity study on aluminium 7075-T6 after a high speed milling process. The results showed that the surface roughness decreases when increasing the cutting speed (110–1,500 m/min), however, an increase of the roughness was observed beyond 1,500 m/min, and the roughness increased when increasing the feed rate. In 2004 Wang and Chang [6] studied the influence of the cutting parameters on the surface roughness of slot end milling AL2014-T6. They concluded that the cutting speed and the feed were factors that affected the dry machining of their developed model. They also concluded that the surface roughness became lower with application of cutting fluid when compared with dry machining and that the BUE formation occurred at low cutting speed 20–40 m/min during dry machining.

Korkut and Donertas in 2007 [7] studied the influence of the cutting speed (44 m/min to 111 m/min) on the cutting forces, surface roughness and chip length on AISI 1020 and 1040 carbon steel. They concluded that an increase on the cutting speed produced an increase of the cutting forces, a decrease of the built-up-edge formation and a decrease on the surface roughness.

In 2009 Sun and Guo [8] conducted a comprehensive experimental study on surface integrity when end milling titanium Ti-6AL-4 V. Their studies show an increase of the surface roughness when increasing the cutting speed toward the feed direction.

With regards the power consumption in 2012 Patel [9] studied the influence of the cutting parameters on the power consumption and surface roughness on 6063 Al alloy TiC composites. They found that at low cutting speeds (i.e., 63 m/min) the surface roughness was high due to BUE formation and then and improve of roughness was obtained when the cutting speed was increased (i.e., 170 m/min). They also concluded that the power consumption increased when increasing the cutting speed and the feed rate.

In 2013 Bhushan [10] conducted CNC turning experiments on aluminium 7075. He concluded that the power consumption increases with the increase in cutting speed and that an increase of the feed produced only a little increase on this parameter.

Based on all these reviews, the aim of this research is to select the appropriate combination of cutting parameters for a low power consumption and a desired surface roughness making a new contribution on the machining of austenitic stainless steels.

# 2 Experimental Procedure

## 2.1 Workpiece Material

A number of 303 annealed stainless steel bars of 65 mm diameter and 120 mm length were pre-machined to 120 × 55 × 32 mm as show in Fig. 1.

Tables 1 and 2 show the chemical composition and the mechanical properties of this 303 stainless steel respectively.

## 2.2 Tool Characteristics

A coated three flute slot drill of $Ø_{Tool} = 14$ mm was used for the conventional milling experiments, with the following code Guhring GTN 03872. This type of tool is recommended for the machining of stainless steel under a dry cutting condition.

## 2.3 Cutting Parameters and Machining Process

Cutting speed and feed per tooth were the variables chosen for the study, since from previous research it was observed that these variables had the most influence on the surface roughness. Selected cutting parameters are shown in Table 3.

The machining process was conducted based on the workpiece dimensions (120 × 55 × 32). Five passes with ae = 11 mm were used to cover the width of the workpiece (55 mm). In order to guarantee that the vice was holding enough material, only a maximum depth of 18 mm could be reached, so six passes with ap = 3 mm each were used to cover this depth. By taking into account these two factors the total length of cut is 3600 mm (120 mm × 5 × 6) per trial. Figure 2 shows a scheme of the cutting process.

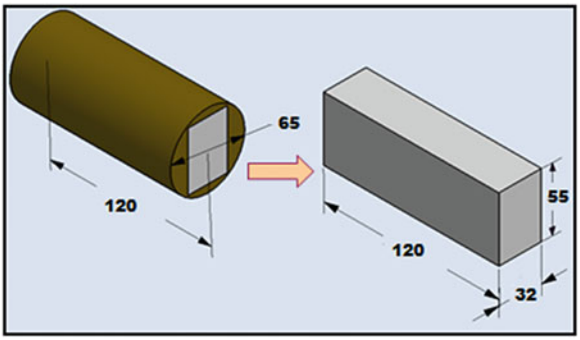



**Fig. 1** Scheme of the workpiece geometry used in this study (units in mm)

**Table 1** Chemical composition of 303 stainless steel bars used for the experiments

| %C | %Cr | %Fe | %Mn | %Mo | %Ni | %P | %Si | %S |
|---|---|---|---|---|---|---|---|---|
| <=0.15 | 18.0 | 69.0 | <=2.0 | <=0.6 | 9.0 | <=0.2 | <=1.0 | >=0.15 |

**Table 2** Mechanical properties 303 stainless steel bars used for the experiments

| BHN | Su [MPa] | Sy [MPa] |
|---|---|---|
| 160 | 620 | 240 |

**Table 3** Experiments cutting conditions

| Trial | *V [m/min] | F [mm/min] | ap [mm] | ae [mm] |
|---|---|---|---|---|
| 1 | 105 | 480 | 3 | 11 |
| 2 | 157 | 717.6 | 3 | 11 |
| 3 | 157 | 535.5 | 3 | 11 |
| 4 | 157 | 364 | 3 | 11 |

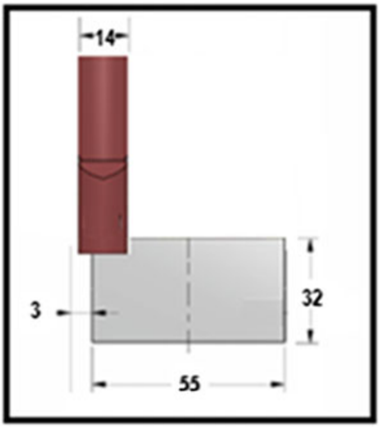



**Fig. 2** Scheme of the cutting process

## 2.4 Equipment Characteristics

A Siemens 840D Bridgeport Vertical Machining center 610XP2 with a maximum spindle speed of 8000 rpm was used for the slot milling operations. The tests were conducted in a dry cutting environment. Since the cutting length is small (L = 3,600 mm) the tool wear is not considered as a criterion that will affect the result of the cutting process.

### 2.5 Surface Roughness Measurements

The surface roughness was measured across the direction of the machined surface lay (feed direction) using a non-contact white lamp profilometer ProScan 2000. The roughness average value of each specimen was determined by measuring five points, located in the center of the specimen, where maximum and minimum values were neglected. The idea of measuring the roughness at the workpiece center was in order to make sure that the obtained values of surface roughness were not affected by possible vibrations due to the impact of the tool entering the workpiece. Then an average of these three values was used to represent the surface roughness value of the specimen (Ra), also the 2D surface roughness profile and 3D surface was also obtained.

### 2.6 Power Consumption Analysis

In order to consider the cost of cutting techniques and energy efficient process planning, the power consumption was registered using a Hioki 3169-20 Power Hitester. The collection data was fixed to 50 Hz frequency at 1 s interval.

## 3 Results and Discussion

Once experiments were concluded the following results were obtained for surface roughness and power consumption.

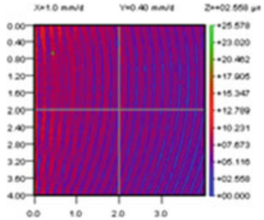
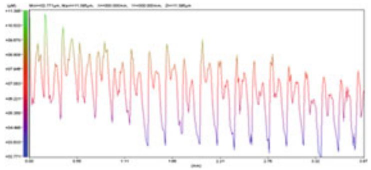
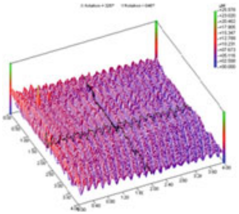
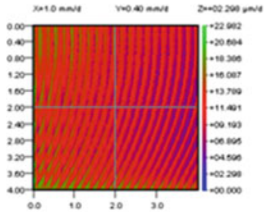
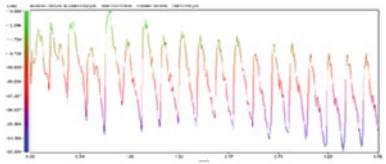
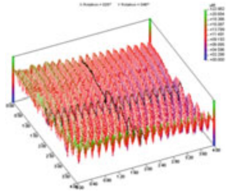
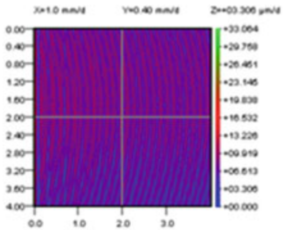
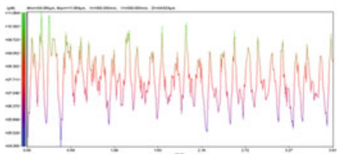
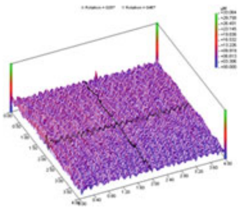
### 3.1 Surface Roughness

Table 4 shows the results of average roughness. Table 5 shows the average surface roughness, plan view, 2D profiles, and 3D surface for 303 stainless steel bars machined under a dry environment with different cutting conditions.

**Table 4** Surface roughness value for each area and average roughness of each trial for 303S301 stainless steel bars machined under a dry environment with different cutting conditions

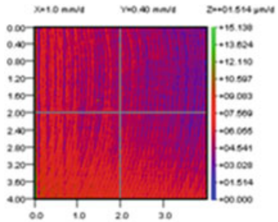
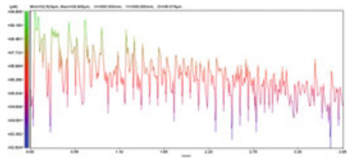
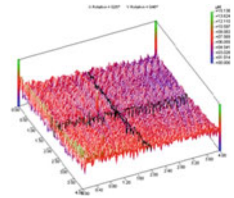
| Trial | V [m/min] | fz [mm/rev * tooth] | ap [mm] | ae [mm] | Ra* [μm] |
|---|---|---|---|---|---|
| 1 | 105 | 0.0670 | 3 | 11 | 1.228 |
| 2 | 157 | 0.0670 | 3 | 11 | 2.045 |
| 3 | 157 | 0.0500 | 3 | 11 | 1.071 |
| 4 | 157 | 0.0335 | 3 | 11 | 0.934 |

**Table 5** Average surface roughness, plan view, 2D profiles, and 3D surface for 303 stainless steel bars machined under a dry environment with different cutting conditions

| Trial | Ra* [μm] | Plan view | 2D profile | 3D surface |
|---|---|---|---|---|
| **1** | 1.228 |  |  |  |
| **2** | 2.045 |  |  |  |
| **3** | 1.071 |  |  |  |

(continued)

**Table 5** (continued)

| Trial | Ra* [µm] | Plan view | 2D profile | 3D surface |
|---|---|---|---|---|
| 4 | 0.934 |   |  |  |

As observed from Table 5 the plan view, shows the normal trail left by the cutting tool on the machined surface, with clear defined feed marks, the 2D surface roughness profile obtained for each trial show a harmonic function, with no kind of irregularity that could lead to an imperfection on the machined surface. In general the results indicate that apparently no defect on the tool or high enough vibrations were presented during the milling process.

### 3.1.1 Influence of the Cutting Speed on the Surface Roughness

In Fig. 3 the influence of the cutting speed on the surface roughness for 303 stainless steel machined under specific cutting conditions can be observed.

When analyzing Fig. 3 it can be observed that an increase of 50 % of the cutting speed (from 105 to 157 m/min) produced an increase of 67 % on the surface roughness (from 1.228 to 2.045 μm). This behavior was probably due to the fact that the machining process was conducted under a dry environment, and despite the advantage that dry machining produces regarding softening the material due to heat generation, it is also known the tendency of adhesion and diffusion tool wear. This result is in agreement with previous research (Weinert et al. 2004 and Yakup Turgut et al. 2011).

### 3.1.2 Influence of the Feed Rate on the Surface Roughness

In Fig. 4 the influence of the feed per tooth on the surface roughness for 303 stainless steel machined under specific cutting conditions can be observed. On analyzing Fig. 4 the surface roughness increases when increasing the feed per tooth. This result is in agreement with previous research and is due to the fact that as the feed is increased, the section of the sheared chip also increases because the metal resists the rupture and requires larger effort for chip removal thus increasing the cutting forces (Shokrani et al. Sureh Kumar Reddy 2008). It can also be observed that a decrease of 50 % of the feed per tooth (from 0.0670 to 0.0335 mm/

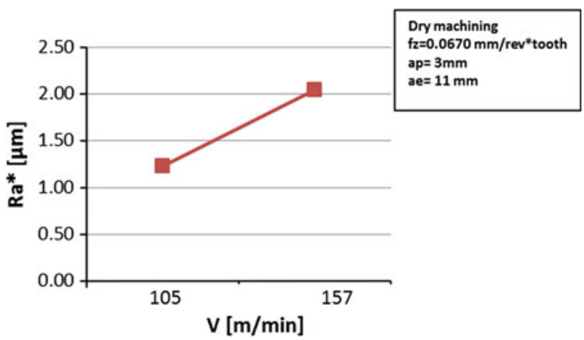



**Fig. 3** Influence of the cutting speed on the surface roughness for 303 stainless steel machined in a dry environment under specific cutting conditions

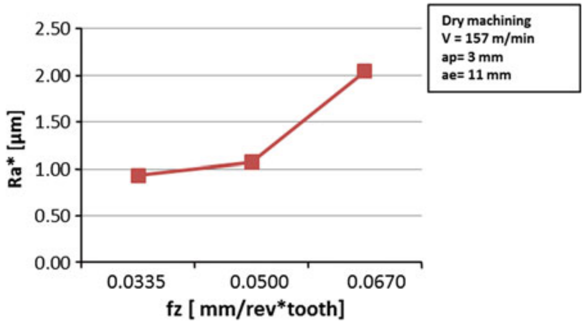



**Fig. 4** Influence of the cutting speed on the surface roughness for 303 stainless steel machined in a dry environment under specific cutting conditions

rev*tooth) produced a decrease of 57 % on the surface roughness (from 2.207 to 0.934 µm)

However, it can be observed that trial 4 resulted in the minimum value of surface roughness (0.934 µm) this is probably due to the combination of cutting parameters used for this trial, V = 157 m/min and fz = 0.0335 mm/rev * tooth, which represent an increase of 50 % of the cutting speed and 50 % decrease of feed rate from the pattern trial (trial 1). This value of 0.934 µm represents an improvement of 32 % of the surface roughness (from 1.228 to 0.934 µm).

As observed it seems that a change in just one of the cutting parameter parameters (cutting speed or feed per tooth) has more influence on the surface roughness than changing both parameters at the same time.

## *3.2 Power Consumption Analysis*

As previously mentioned above, while the machining process was conducted the power consumption was registered. The Power consumption when machining the 303 stainless steel under specific cutting conditions is shown in Fig. 5. In order to simplify the analysis, Table 6 reports the average power consumption for each trial during the machining operation which takes into account the cutting time and dead time. As can be seen from Table 6 when analyzing the average power consumption results Trial 1 reported the lowest value of average power consumption in this case 1,553 W followed by trial 4 with 1,577 W, the difference of power consumption between these two trials is 1.5 %, despite the increase of 50 % of the cutting speed and a decrease of 50 % on the feed per tooth for trial 4.

### 3.2.1 Influence of the Cutting Speed on the Average Power Consumption

Figure 6 show the influence of the cutting speed on the average power consumption for 303 stainless steel machined under different cutting conditions. On

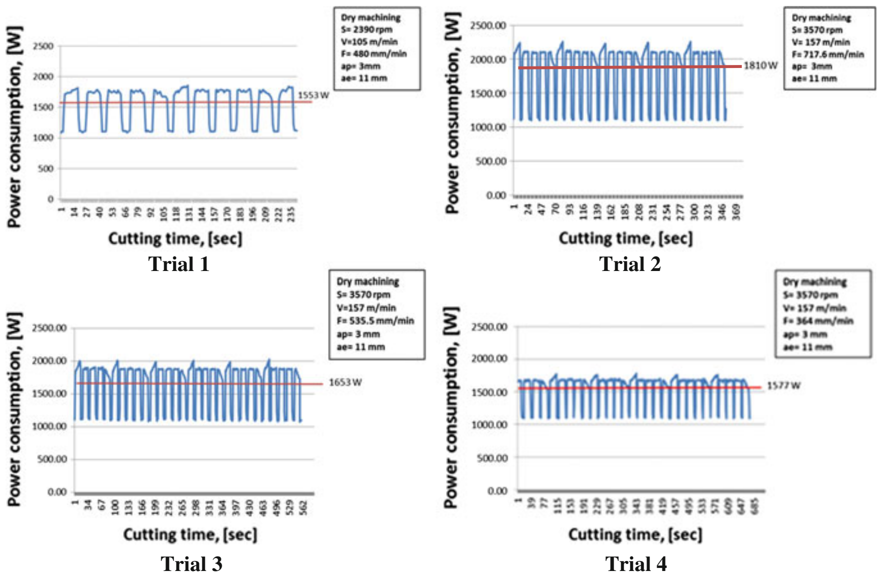



**Fig. 5** Power consumption graphs for 303 stainless steel bars machined under a dry environment with different cutting conditions

**Table 6** Average power consumption for 303 stainless steel machined under a dry environment using different cutting conditions

| Trial | S [rpm] | V[m/min] | F [mm/min] | fz[mm/rev*tooth] | P* [W] |
|---|---|---|---|---|---|
| 1 | 2390 | 105 | 480 | 0.067 | 1553 |
| 2 | 3570 | 157 | 717.6 | 0.067 | 1810 |
| 3 | 3570 | 157 | 535.5 | 0.050 | 1653 |
| 4 | 3570 | 157 | 364.14 | 0.034 | 1577 |

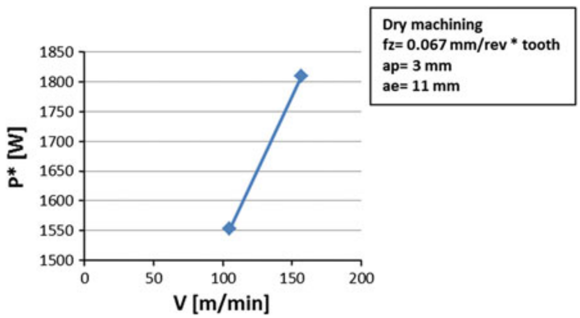



**Fig. 6** Influence of the cutting speed on the average power consumption for 303 stainless steel machined under different cutting conditions

analyzing Fig. 6 the average power consumption increases when increasing the cutting speed, where an increase of 50 % of the cutting speed (from 105 to 157 m/min) produced an increase of 16.5 % of the average power consumption (from 1,553 to 1,810 W). This result is in agreement with previous research [9].

### 3.2.2 Influence of the Feed on the Average Power Consumption

Figure 7 shows the influence of the feed per tooth on the average power consumption for 303 stainless steel machined under different cutting conditions. When analyzing Fig. 7 it is observed that the average power consumption increases when increasing the feed per tooth, where an increase of 50 % of the feed per tooth (from 0.0345 to 0.067 mm/rev * tooth) produced an increase of 15 % of the average power consumption (from 1,577 to 1810 W). This result is in agreement with previous research (Palter 2012).

As observed the power consumption of the machine tool becomes higher as the cutting speed and the feed per tooth are increased. This result is probably due to the fact that as the cutting parameters are increased, the material removal also increases forcing the system to spend more power, however, it can be observed that a proper combination of cutting parameters can also produce a small change on the average power consumption as observed when comparing trial 1 and 4 respectively (see Table 6) where the difference of average power consumption is only 1.5 %, despite of an increase of 50 % on the cutting speed and a decrease of 50 % on the feed per tooth.

## *3.3 Influence of the Cutting Parameters on the Material Removal Rate*

Table 7 shows the Material Removal Rate for each of the trials. Figures 8 and 9 show the influence of the material removal rate on the surface roughness and power consumption respectively when machining the 303 stainless steel under

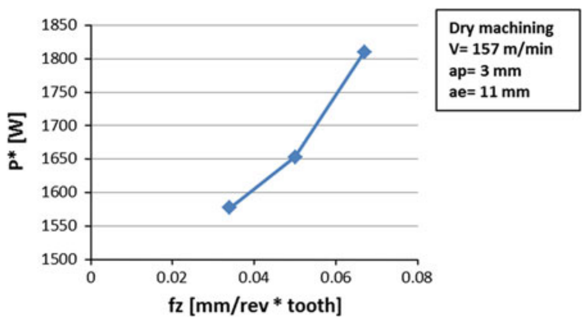



**Fig. 7** Influence of the feed per tooth on the average power consumption for 303 stainless steel machined under different cutting conditions

**Table 7** Material removal rate for 303 stainless steel milled in a dry environment under different cutting conditions

| Trial | V [m/min] | F [mm/min] | fz (mm/rev*tooth) | ap [mm] | ae [mm] | MRR [$cm^3$/min] |
|---|---|---|---|---|---|---|
| 1 | 105 | 480 | 0.0670 | 3 | 11 | 15.84 |
| 2 | 157 | 717.6 | 0.0670 | 3 | 11 | 23.68 |
| 3 | 157 | 535.5 | 0.0500 | 3 | 11 | 17.67 |
| 4 | 157 | 364.14 | 0.0335 | 3 | 11 | 12.02 |

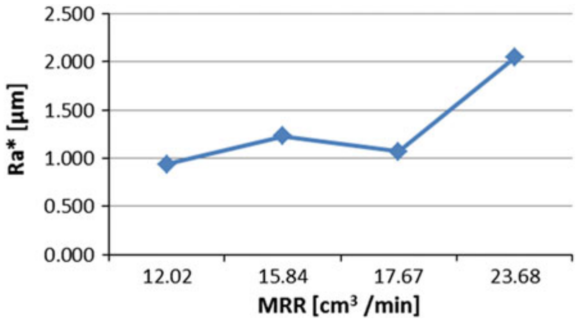



**Fig. 8** Influence of the material removal rate on the surface roughness for 303 stainless steel machined under different cutting conditions

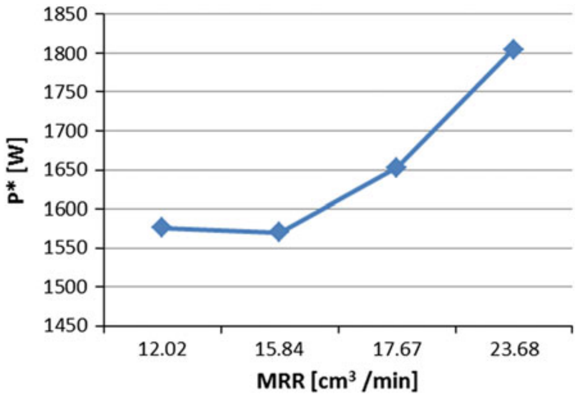



**Fig. 9** Influence of the material removal rate on the power consumption for 303 stainless steel machined under different cutting conditions

different cutting condition. As observed for both cases as the material removal rate increases both of this parameters are increased.

## 4 Conclusions

From the test results it can be seen that:-

- Trial 4 represents the optimal combination of cutting parameters for a minimum surface roughness and power consumption.

- The cutting speed seems to have more influence on the surface roughness than the feed per tooth.
- A careful combination of cutting parameter can achieve low values of surface roughness and power consumption.
- The cutting speed and the feed per tooth have the same influence on the power consumption (around 16 % each).
- The higher the material removal the higher the power consumption and the surface roughness.

## References

1. Lin T (2002) Experimental design and performance analysis of TiN-coated carbide tool in face milling stainless steel. J Mater Process Technol 127:1–7
2. Bernardos PG, Vosniakos GC (2003) Predicting surface roughness in machining: a review. Int J Mach Tools Manuf 43:833–844
3. Ghani JA, Choudhury IA, Hassan H (2004) Application of Taguchi method in the optimization of end milling parameter. J Mater Process Technol 145:84–92
4. Abou-El-Hossein KA, Yahya Z (2005) High speed end milling of AISI 304 stainless steels using new geometrically developed carbide inserts. J Mater Process Technol 162–163:596–602
5. Rao B, Shin Y (2001) Analysis on high-speed face-milling of 7075–T6 aluminium using carbide and diamond cutters. Int J Mach Tools Manuf 41:1763–1781
6. Wang M-Y, Chang H-Y (2004) Experimental study of surface roughness in slot end milling AL2014-T6. Int J Mach Tools Manuf 44:51–57
7. Korkut I, Donertas MA (2007) The influence of feed rate and cutting speed on the cutting forces, surface roughness and tool–chip contact length during face milling. Mater Des. 28:308–312
8. Sun J, Guo YB (2009) A comprehensive experimental study on surface integrity by end milling Ti–6Al–4V. J Mater Process Technol 209:4036–4042
9. Patel P, Patel VA (2012) Effect of machining parameters on surface roughness and power consumption for 6063 Al alloy TiC composites (MMCs). Int J Eng Res Appl (IJERA) 2(4):295–300
10. Bhushan R (2013) Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites. J of Cleaner Prod 39:242–254

# Development of an Intelligent Bolt Tensioning System and Adaptive Process for the Automated Pitch Bearing Assembly of Wind Turbines

**Leenhard Hörauf, Rainer Müller, Jochen Bauer, Holger Neumann and Matthias Vette**

**Abstract** During the rotor blade bearing assembly of wind turbines three bearings, which have a diameter of several meters, are bolted to the rotor hub with hundreds of bolts. Although the introduced preload force on these bolts should be subjected to only minor deviations, the tightening process is performed manually despite of its high labor intensity. To ensure a reproducible quality of the bolt connection and to increase the efficiency of the assembly process, an adaptive automation solution with viable and flexible automation strategy has been developed. This automation allows for an adaptation to different types of wind turbines and a compensation of even larger tolerances of the components. Due to the integration of sensors and actuators in a newly developed robot-guided bolt tensioning tool, process variables are recorded and a response to errors by adjusting process parameters is possible. As a result, the tightening process is carried out automatically and the unreliable sensitivity of employees is replaced by an intelligent tensioning system.

## 1 Introduction and State of the Art

Due to advances in technology, increasing environmental awareness and rising oil prices, the global installed wind turbine capacity has increased steadily in recent years. Additionally, a further increase of installed renewable energy capacity is expected [1, 2]. In order to meet the rising demand as well as maintain its competitiveness against contestants from overseas, the European wind turbine manufacturers have to improve both the productivity and the efficiency of their assembly processes.

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One approach to improve the assembly process is the introduction of automation solutions and the replacement of manual labour. This is problematic in assembly processes, in which product components have large dimensions and tight tolerances have to be met. Due to the small production volume and the large expenses that have to be made, automation solutions were not introduced in the past and manufacturers still rely on the more flexible manual assembly [3].

In a wind turbine assembly, three bearings are joined to the rotor hub in the wind turbine factory. These bearings are assembled between the rotor blade and the rotor hub and ensure the rotation of the blades about their longitudinal axis to influence the rotor′s rotational speed, as shown in Fig. 1 [4, 5]. In modern wind turbines, these bearings have an outer diameter of up to 4 meters. Depending on the loads and the length of the rotor blades, the bearings are connected to the rotor hub with over 120 bolts ranging in size from M30 up to M36.

These critical bolted joints are allowed to have only very small deviations from their exact preload force because the wind turbine has to safely withstand 100 million cycles, without compromising the reliability during its 20-year operating period [7]. Thus, high force requirements are set for the bolt and bolted joint of a wind turbine pitch bearing. Although the product types have minor differences, e.g., in bolt or pitch bearing diameter, and the screw hole pattern for each product type looks the same, nonetheless the bolt tensioning process is performed manually with tensioning cylinders [8]. Therefore, the quality of the connection is influenced by the experience of the worker and the execution of the tensioning process tool. For this reason, viable and flexible technologies are necessary to detect process variables via sensors and to react by adjusting the process parameters in case of errors and different product type variances, such that the tensioning process can be automated and the expenses are kept within limits.

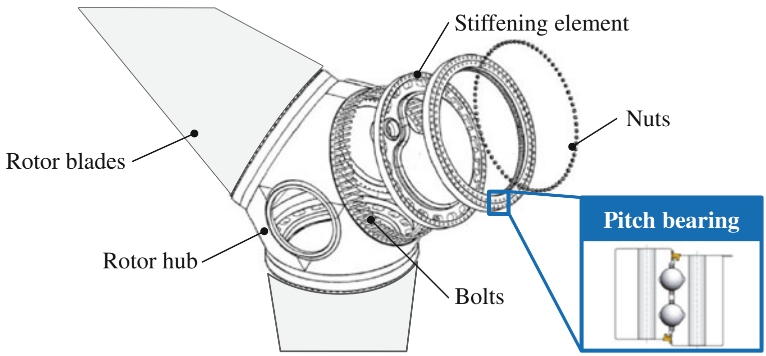


**Fig. 1** Assembly of the pitch bearing between the rotor hub and the rotor blade (*Image Sources* [5, 6])

# 2 Analysis of the Manual Bolt Tensioning Process of Rotor Hub Bearings

To ensure the reliability of a bolted joint, the preload force in the connection has to be set as precisely as possible because the behavior of the joint depends on the clamping state. For example an excessive assembly preload force leads to an overstrain of the bolt. However, if the preload force is too low then the required function cannot be guaranteed. Thus, the tightening tool and process have a significant impact on the functionality of the bolted joint, whereby the usual tightening processes does not allow a direct detection of the preload force within the bolted joints.

The frequently applied tightening method uses the pitch of the bolt thread when the bolt is rotated to calculate the preload force. Due to the thread, the introduced rotary motion is converted into a longitudinal motion and the torque is converted into a longitudinal force. The rotating tools are especially suitable for the assembly of bolts with smaller dimensions because the required tightening torques increase with larger bolt dimensions and also because it becomes difficult to support the torque against adjacent parts. The bolts of a pitch bearing ring require a particular equal and reproducible application of the preload force for all bolts because this has a significant effect on the stiffness of the connection and the service life of the bearing [9]. The preload force application via a torque is relatively inexpensive and simple, but the calculated torques do not match with the actual necessary torques due to frictional influences which cannot be exactly determined. Therefore, the preload force is subject to fluctuations. Moreover, the friction between the nut and the bearing surface leads to deformation and damage of the component surface which causes problems while releasing the bolt. Consequently, the torque-controlled method is an unsuitable tightening method for bolts of wind turbine pitch bearings [6, 10]. Thus, hydraulic bolt tensioning cylinders are used at the pitch bearing assembly with the advantage that the preload force is directly applied and the preload force can be controlled and reproducibly applied. Another advantage is the absence of the additional stress on the bolt cross-section due to torsion and bending. Thus, the bolt is free of shear stress and has only pure axial stress, so that the bolt sustains a higher tensile stress [11].

## *2.1 Analysis of the Bolt Tensioning Process*

In the first step of the manual tensioning process at the wind turbine manufacturer, the bolted connection is subjected to a visual inspection by the worker and the compatibility of the bolting tool and the bolted joint is controlled. After this inspection process, several tensioning cylinders are attached to the bolts which then apply a defined preload force to the bolts, as shown in the upper left corner of Fig. 2.

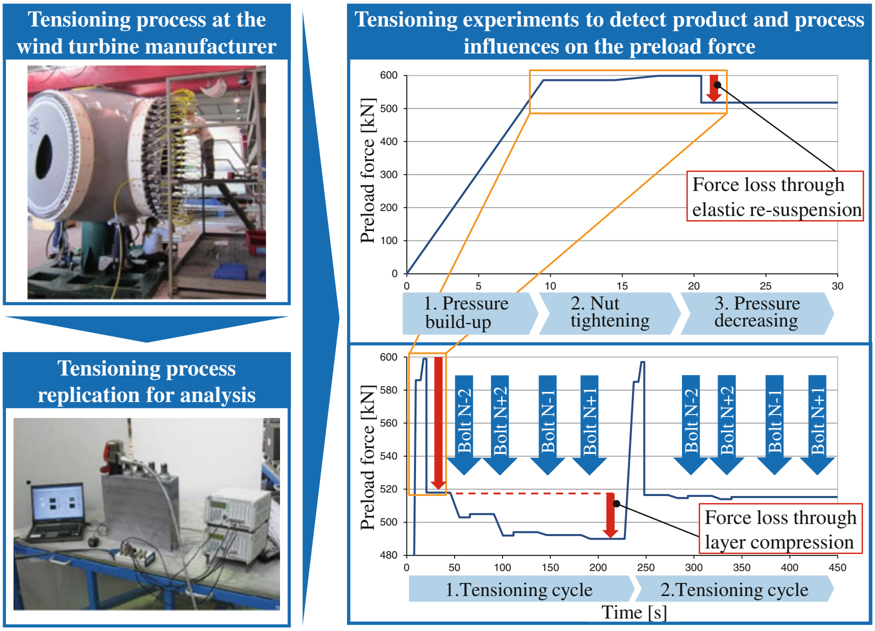


**Fig. 2** Tensioning process and analysis of influences on the preload force

To determine the product and process parameters, which have an effect on the preload force during the tensioning process, investigations have been undertaken and the bolting process was practically simulated on a demonstrator. The experimental setup consists of a test rig which contains a bearing section with five M36 bolts. More components like a manual tensioning cylinder and measurement equipment are used for the tensioning process replication, as shown by the lower left picture in Fig. 2. The applied preload forces are measured during the whole tightening process by strain gauges which are attached to the bolts and connected to an amplifier. The output voltage of the amplifier is converted into a digital signal by an analog-to-digital converter which is connected to a PC.

In the first test series, the influence of the pressure of the tool and the tightening torque of the nut and their effect on the preload force are investigated. The tensioning process is executed with different tool pressures (600, 900, and 1,200 bar) and preset torques (20, 35, and 50 Nm). The results of the tests are simplified and summerized in the upper diagram in Fig. 2. The tightening process is subdivided into the three steps of pressure build-up, nut tightening, and pressure decreasing. In the pressure build-up stage, the pressure increases linearly along the axis of time. In the nut tightening step, the defined torque is applied to the nut with a torque wrench on the gear drive after an approximate constant level of pressure has been reached. During the nut tightening step, the hydraulic unit holds constant pressure while the measured force of the bolt rises. This force increase is caused by extra strain resulting from the applied torque on the nut. In the pressure decreasing step, the measured force of the bolt abruptly reduces, which is referred to as elastic resuspension. This resuspension increases with the applied pressure, but decreases with higher torques at the same pressure level. Thus, the force loss depends on the nut tightening torque and the pressure between 9 and 22 % of their respective maximum target preload force value. To compensate for the preload force loss and to apply the target preload force, the applied pressure has to be higher than the pressure equivalent to the target preload force. A higher torque would reduce the force loss but an additional torsion stress would be applied.

In a further series of experiments, the effects of repeated tensioning of the bolts and the interaction between adjacent bolts on the preload force are investigated. In order to investigate the interaction of adjacent bolts to each other by repeated tensioning, the tensioning cycle was performed twice. During both tensioning cycles the bolts are tensioned with a tool pressure of 1,200 bar and a torque wrench of 50 Nm. In the lower diagram, in Fig. 2, the results of the study are drawn at the force trace of the third bolt showing the interaction by the adjacent tensioning. The biggest loss of preload force results from the pressure reduction of the tool. During the first tensioning cycle, the preload force decreases due to compression in the intermediate layer. This compression effect of directly adjacent bolts is bigger than the influence of the outermost bolts of the test bench. In the second tensioning cycle, the effect of the preload force lost due to adjacent bolt tensioning is less compared to the first cycle. Only the directly adjacent bolts have an effect on the preload force because the intermediate layer has already been compressed in the first tensioning cycle. Because of the compression effect of the intermediate layer and the resulting preload force loss, the bolts are repeatedly tightened in the real process at the wind turbine manufacturer to compensate for this effect. Instead of a repeated tensioning cycle, the multi tensioning is another method to compensate the force loss, where tensioning cylinders are attached to every second bolt.

## 2.2 Definition of Requirements for the Adaptive Tensioning Process

As described in the previous parts of this paper, the present tensioning process of pitch bearing bolts is performed manually by a worker. The objective of this research project is to develop an automated and intelligent tensioning system. The process parameters of this system are adaptable which allows for differentiated response strategies depending on the surrounding conditions. In the previous paper, various examinations were performed to detect the influences of process and product parameters on the preload force. These practical investigations show that adaptivity is required for the preloading process. However, the preloading process is not the only process step that should be performed in an adaptive way. Moreover, this should apply for the total tensioning process starting with the attachment of the tensioning cylinder to the bolt. Due to this, three requirements are defined for the flexibility of the process.

The first requirement is the compensation of the preload force loss. Therefore, it is necessary for the adaptive system to have the ability to adjust the parameters like pressure and torque in a way that the preload force is set up within the specified tolerances. Until now, these parameters are based on the experience of the workers and the optimal parameter setup is investigated in labor-intensive practical experiments. Due to this, the parameter investigation and the tensioning process should be realized in an automated process.

Another requirement is the compensation of product and process tolerances. The rotor hub with the assembled pitch bearings has a weight of almost 25 t. Because of the weight and the dimensions, the positioning process of the rotor hub is difficult and it is not positioned and oriented precisely. Furthermore, the assembled bolts and components of the bolted joint have dimensional tolerances. Due to the amount of tolerances, they have to be detected and the positioning of the tensioning tool has to be made in a flexible manner which allows for a position and orientation adaption based on the detection.

Instead of being used for one specific type of bolted joint and product type, the self-adaptive assembly process aims at flexibility for different assemblies and product types. Thus, the self-adaptive assembly process is able to be used for wind turbine types which differ in the size of bolt diameter and the pitch bearing diameter (Fig. 3).

If the aforementioned requirements are implemented in an automatic system, a reproducible tensioning process is realized which would lead to a consistent quality and safety as no worker interaction is required.

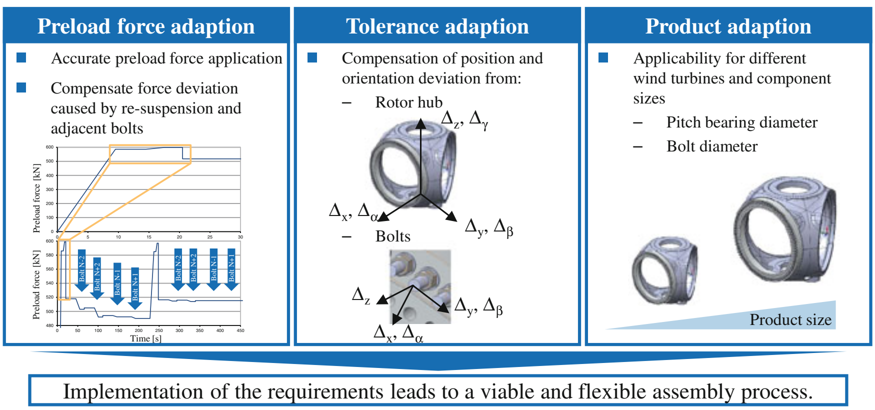


**Fig. 3** Requirements for the adaptive assembly process

## 3 Development of the Adaptive Assembly Process

Regarding the difficulties to automate complex processes like the bolt tensioning process, adaptations have to be taken in order to meet the requirements which were defined in the previous paper. Since the process is nonlinear and tightening of one bolt affects the preload force of the adjacent bolts, it is essential to take different steps to perform the process. Furthermore, the adaptive assembly process should be performed automatically without the influence of a worker. Thus, the process is monitored by sensors and applies the required forces with active drives.

At the beginning of the controlled process, the tensioning cylinder has to be aligned to the bolt at the rotor hub. This guidance is performed by a robot because of its flexibility to different process conditions and to compensate tolerances and inaccuracies of the assembly process and product positioning. To perform the tightening process, the bolt coordinates have to be generated for the robot positioning system. For example this generation can be made by running a simulation of the assembly process in simulation software. Beforehand, a model consisting of all relevant parts and necessary specifications is created in the simulation software. Due to the heavy weight of the rotor hub and other parts of the assembly, precise positioning cannot be accomplished in reality and deviations have to be compensated for. Thus, adapting the coordinates gained out of the simulation is essential. In order to correct the coordinates and to get the real bolt positions, a vision system is used to validate the exact positions and orientations of the bolts. The vision system analyses and processes the images taken of the assembly from camera support points. Due to processing the images, the coordinates of the tensioning points are adapted to achieve an accurate positioning of the tensioning tool. In the next step, the coordinates, which were initially generated in the robot cell simulation, are modified by the vision system and inverse transformed in the robot control to move the six robot axes. As a result, the tensioning cylinder is accurately positioned and orientated to the bolt. Furthermore, the vision system checks whether the components of the bolted joint (bolt, nut, and washer) are present and measures their dimensions. Due to the visual inspection, possible errors are recognized before the tensioning cylinder is attached onto the bolt (Fig. 4).

After the tensioning points identification is finished and the tensioning tool is moved to an offset position above the bolt, the actual tensioning process starts, which is controlled by a programmable logic control (PLC) and is shown in Fig. 5. In the first tensioning process step, the tensioning cylinder is threaded on the projecting thread of the bolt by a drive. Due to a simultaneous monitoring of the torque and the angle of rotation at the change bushing as well as the correct end position of the tensioning cylinder, it is guaranteed that the tensioning cylinder threading process is carried out correctly. This monitoring is necessary to detect thread flaws and to ensure that the thread of the bolt fits into the thread of the change bushing. A deviation in the correlation between the torque and the angle of rotation indicates a flaw in the process. If a flaw is detected the tensioning point

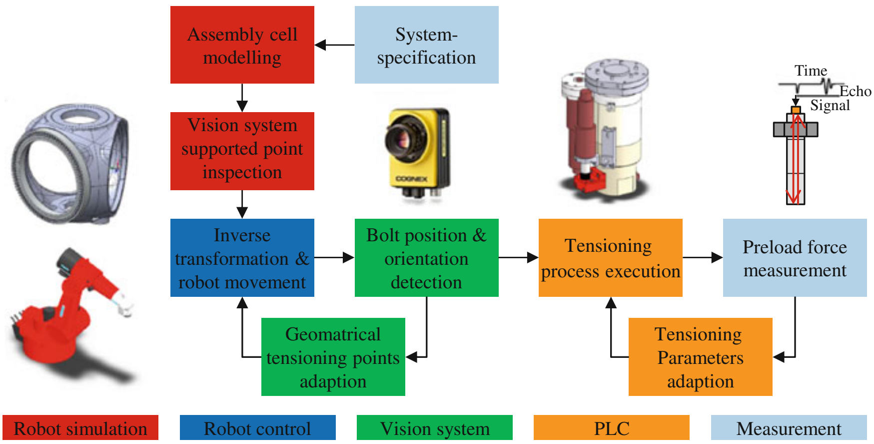


**Fig. 4** Adaptive process for the automated pitch bearing assembly (*Image Sources* [11–13])

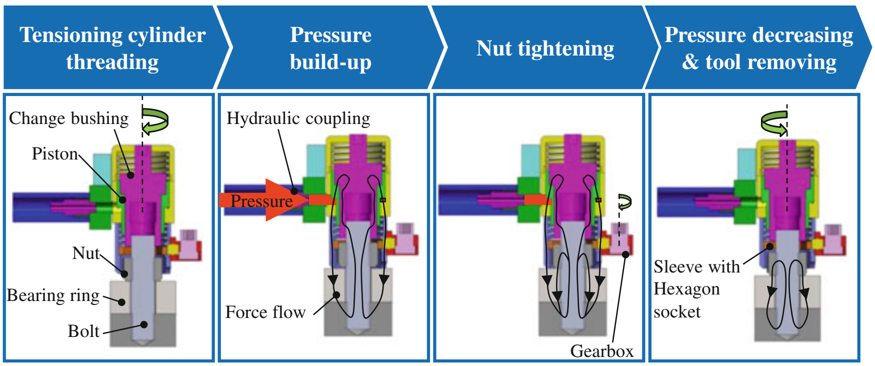


**Fig. 5** Steps of the bolt tensioning process for preload application

has to be adapted and the tensioning tool has to be repositioned as far as possible, otherwise worker intervention is required.

In the following tensioning process step the bolt is tensioned due to the pressure in the tensioning cylinder. During this process the pressure is monitored by a sensor and regulated to set up the pressure precisely and to avoid an overload of the bolt. When the tension cylinder is pressurized and the bolt is stretched, the nut is tightened by a drive. The nut tightening process step has to be monitored and controlled, similar to the tensioning cylinder threading in the previously mentioned process step, in order to detect process faults. In this case, possible faults are thread flaws, a too short thread and a nonfitting hexagon socket compared to the spanner size of the nut. If one of these flaws is detected, parts at the bolt joint or the tensioning tool have to be changed which requires an intervention of the worker.

In the final step of the tensioning process, the pressure is decreased in the tensioning cylinder which is monitored by a pressure sensor. When the pressure decrease is finished the tensioning cylinder is unthreaded from the bolt. For the tool removal, the same drives and sensors are used as in the tensioning cylinder threading process step. To control the tensioning process the preload force is measured by a ultrasonic measurement system to compensate deviations from the reference value and to adapt tensioning parameters, for example the applied pressure and torque at the nut.

The assembly process can be performed on different types of rotor hubs which are considered through task recognition. Beforehand, different parameters for each type of rotor hub are identified and stored in the PLC, which enables the system to access them. The stored parameters are, for example, the bolt positions and dimensions, the sequence in which the bolts are tightened and the required preload force. Depending on the rotor hub type a specific task is started.

## 4 Development of the Intelligent Tensioning System and Self-Adaptive Tensioning Cylinder

For the implementation of the tensioning process, a technical system is developed which is illustrated in Fig. 6. These components are controlled by an overlaying PLC, which works as a guidance system monitoring all sensors and controlling all drives over different inputs and outputs. To have the ability to operate and monitor the process locally, visualization software is running on the panel IPC (Industrial PC) which is communicating with the PLC over TCP/IP on standard Ethernet. Moreover, the intelligent tensioning system offers the opportunity to be connected to a factory control system over OPC to be operated decentralized and to perform a data exchange. The vision system and robot for the tensioning tool guidance are connected over PROFINET to the PLC. The data exchange with the ultrasonic measurement system is also done via TCP/IP on Ethernet. The drives and sensors of the self-adaptive tensioning cylinder and the hydraulic system are connected to the PLC with analog or digital inputs and outputs, which is shown in Fig. 6.

Based on the adaptive tensioning process, the prototype of the tensioning cylinder has been developed in partnership with the company ITH who has many years of experience in the construction of tensioning tools. The tool has two connectors at the top of the tensioning cylinder, as shown in Fig. 7. One connector is an adapter plate to attach the tensioning cylinder to the robot and the other connector attaches the vision system at the side of the tool.

Inside the tensioning cylinder the change bushing is driven by a spline shaft which allows a linear motion of the change bushing. Due to the movable change bushing, the tensioning cylinder can be fitted to the bolt without turning the change bushing. The “sensor—surface contact” is attached to the support sleeves and monitors the placement process. While the tensioning cylinder is moved onto the bolt, the change bushing is moved inside of the cylinder in the direction of the

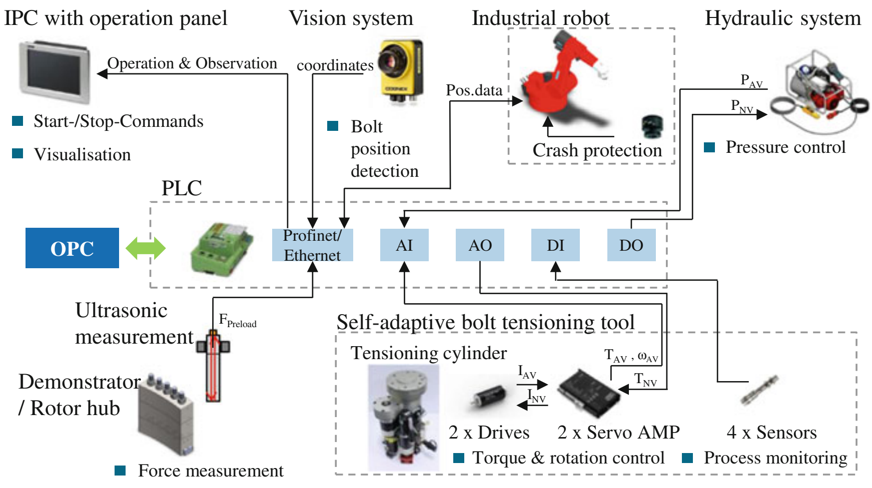


**Fig. 6** Components of the tensioning system and control system architecture (*Image Sources* [12–15])

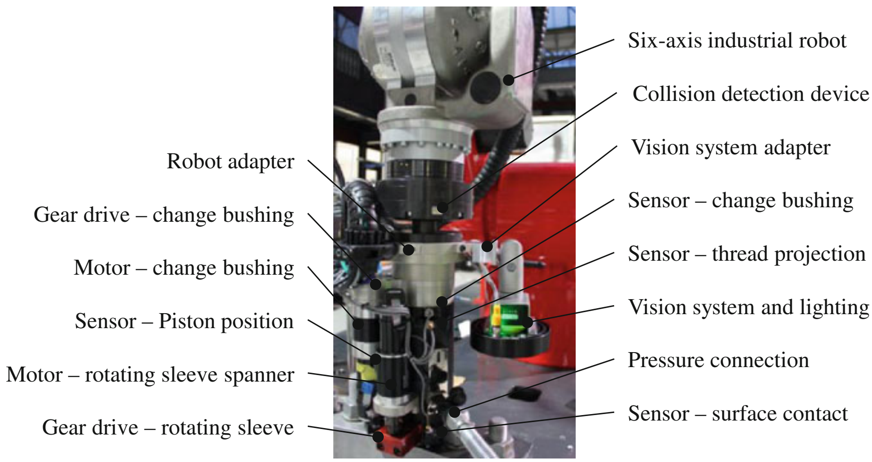


**Fig. 7** Automated tensioning cylinder with integrated sensor system to gain self-adaptivity

safety cover away from the piston until the sensor detects a contact with the bearing surface which stops the placement process.

In this state, the "sensor—thread projection" measures the position of the change bushing to ensure that there is sufficient thread projection above the nut for safety reasons. The height of thread projection above the nut should be equivalent to one bolt diameter at least. Thus, a measuring pin with an indicator is guided on the top of the change bushing. If the indicator on the measuring pin passes the sensor, then an output signal is sent indicating that the process can safely be started.

In order to thread the change bushing on the bolt, it is driven by the “motor—change bushing” via the “gear drive—change bushing”. The threading process will be stopped if the change bushing contacts the piston inside of the tensioning cylinder. In order to prevent high friction forces between the piston and the change bushing surface which results in the wear of the components, this process is also monitored through motor torque measurement. An increase of the motor torque indicates a contact of the change bushing with the piston. Furthermore, the “sensor—change bushing” detects another indicator at the measurement pin when the change bushing and the piston are in contact. This sensor ensures that the change bushing is threaded sufficiently on the thread projection of the bolt. In case of an increasing motor torque, e.g., if the bolt thread has any faults or the change bushing is blocked, this sensor can prevent any damage to the components.

When the change bushing has reached its initial position the pressure is built-up by an external hydraulic unit. The external hydraulic unit is connected via a hydraulic hose with the pressure connection of the tensioning cylinder. Once the nominal hydraulic pressure has been reached the unit is switched off and the pressure level is kept constant. In this stage the nut is tightened onto the bearing surface by driving the rotating sleeve spanner via the “gear drive—rotating sleeve spanner” by the “motor—rotating sleeve spanner.”

At the end of the tensioning process the pressure is decreased with a valve at the hydraulic unit and the piston is automatically returned to its end position by the automatic piston return component. Before the change bushing is rotated contrary to the initial direction, it has to be ensured that the piston is in its end position and the tensioning system is depressurized. For this purpose, the “sensor—piston position” is integrated into the tool. Even if the manometer of the hydraulic unit and the pressure sensor in the hydraulic unit indicate a depressurized system a bending of the hydraulic hose could cause remaining pressure in the system which is indicated by the “sensor—piston position”.

The bolt elongation has to be measured to monitor the applied preload force and to adjust the parameters of the tensioning process. This measurement should be flexible and performed on all bolts of a wind turbine. For these reasons, the preload force is measured with an ultrasonic measuring instrument. The piezoelectric ultrasonic probe is manually attached to the bolt head where it generates a longitudinal ultrasonic wave. Between the ultrasonic probe and the bolt tip, a foil couplant is used to introduce the ultrasonic wave into the bolt [16]. In order to measure the applied preload force, the ultrasonic measuring instrument measures the signal transit time of the introduced signal before and after the bolt tensioning. The difference in the signal transit time value is equal to the bolt elongation and compared with the target preload force value to compensate for deviations due to a feedback to the tensioning process and changes in the process parameters, e.g., applied pressure and nut tightening torque.

## 5 Summary and Outlook

The research contribution of this paper is the development of an adaptive assembly process for wind turbine pitch bearings which performs the tensioning process automatically in an adaptive and flexible approach. The described development process starts with an analysis of the manual tensioning process of bolts. Different experiments are performed on a replica of a pitch bearing ring to detect the influences of elastic resuspension and layer compression on the preload force of the bolts leading to a preload force loss. Based on the analysis and experiments the requirements (preload force adaption, tolerance adaption, and product adaption) for the assembly process are defined.

In the traditional manual process the worker performs, monitors, and controls the process and is able to adapt to different process conditions. Due to the requirements for self-adaptivity and the gained experience in the manual assembly process, a strategy to automate the tasks of the worker and to improve the result, e.g. more accurate application of the preload force, is devised. Therefore a self-adaptive tensioning cylinder is developed with integrated sensors and drives to perform and monitor the tensioning process. This tensioning cylinder is part of an intelligent system with further sensors, e.g., vision sensor and ultrasonic measurement equipment as well as a robot for an automatic positioning and orientating of the tool. All components of the assembly system are connected to a PLC where the developed self-adaptive assembly process is implemented.

Further developments of this research project include the validation of the self-adaptive assembly process and the tensioning system. For this purpose, the adaptive system consisting of the tensioning cylinder with its sensors, the robot, the hydraulic system and the camera will be set up. Furthermore, the assembly parts of a wind turbine rotor hub will be set up in the facilities of ZeMA. Thus, the validation setup consists of the tensioning tool with its drives and sensors, the rotor hub, pitch bearings and components of the bolted joint. The total assembly process will give the possibility to reproduce different conditions in order to validate the adaptive control and system flexibility. After a successful process validation, the research focus for the future will be the multi tensioning cylinders handling of a robot so that one robot is able to attach more than one tensioning cylinder and these cylinders work in parallel.

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## References

1. http://www.wind-energie.de/en/infocenter/statistics. Accessed 2 Jan 2013
2. Musgrove P (2010) Wind power. Cambridge University Press, Cambridge
3. Nordex AG (2009) Lean processes for large orders (Schlanke Prozesse für große Aufträge). Maschine + Werkzeug, No. 6
4. Hau E (2008) Wind turbines: fundamentals, technology, applications, cost-efficiency (Windkraftanlagen – Grundlagen, Technik, Einsatz, Wirtschaftlichkeit), vol 4. Springer, Berlin
5. Kirchner J, Göpfert U, Koop K (2008) Wind turbine with a pitch bearing (Windenergieanlage mit einer Pitchdrehverbindung) Patent No EP 1,959,132 A2
6. Rothe Erde (2013) Slewing bearings, catalogue
7. Argyris JH, Braun KA (1979) Load cycles and material values for the design of a wind turbine hub (Lastwechselzahlen und Materialwerte für die Auslegung einer Windturbine spezieller Nabenkonstruktion), ISD-Report, No 260, Stuttgart
8. http://www.gamesacorp.com. Accessed 2 Jan 2013
9. Monville JM (2005) Hydraulic bolt tensioners for accurate, safe and secure tightening. Evolution—the business and technology magazine from SKF, No 3
10. Lewis TC (1998) Driving outage times down and improving joint integrity using bolt tensioning. Conference publication of power station maintenance: profitability trough reliability, No. 452, pp. 154-156, England, 1998
11. SKF (2011) Bolt-tightening handbook
12. http://www.cognex.com. Accessed 2 Jan 2013
13. http://www.reisrobotics.de. Accessed 2 Jan 2013
14. http://www.phoenixcontact.de. Accessed 2 Jan 2013
15. http://www.maxonmotor.de. Accessed 2 Jan 2013
16. Schneider E, Herzer R (2006) Ultrasonic system for online determination of the bolt preload force and control (Ultraschall-System zur online Bestimmung der Schraubenvorspannkraft und zur Schraubensteuerung), ZfP-NEWS, vol 100, pp 40–46

# Knowledge-Based Operation Planning and Machine Control by Function Blocks in Web-DPP

**Mohammad Givehchi, Bernard Schmidth and Lihui Wang**

**Abstract** Today, the dynamic market requires manufacturing firms to possess high degree of adaptability and flexibility to deal with shop-floor uncertainties. Specifically, targeting SMEs active in the machining and metal cutting sector who normally deal with complex and intensive process planning problems, researchers have tried to address the subject. Among proposed solutions, Web-DPP elaborates a two-layer distributed adaptive process planning system based on function-block technology. Function-block enabled machine controllers are one of the elements of this system. In addition, intensive reasoning based on the features data of the products models, machining knowledge, and resource data is needed to be performed inside the function blocks in machine controller side. This paper reports the current state of design and implementation of a knowledge-based operation planning module using a rule-engine embedded in machining feature function blocks, and also the design and implementation of a common interface (for CNC milling machine controller and its specific implementation for a specific commercial controller) embedded in the machining feature function blocks for controlling the machine. The developed prototype is validated through a case-study.

## 1 Introduction

Today, the dynamic market requires manufacturing firms to possess high degree of adaptability and flexibility to deal with shop-floor uncertainties [1]. Increasing trend of outsourcing, joint ventures, and cross-border collaborations have led to a

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job environment geographically distributed across organizational and national boundaries [2]. This distributed environment raises level of complexity in critical processes and management and level of uncertainties. Specifically, Small-and-Medium-sized Enterprises (SMEs) active in the machining and metal-cutting sector who normally deal with complex and intensive process planning problems in their manufacturing firms are experiencing more shop-floor uncertainties today than ever before. Uncertainties include frequent product changeover, urgent job insertion, job delay, broken tools, unavailability of machines or fixtures, and labor shortage, due to multitier outsourcing, customized product demand, and much shortened product lifecycle, etc. [2].

One of the mission-critical processes and elements in machining job-shops that needs to be adaptive, flexible, and responsive in such a dynamic environment with uncertainties is process planning. Unfortunately, traditional process planning methods are time-consuming and error-prone, if applied directly to such a changing environment. Therefore, adaptive and intelligent process planning has been a hot topic for more than a decade. A process plan generated in advance is often found unsuitable or unusable to targeted resources, resulting in wasted effort spent in early process planning and productivity drop when idle machines are waiting for replanning the remaining machining operations.

Process planning in machining generally refers to those preparatory tasks from design to manufacturing of a mechanical product, such as process sequencing, machine and cutter selection, tool path planning, operation optimisation, NC code generation, as well as setup/fixture planning, etc. Since the introduction of computers to the field of process planning in the 1960s, subsequent research has been numerous. By the end of 1980s, more than 156 computer-aided process planning (CAPP) systems have been reported in the literature survey by Alting and Zhang [3]. CAPP domain is surveyed and reported by Marri et al. [4] in 1998. Xu et al. [5] conducted a more recent survey on the related research, including object-oriented approach, neural network-based approach, Petri net-based approach, genetic algorithm-based approach, multi-agent bidding-based approach, constraint-based approach, feature-driven approach, and information and knowledge management. The reported approaches in [5] and their combinations have been applied to several specific problem domains, such as setup planning, process sequencing, tool selection, cutting parameter selection, and tool path planning, to name a few. More recently, research efforts on process planning have shifted to distributed process planning [2], planning and scheduling integration [6], reconfigurable process planning [7], and intelligent process planning based on capacity profile of machine tools [8]. The common objective of the recent research is to generate robust, precise yet flexible process plans, effectively.

Among proposed solutions, Web-DPP elaborates a two-layer distributed adaptive process planning system based on function-block technology (reported for instance in [2]).

Function-block-enabled intelligent machine controllers are one of the elements of Web-DPP. This topic has been identified as one of the parts of the methodology that needs further investigation both for future generation machine controllers with native function block (FB) support and for legacy machines with traditional NC code support with limited feedbacks. While no commercial FB-enabled controller exists today, some research works have been conducted in the area such as open CNC architecture based on STEP-NC data model and IEC 61499 function blocks by Minhat et al. [9]. Some other works related to function block controlling of a CNC-milling machine and an industrial robot for executing feature-based function blocks are reported in [1] and [10].

Intelligent operation planning is another area that needs further investigation according to the special needs in Web-DPP. Intensive reasoning based on the features data of the products models, machining knowledge, and resource data is needed to be performed inside the function blocks in machine controller side. Machine controllers are considered intelligent units in Web-DPP, which have the intelligence and know-hows about how to manufacture the features. There is a long track of research works in this area of feature-based machining and knowledge-based operation planning until today. Using of expert systems in manufacturing and process planning during 1980s is surveyed by Gupta and Ghosh [11]. Carpenter et al. [12] described methods and a computer based system for automated machinability assessment and tool selection for milling. Their research is based on the increasing demands on competitive cutting tool manufacturers to supply a comprehensive advice service with relation to selection of appropriate tools and cutting data for different applications. Arezoo et al. [13] presented a tool selection and condition selection tool for machining operations using an expert system. Denkena et al. [14] reviewed the CAPP systems from the Knowledge Management perspective in 2007. Waiyagan et al. [15] reported an intelligent feature-based process planning for five-axis mill-turn parts that discussed about machining knowledge representation as production rules of an expert system. Park [16] covered a knowledge capturing methodology in process planning. Li et al. [17] reported about knowledge base and architecture of a STEP-NC Compliant Intelligent Process Planning Module. A knowledge-based hole-machining process planning system is proposed by Lee et al. [18].

In the context of Web-DPP methodology, this paper reports the current state of design and implementation of (1) a knowledge-based operation planning module and a production rules system embedded in machining feature function blocks, (2) design and implementation of a common interface for CNC milling machine controller and its specific implementation for a specific commercial controller embedded in the machining feature function blocks for controlling and monitoring the machine, and (3) a hybrid function-block-enabled machine controller to execute the machining feature function blocks. The components are used in a real-world case study for proof of concept. More details of the problem definition and motivation of the research work are discussed in Sect. 2. Methodology elaboration in different subproblems is elaborated in Sect. 3. The system design and implementation and used technologies are presented in Sect. 4. Test case results are reported in Sect. 5 followed by the summary of the research in Sect. 6.

## 2 Problem Definition

The scope of this paper is about a part of the Web-DPP methodology that is responsible for resource-specific detailed operation planning and execution for the machining features. As Web-DPP methodology declares [2], at first central generic process planning (feature-sequencing, setup-planning, machine selection, …) is performed by the supervisory planning unit and the result in form of a function-block network is deployed to the selected machines. Then the function-block-based process plans are executed on the machine. The main types of function blocks in such programs are machining feature function blocks that are responsible to perform resource-specific detailed operation planning and execution at runtime. The problem to be addressed is what algorithms and technologies are needed for run-time, automatic, resource-specific, detailed operation planning, and execution to be implemented in the machining feature function blocks.

Another aspect of the problem is about the machine controller. Web-DPP demands the machine controllers to be function-block-enabled and be able to execute function block applications. However, in the absence of such controllers in the market, it should still be possible to use commercial NC-based controllers and form function block-enabled controllers. However, they might not necessarily provide all the features that a function-block-based machine controller can provide. Another important requirement that should be taken into consideration in such controllers is that complex algorithms and information/knowledge handling logics need to be implemented inside the machining feature function blocks. It is reasonable for these kinds of programs to be implemented in high-level programming languages. Therefore, one part of the problem is how to design a function block enabled machine controller based on a commercial NC-based machine controller. The controller should also be capable of running the algorithms implemented in high-level languages such as Java.

A test case suggested by industry, as shown in Fig. 1, is used to prove the suggested solution. To create the part, four faces, a deep rectangular pocket and a deep flat-end chamfered hole on top, and a shallow rectangular pocket on the side should be cut from a rectangular cuboid steel stock.

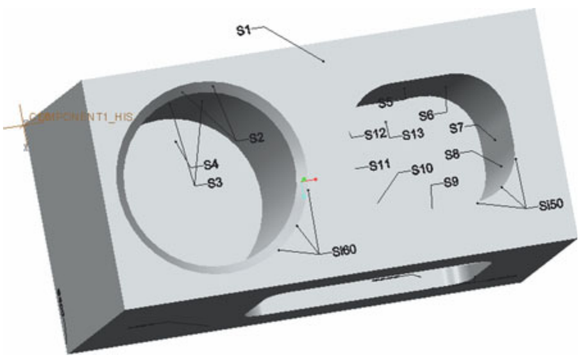



**Fig. 1** A test case with prismatic features (faces, a flat-end chamfered hole, a deep, and a shallow rectangular pocket)

The machine tool is a four-axis horizontal milling machine with locked fourth axis (to be used as a 3-axis machine). The make and model of the machine and its controller are Mori-Seiki NH8000 and FANUC 18i, respectively. The machine is equipped with two different sets of tools representing two different logical machines. Each tool-set consists of twenty tools and should contain necessary tools for at least one possible operation plan for each feature. One of tool sets can be active at a time. One or more tools might be deactivated in the tool sets (representing missing or broken tools). Each feature can be cut by several different alternative strategies and tool types. Depending on the available tools on the machine at the time of execution, a feasible method with the highest priority is planned before actual machining operations.

# 3 Methodology

As the case-study demands, the methodology needs to possess necessary adaptability and interoperability in order to handle different scenarios consisting of different (logical) machines and different available tools. The two-layer methodology of Web-DPP consists of generic process planning (central supervisory planning) at shop-floor level and resource-specific detailed operation planning and execution at machine level. It is also based on the principle that the decisions and planning should be performed on demand and based on real-time situations instead of presumptions. It is designed as a distributed system supporting the related processes from upstream activities after product design until the downstream execution, controlling and monitoring of operations. These aspects of Web-DPP make it suitable for the cases similar to what is defined in the case study demanding flexibility and adaptability. However, different elements of the methodology can be elaborated in different ways. As mentioned before, two of these elements targeted in this paper are (1) knowledge-based resources-specific detailed operation planning, and (2) function block-based execution of process plan and machine control. These functions belonging to the second layer of the methodology are performed by the machining feature function blocks deployed to the machine.

## *3.1 Knowledge-Based Operation Planning for Machining Feature Function Blocks*

Operation planning for machining features is a knowledge intensive and potentially complex decision making process that is traditionally performed by experienced operation planners who are experts in this field. One source of knowledge in this field is the scientific and experimental information provided in formulated and structured formats. They also might be converted to recommendations to be used in operation planning. There is not any unique fully structured and formulated method for operation planning to be used for all cases, domains, and users in the same way. However, to create a desired automatic operation planning component, the methodology needs to be formulated at least to some level. This formulation and structuring should not lead to rigidity of the system. Instead, it should provide ease for supporting a dynamic flexible knowledge-based planning. Knowledge capturing from the domain experts is impossible without some level of structuring [16]. But the system should have the flexibility and supporting elements for wider diversity of the ways information and logic is presented. Several research efforts are conducted related to Computer Aided Process Planning (CAPP) and Computer-Aided Manufacturing (CAM) in scope of feature-based machining and knowledge-based operation planning [4, 5, 11, 13–18].

An automatic operation planning component needs to be based on an artificial intelligence methodology in order to imitate the decision making by humans. Production Rules systems are one of the best disciplines in artificial intelligence that can capture and support the explicit knowledge of the domain experts and other supporting information in form of rules and imitate the logical inference of humans based on the knowledge in hand and given information.

Knowledge management discipline of the system should be able to support different requirements and aspects. For example, cutting tool manufacturers and manufacturing consultant companies have faced an increasing demands to supply a comprehensive advice service with relation to selection of appropriate tools and cutting data for a wide variety of workpiece materials and component geometries [12]. These services are also expected to be used as an integrated component with CAPP and CAM tools. Moreover, distributed manufacturing is being combined with the newer business model concept of cloud computing and is forming newer landscapes in manufacturing business. Providing cloud manufacturing services and forming collaboration based on this concept is one of the drives of research in industry and academy. Web-DPP methodology can be evolved to be used in cloud manufacturing. For this purpose, knowledge-based operation planning component is a key element in the provided services by suppliers. In such environment, knowledge management and providing related collaborative services are key value-added and essential subjects.

Operation planning knowledge captured from domain experts on the main level can be represented by rules. However, these rules in details are referring to different types of data, formulas, logics, and algorithms. Neither the rules nor the referred pieces of knowledge should be hard-coded rigid parts of a CAPP system. In many systems some portion of the knowledge is exposed as manageable and configurable information but the large essential portion is either hard-coded fixed logic or there is no way to add it to the system. For handling the complexity of operation planning knowledge with full flexibility, at least a scripting programming language and data management component with dynamic schema management is required. In addition depending on the system, other sophisticated means are required such as a rule and logic definition language for production rules systems. A difficult challenge in such a system is that operation planning experts are not normally experts in programming, related technologies and knowledge management. It is also not productive if the knowledge management is always dependent to programmers and domain experts simultaneously. To overcome this challenge while providing fully dynamic knowledge management functionality that can represent any level of complexity of knowledge, some measures can be taken. First, a versatile knowledge development environment is needed. Graphical aids, interactive assistance, and pedagogical design are crucial for this environment. These are in addition to the standard level of a user-friendly development environment with modern authoring and proofing tools. Second, using Domain Specific Languages (DSLs) are suggested where familiar manufacturing terms and language is used to convey the logic and information. DSLs are languages tailored to a specific application domain such as machining while advantages and disadvantages should be taken into account and a carefully designed methodology for developing them should be employed [19].

In the current research, the core of operation planner unit is designed as a production rules system in which rules are main building block of knowledge that are grouped into different stages of a decision making flow. The rule-based inference engine goes through the stages of the decision making flow and use forward-chaining technique to activate the necessary rules and infer the desired operation plan. Figures 2 and 3 show two different rules flows with different stages. The first one is for the cases where rules are mainly defined in context of an explicit strategy and hence different operations related to different steps of the strategy are created and completed through the next stages. This flow is suitable for the cases where a set of alternative parametric operation plans or strategies are suggested for a conditioned feature. The second flow is based on the first group rules representing granulated and atomic single step strategies that convert one feature to another. At runtime, different suitable steps would get chained together dynamically to form an operation plan. While the first approach might be more comprehensive for operation planners and knowledge managers, it suffers from knowledge redundancy and resulted change management difficulties and error and lack of existing knowledge reuse.

A machining solution is generated and completed gradually through the operation planning flow. A machining solution consists of one or more atomic machining operations, each of which is associated with a cutting tool assembly

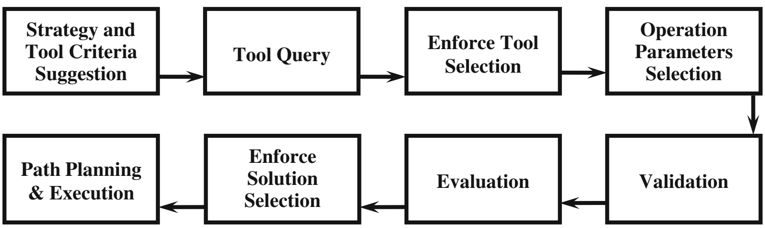



**Fig. 2** Operation planning rules flow with explicit machining strategy

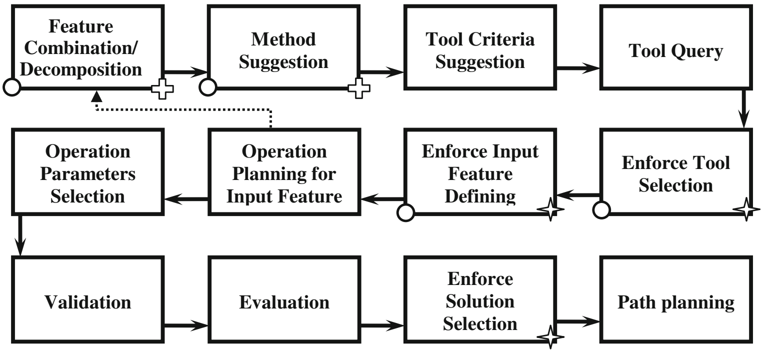


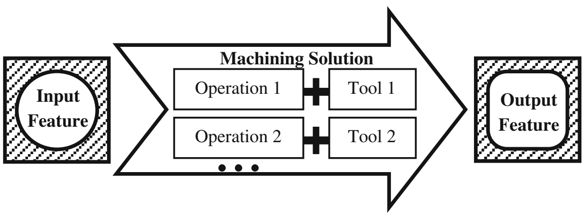

**Fig. 3** Operation planning rules flow without explicit machining strategy (*circle* decisions that can be made automatic and might be overridden by the user; *plus* generating parallel solutions based on decision alternatives; *star* save points for rolling back of decision steps for invalid solutions)

(Fig. 4). More than one machining solutions might be generated by different rules that are to be validated and evaluated. The best feasible solution out of the suggested solutions would be selected. However, other valid but less-favored parallel solutions might be used to override the main solution by an intervening operator.

A rule definition language and a scripting language are needed to author the rules. These languages can be partially or completely replaced by a domain specific language. One feature that is required in authoring the machining rules is the ability to define the criteria over a data type or some related data types. For example, the rule author might need to define a cutting tool criteria set that represents all the tools with a special type and a range of diameters and a range for number of flutes. Normally, rule definition languages have syntaxes for how to define these criteria as conditions in their condition part in a static way. However, it is also required to create and alter object criteria in a dynamic way and use it instead of fully defined object when planning is in progress. These object criteria gradually get tighten in the scope and converted to a concrete and fully defined solution. Also in this process, comparison operators between two object criteria or between object criteria and fully defined objects are required.

At some of the decision points such as feature combination/decomposition and method selection, when more than one valid decision is suggested by the rules, parallel solutions start to emerge. The reason is that number of parallel solution

**Fig. 4** Machining solution as a set of operations and assigned tools for making an output feature



being generated simultaneously by the system is anticipated to be small. On the other hand, at some other decision points such as tool selection and input feature definition, only the best suggested decision alternative is selected. However, this best decision might not necessarily result in a feasible and valid solution. To solve this problem, a decision tracking and decision making transaction control unit is suggested to be used in combination with the inferring engine. This unit stores the track of decisions made in the process of gradual evolving of the solution by the rules. It also stores decision alternatives, or alternative generators for the decision points with multiple valid alternatives. These information can be used either automatically by the system to rollback a decision causing an invalid solution or manually by the user to override a decision.

## 3.2 Using a Conventional Machine Controller as a FB-Enabled Controller

In supervisory planning phase of Web-DPP methodology, through different steps of feature-model analysis, feature sequencing, setup planning, and machine assignment, a generic process plan is generated. This process plan is in form of a FB network and is to be deployed to the FB-enabled controller of a chosen machine. Each machining feature function block instance of the process plan program refers to a corresponding FB type in an existing FB library in the machine controller. Each machining feature function block in the machine library contains the know-hows and ability to provide the resource specific details of the process plan and to cut the feature. These function blocks are to be developed and embedded by machine builders, operation planning experts, and programmers. Therefore two units are required in the system. One is a FB-enabled machine controller that is able to execute a deployed function-block network corresponding to a machining setup and the other is a development environment to create machining feature function block library. When function blocks for a certain set of machining feature is developed and tested and put into the machine controller library, that machine is capable of cutting those features without telling it how to do it.

As it was mentioned before, the first requirement is having a FB-enabled machine controller while no commercial FB-enabled controller exists today, although some research works are conducted [1, 9, 10]. One solution is integrating a FB runtime environment hosted in a separate computer with a commercial controller and considering the whole combination as the FB-enabled controller (Fig. 5). Machine controllers might provide different levels of access to its internal data and commands through a published Application Programming Interface (API). To this extent, the developed logical FB-enabled controller can have different portion of functionalities that a native FB-enabled controller provides. The minimum requirement that also works with a large number of legacy controllers is the ability to send the conventional NC code to the machine through DNC

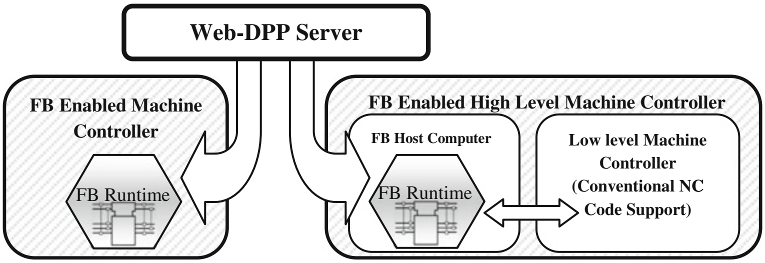



**Fig. 5** Integrating a commercial CNC controller and an external FB host, as a FB-enabled machine controller in Web-DPP

functionality. Controlling the machine is supposed to be done by function blocks at runtime and therefore an adapting layer should be created to convert the command to NC code at runtime. This is in contrast with the approach to generating whole NC code and sending it to the machine to execute with no further control. NC commands in this way are generated at runtime to translate the function-block control logic to the commands understandable by the machine. Due to the fact that planning and control is being done at runtime when the machining is being performed, operation plan adaptation and tuning is possible even during the machining process. It is recommended to define a unique machine controller interface to be used by feature function block to control different machines in the same way. This unique machine control interface should be implemented and configured for different machine types with suitable underlying implementations.

For the second requirement to have a development environment for making machining feature function blocks for the machines, a Web-based development environment is suggested. Figure 6 shows the architecture of the Web-based function-block development environment and function-block runtime environment.

## 4 Design and Implementation

An in-house developed function-block java-based runtime environment based on the architecture illustrated in Fig. 6 is installed and configured on a computer connected to the FANUC 18i machining center controller through an Ethernet network. These two systems together represent a FB-enabled machine controller. Also, a simple Graphical User Interface (GUI) is designed and installed in the controller (Fig. 7) that has the role of Human-Machine Interface (HMI). It shows the process plan FB networks corresponding to different setups deployed by the Web-DPP supervisory planning server to the machine. It is possible to start the process for each setup and see which function block is running at the moment. Detailed operation plan generated by each FB is also visible through the HMI.

Machining feature function blocks are independent in the way they plan and perform the related material removal and they might have heterogeneous

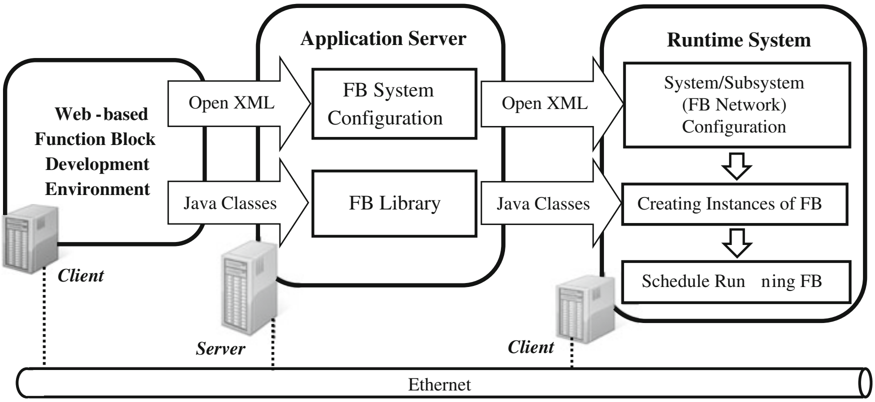



**Fig. 6** Architecture of a web-based function-block runtime environment and its interaction with the server

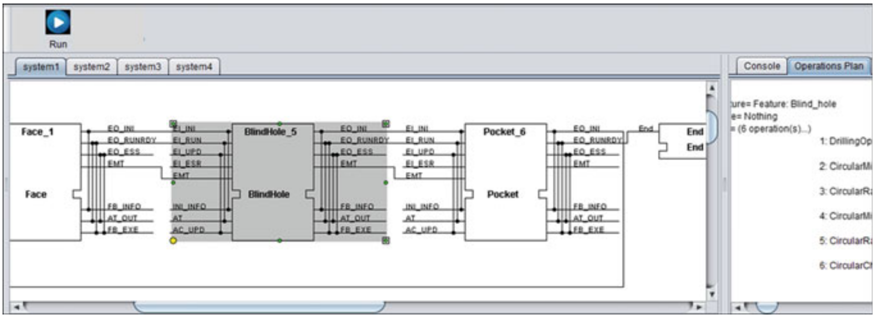



**Fig. 7** FB-enabled machine controller user interface running a process plan deployed from the supervisory planning server

implementations with different techniques. However, all the machining feature function blocks developed for this project, are based on the knowledge-based operation planning method explained in the methodology. Necessary algorithms to perform the operations of generated detailed plans were also implemented for function blocks. Figure 8a illustrates how operation planning algorithms of machining feature function block use the provided production rules engine, machining knowledge base, and resource database to perform operation planning. Drools, an open source Java-based production rules system, is used in the development of the system. The object-oriented rule-based inferring engine with a Rete algorithm implementation provided by Drools is used for operation planning. Moreover, its development environment and tools for rule authoring were used in development of the system.

A common interface, machine controlling API including definition of a set of controlling commands and their parameters (such as commands for spindle start/stop, linear and circular interpolation, tool-change, coolant control, etc.), was

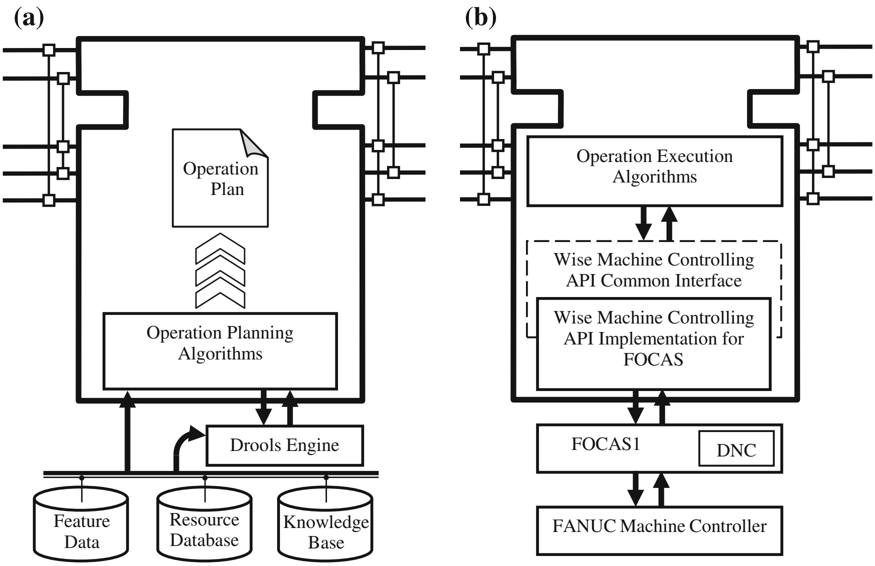



**Fig. 8** Machining feature function blocks: **a** providing production rules engine for operation planning algorithms. **b** Interaction of operation execution algorithms with machine controller

designed. Then, this common interface was implemented for the controller used in the test case. The machine controller vendor provides an API to access some functionalities and data of the controller. This API is called FOCAS and is published as Windows Dynamic-Link Library (DLL). This library was used in C# language in order to implement machine control API for Web-DPP. Then this library was wrapped and adapted as a Java library using jni4net tool to be used in Java-based function-block algorithms. Using this machine controlling interface, function blocks are able to perform higher-level controlling logics that need lower-level runtime interaction with machine. Figure 8b illustrates how the machine is controlled by function blocks and different elements designed for it.

A set of operation types necessary to perform a few different alternative process plans for the test case were developed. These operation objects can be configured and added to the process plan of a feature by the corresponding function block operation planning algorithm (in this work, related rules configure and add the necessary operations to a machining solution for the feature). High-level controlling logic to perform each operation is also implemented and can be used by process plan execution algorithms of the machining feature function blocks. The controlling logic performs tasks such as tool change, spindle speed change, and related runtime path planning and control for approaching, cutting, and retracting using lower-level controlling commands exposed by the underlying common machine control interface.

The mentioned designed and implemented components were integrated to Web-DPP system used in machining the test part.

## 5 Test and Results

Before the system can be used, tool set data with all detailed information of the tools were introduced to the resource database. In addition, machining knowledge for the related features were taken from operation planners, technical handbooks, tool catalogs, etc. The knowledge was then compiled into different rules according to the methodology. Due to the content of the main planning suggestions from experts, the first operation planning flow of the methodology with focus on a multistep complete strategy for a feature is employed. Machining parameter recommendations for different tool types and operation types are also implemented from tool provider catalogue and added to the system as add-ons. These recommendations are used as functions inside the rules. In total, 20 rules are defined in context of different rule-groups. Figure 9a illustrates the results of part model analysis, feature sequencing, and setup planning performed by the supervisory planning layer in Web-DPP server (out of scope of this paper). This generic process plan is converted to a function-block network and is deployed to the hybrid FB-enabled machine controller.

The deployed FB network is shown on the machine HMI in Fig. 7. The function-block network instantiates the machining feature function blocks stored in the machine and performs the detailed operation planning and execution at runtime, resulting in the machined part as shown in Fig. 9b. This test is repeated with changing tool-sets while disabling some of the tools to prove how the system is able to perform feasible operation planning in an adaptive way at runtime based on the available tools.

Table 1 shows the required tools for each strategy. These exact required tools are unknown to the system and finding them is a part of operation planning. They are listed here for the ease of understanding of the scenarios. Strategies are named as $F_xS_y$ where x is one of the feature subtypes (1: flat end hole, 2: Deep rectangular pocket, 3: Shallow rectangular pocket) and y is the identifier of an strategy for that feature. Table 2 shows tool numbers of the tools available in each tool set. Table 3

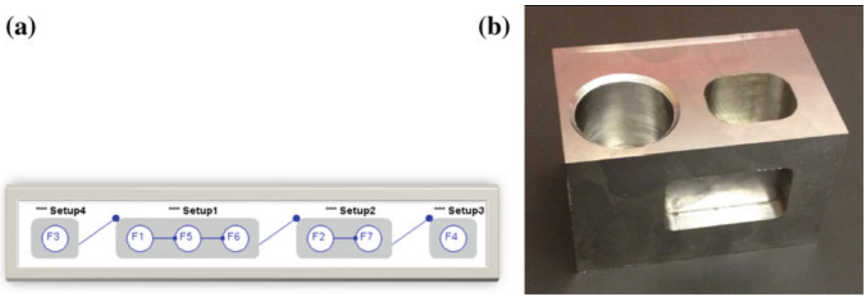



**Fig. 9** **a** Generic operation plan generated by the supervisory planning that is deployed to the machine as FB network. **b** Detailed operation planning and execution performed on the hybrid FB-enabled controller to manufactured the part

**Table 1** Available strategies for each feature type and numbers of matching tools

| Feature-strategy | Matching tool# |
|---|---|
| $F_1S_1$ | 13, 30 |
| $F_1S_2$ | 21, 22, 23 |
| $F_1S_3$ | 3, 29, 30, 10 |
| $F_2S_1$ | 15, 22 |
| $F_2S_2$ | 33, 30 |
| $F_2S_3$ | 34, 37, 30 |
| $F_3S_1$ | 38, 1 |
| $F_3S_2$ | 39, 27 |
| $F_3S_3$ | 15, 22, 1 |

**Table 2** Tool numbers in each toolset

| Toolset | Tool numbers |
|---|---|
| **1** | 1–18, 22, 27, 29, 30, 38 |
| **2** | 21–28, 30–37, 39 |

**Table 3** Test scenarios and strategies selected by the machine

| Scenario | Machine (toolset#) | Special conditions (unavailable tools) | Selected strategies |
|---|---|---|---|
| 1 | 1 | None | $F_1S_1$, $F_2S_1$, $F_3S_1$ |
| 2 | 1 | #13 | $F_1S_3$, $F_2S_1$, $F_3S_1$ |
| 3 | 1 | #38 | $F_1S_1$, $F_2S_1$, $F_3S_3$ |
| 4 | 1 | #13 & #38 | $F_1S_3$, $F_2S_1$, $F_3S_3$ |
| 5 | 2 | None | $F_1S_2$, $F_2S_2$, $F_3S_2$ |
| 6 | 2 | #33 | $F_1S_2$, $F_2S_3$, $F_3S_2$ |

shows six scenarios in which supervisory planner has sent the same generic process plan to one of the two different machines (identical with two different tool sets). The scenarios include special conditions in which some of the tools are not available. The last column of the table shows how the machine has decided to create the part based on the available tools at runtime.

# 6 Summary

In this paper, a knowledge-based operation planning module for machining feature function blocks and a hybrid FB-enabled milling machine controller are introduced to an adaptive distributed process planning and execution framework (Web-DPP). It features an intelligent controller performing knowledge based real-time planning and execution to realize the generic process plan provided by supervisory planning. This machine acts as a seamless part of the whole system with two-way communication. Related methodology, employed technologies, and implementation are reported, and the system is proven through case-study scenarios in practice to perform adaptive operation planning and execution.

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## References

1. Wang L, Givehchi M, Schmidt B, Adamson G (2012) Robotic assembly planning and control with enhanced adaptability. Procedia CIRP 3:173–178
2. Wang L, Givehchi M (2011) Web-DPP: an adaptive approach to planning and monitoring of job-shop machining operations. In: Proceedings of the 7th CIRP international conference on digital enterprise technology
3. Alting LEO, Zhang H (1989) Computer aided process planning: the state-of-the-art survey. Int J Prod Res 27:553–585
4. Marri HB, Gunasekaran A, Grieve RJ (1998) Computer-aided process planning: a state of art. Int J Adv Manuf Technol 14:261–268
5. Xu X, Wang L, Newman ST (2010) Computer-aided process planning—a critical review of recent developments and future trends. Int J Comput Integr Manuf 24:1–31
6. Ueda K, Fujii N, Inoue R (2007) An emergent synthesis approach to simultaneous process planning and scheduling. CIRP Ann Manuf Technol 56:463–466
7. Azab A, ElMaraghy HA (2007) Mathematical modeling for reconfigurable process planning. CIRP Ann Manuf Technol 56:467–472
8. Newman ST, Nassehi A (2009) Machine tool capability profile for intelligent process planning. CIRP Ann Manuf Technol 58:421–424
9. Minhat M, Vyatkin V, Xu X, Wong S, Al-Bayaa Z (2009) A novel open CNC architecture based on STEP-NC data model and IEC 61499 function blocks. Robot Comput Integr Manuf 25:560–569
10. Holm M, Adamson G, Wang L, Moore P (2012) An IEC 61499 function block based Approach for CNC machining operations. In: Presented at the proceedings of the 13th mechatronics forum
11. Gupta T, Ghosh BK (1989) A survey of expert systems in manufacturing and process planning. Comput Ind 11:195–204
12. Carpenter ID, Maropoulos PG (2000) A flexible tool selection decision support system for milling operations. J Mater Process Technol 107:143–152
13. Arezoo B, Ridgway K, Al-Ahmari AMA (2000) Selection of cutting tools and conditions of machining operations using an expert system. Comput Ind 42:43–58
14. Denkena B, Shpitalni M, Kowalski P, Molcho G, Zipori Y (2007) Knowledge management in process planning. CIRP Ann Manuf Technol 56:175–180
15. Waiyagan K, Bohez ELJ (2009) Intelligent feature based process planning for five-axis mill-turn parts. Comput Ind 60:296–316
16. Park S (2003) Knowledge capturing methodology in process planning. Comput Aided Des 35:1109–1117
17. Li P, Hu T, Zhang C (2011) STEP-NC compliant intelligent process planning module: architecture and knowledge base. Procedia Eng 15:834–839
18. Lee C-S, Lee J-H, Kim D-S, Heo E-Y, Kim D-W (2013) A hole-machining process planning system for marine engines. J Manuf Syst 32:114–123
19. Mernik M, Heering J, Sloane AM (2005) When and how to develop domain-specific languages. ACM Comput Surv 37:316–344

# Self-Learning Production Systems: Adapter Reference Architecture

**Gonçalo Cândido, Giovanni Di Orio and José Barata**

**Abstract** To face globalization challenges, today manufacturing companies require new and more integrated monitoring and control solutions in order to optimize more and more their production processes to enable a faster fault detection, reducing down-times during production, and improving system performances and throughput. Today industrial monitoring and control solutions give only a partial view of the production systems status, what compromises the accurate assessment of the system. In this scenario, integrating monitoring and control solutions for secondary processes into shop floor core systems guarantees a comprehensive overview on the entire system and its related processes since it provides access to a greater amount of information than before. The research currently done under the scope of Self-Learning Production Systems (SLPS) tries to fill this gap by providing a new and integrated way for developing monitoring and control solutions. This paper introduces the research background and describes the generic SLPS architecture and focus on the Adapter component responsible for adapting the system according to current context information. The proposed Adapter architecture and its core components are introduced as well as the generic Adaptation Process, i.e., its "modus operandi" to face context changes. Finally, one of three distinct business-case scenarios is presented to demonstrate the applicability of the envisioned reference architecture and Adapter solution into an industrial context as well as its behavior and adaptive ability along system lifecycle.

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## 1 Introduction

As in other domains, production market has deeply felt the effects of globalization on all its different layers [1–3]. The increasing demand for new, high quality, and highly customized products at low cost and with minimum time-to-market delay is radically changing the way production systems are designed and deployed. Production companies are engaged in an innovation race to implement more and more exclusive and efficient production systems able to produce as many product variations as quickly as possible with reduced costs [4]. To achieve this goal, modern production companies need to take into account not only production control and execution processes but also associated secondary processes in a fully integrated approach.

Secondary processes, such as maintenance, energy saving and/or lifecycle optimization, have always been very important for industrial production systems [5] even if they are typically detached from the core monitoring and control system, implying poor machine performance and higher lifecycle production costs. As stated in [6], an integrated approach merging the main production processes with the named secondary processes will enhance the efficiency of production as well as of maintenance and optimization tasks during production systems lifecycle. Therefore, a rational way to attain this goal is to embed self-learning skills into monitoring and control solutions for manufacturing production systems improving system capabilities in terms of reconfiguration, monitoring of equipment performance degradation, optimization of control parameters, sustainability, etc. In this scenario, a Self-Learning Production Systems (SLPS) will be able to both control the production process and constantly monitor all the processes related to it, extracting the particular system context, and adapting all the production parameters such as machine configurations, production strategies, and so on if a context change is perceived.

This paper presents the research and developments related to the *Adapter* proposed architecture in the scope of the integration of SLPSs supported by the use of Service-Oriented Architecture (SOA) principles and technology. Pushing SOA into production control and monitoring levels is becoming increasingly appealing since it leads to the usage of a service-based communications infrastructure to build an unified solution transparently compliant along enterprise ICT levels [7, 8]. The *Adapter* is the component responsible for starting an *Adaptation Process* whenever a change in the actual production system context is perceived. The use of machine learning techniques along production system lifecycle ensures that the *Adapter* naturally calculates the adaptation that best fits the current context based on context data. The reminder of this paper is organized as follows: Sect. 2 presents the SLPS architecture followed by this work; Sect. 3 focuses on the Self-Learning *Adapter* (commonly referred simply as the *Adapter*) generic architecture, on its new *Proactive behaviour* component and on the aspects related with the *Adaptation Process*; Sect. 4 presents the three business cases used for testing and validation of the proposed architecture in real production contexts; finally, Sect. 5 presents the main conclusions and possible future work.

# 2 Self-Learning Production Systems

## *2.1 Motivation*

The research motivation behind this work relates with the strategic objective of strengthening EU leadership in production technologies in the global marketplace by developing innovative self-learning solutions to enable tight integration of control and maintenance of production systems. This approach requires a paradigm shift to support the merging of the world of control with other manufacturing activities of the production systems so-called secondary.

## *2.2 Goals*

The main goal of the FP7-NMP Self-Learning project is to develop innovative self-learning solutions to enable a tight integration of control and other processes of production systems, through the implementation of a SOA infrastructure used to support the proposed reference architecture.

The self-learning approach is intended to have a high impact on manufacturing industries and solve open questions concerning:

- Reduction of time and efforts needed for development/installation of production lines control systems.
- High degree of flexibility in the development and installation of production control systems.
- Reduction of down times during product exchange and/or conflicts situations.
- Increasing of Overall Equipment Effectiveness (OEE), i.e., plant availability and its productivity over time.

This research initiative is driven by three disparate application scenarios applied to real world industrial environment. However, this paper refers to the business case proposed by Fastems-Factory Automation,[1] which specifies the integration of SLPS solution into existent control and monitoring solution to optimize job scheduling and dispatching of flexible production cells for the automotive sector.

[1] See http://www.fastems.com/

## 2.3 Architecture

The reference SLPS architecture [9] (see Fig. 1) has two central components: the *Extractor* and the *Adapter*. These two together are responsible for identifying the current context under which the production system is operating (*Extractor*) and adapt the production system behavior in order to improve its performance in face of that contextual change (*Adapter*). Therefore the *Extractor* acts as an observer of manufacturing process, while the *Adapter* acts as a doer allowing adaptation of manufacturing process parameters.

The result of the context extraction process will be a standardized meta-model gathering all context relevant information obtained by monitoring process machines and devices. This standardized meta-model will be used by the *Adapter* to start an evaluation process for improving production system productivity, efficiency, and performance. Finally, the outcome of the adaptation activity, the *Adaptation* itself, is exposed to the system expert through the *Expert Collaboration UI* for a system expert evaluation.

Since the system response must take into account not only the particular context, but most important, the entire lifecycle behavior of both system and expert, a Learning module has been provided to execute data mining tasks and exploit operator decisions along the system lifecycle. All processed data and knowledge generated are stored in *Data Access Layer* repositories for continuous recording to

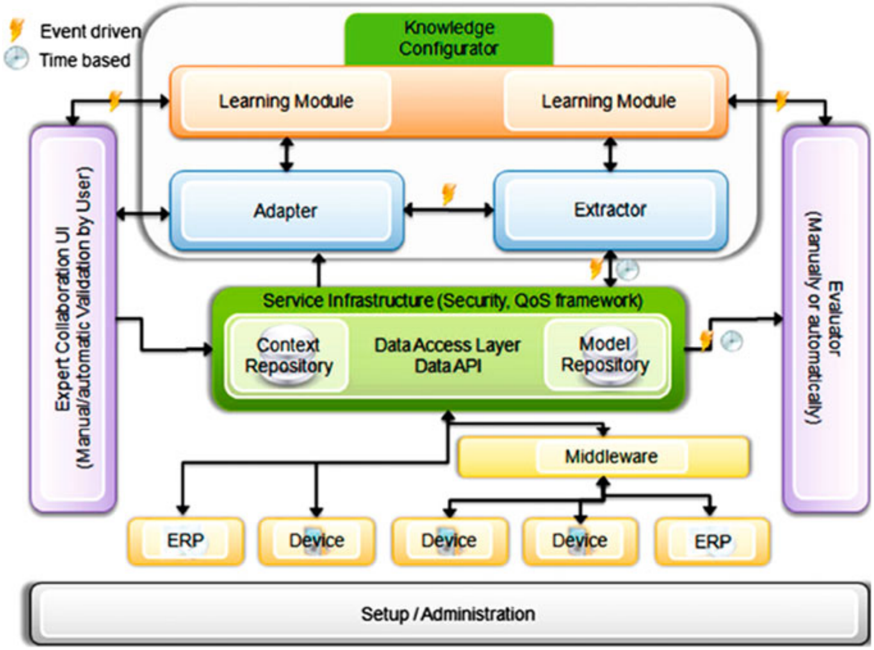


**Fig. 1** Self-learning architectural overview [9]

support consequent evolution. These components allow both *Extractor* and *Adapter* to access it when they need further information about current context.

# 3 Self-Learning Adapter

This section details the *Adapter* component within the SLPS architecture. It was developed to provide system adaptations in response not only of the current system context but also considering system evolution along system lifecycle. The *Adapter* will be described by describing its behavior on top of the proposed architecture. Its main components and the interactions between them are described during each adaptation process.

The issues briefly introduced in the previous sections have been deeply studied during the first stage of the Self-Learning project, reaching a set of required features and functionalities for the *Adapter*:

- React to a change of context and provide a suitable adaptation proposal to be validated by the system expert.
- Employ the *Learning Module* as a mean to process large amounts of data concerning a particular context and identify the fittest adaptation proposal to be presented to the system expert.
- Detect system expert decisions about system adaptation result and deploy the validated adaptation into the system.
- Manage *Adaptation Repository* ensuring that each adaptation record is stored for future use and analysis.
- Proactively process existing data during system idle time and/or when a model is considered out-dated to update its core knowledge about system evolution.

## *3.1 Architecture*

The generic *Adapter* architecture is shown in Fig. 2. The core task-oriented components of the proposed architecture are the following:

- *Context Change Handler*: Responsible for asynchronously handle notification events sent by the *Extractor*, whenever a change in context is detected. These events will be the trigger of the *Adaptation Process*.
- *Repository Extractor*: Responsible for retrieving the necessary information from the *Data Access Layer* repositories related to the current context change. The retrieved data set includes all the information necessary to support the adaptation process that will, in turn, determine the appropriate adaptation proposal, i.e., machines/processes parameters and/or configurations adaptation to the new context.

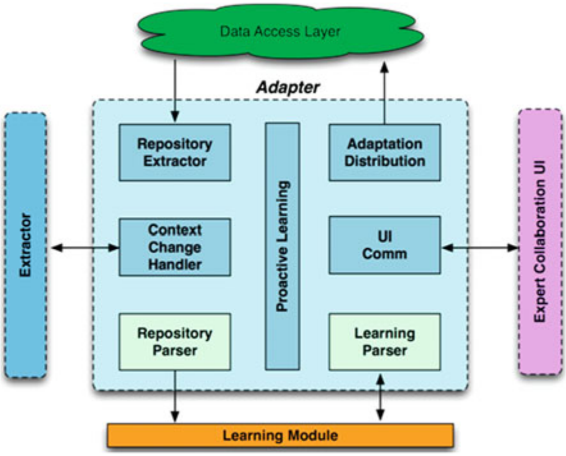


**Fig. 2** Adapter reference architecture

- *Repository Parser*: The data set retrieved from *Data Access Layer* repositories contains raw information that needs to be processed by the *Learning Module*. In summary, the *Repository Parser* creates a generic data structure that will serve as input for the *Learning Module*.
- *Learning Parser*: Similar to the *Repository Parser*, this component acquires the result of the learning reasoning task and parses it to create a generic data object (*Adaptation*), which includes all the information needed by the system expert for validation purposes. Furthermore, it is also responsible for receiving a complete *Adaptation* instance (including the original proposal and result of the system expert validation). This information is crucial to support the accuracy of future adaptation proposals.
- *Adaptation Distribution*: Responsible for distributing an *Adaptation* instance along the SLPS infrastructure environment after it was transferred into the real system. It will store the current *Adaptation* instance in the *Adaptation Repository* and it will inform *Extractor* that an adaptation was done in the system.
- *Proactive Learning*: This module embodies the proactive behavior of the *Adapter* component by proactively performing the relearning of the models based on existing context data. This task can be event-triggered or a cyclic task depending on initial configuration. The major goal is to improve future adaptation proposals and exploit system idle times by running time and processor consuming learning tasks.

Each component has a different role during the process of collaboratively providing adaptation proposals concerning the behavior and parameters of the current context. Since the *Adapter* is simply one brick of the overall infrastructure, it needs to interact with other surrounding modules to entirely fulfill its goals. This way the *Adapter* will interact with the following infrastructure modules: *Extractor*, *Learning Module*, *Expert Collaboration UI* and *Data Access Layer*.

The envisioned architecture points out a purely reactive behavior since the adaptation process is triggered by the *Extractor* whenever a change in production context is detected. However, some kind of proactivity has been embodied in *Adapter* architecture for increasing its autonomy, saving time and resources during system run-time while allowing configuration of the learning models evolution trend along time through some settable parameters. To better clarify the *Adapter* role within the SLPS environment and thus the interactions with the others modules as well as the rule of its own constituent components, an *Adaptation Process* will be explained in Sect. 3.2.

### 3.2 Adaptation Process

The *Adaptation Process* (see Fig. 3) refers to the execution of a sequence of tasks for evaluating production system parameterization consistency, which are performed every time the *Context Extractor* notifies the *Adapter* about a change of context. This notification represents the trigger that will drive the SLPS to adapt itself to the current context.

After being notified about a change of context, the first thing the *Adapter* do is to retrieve all the available information related to this new context. This task is performed by the *Repository Extractor*, which retrieves, from the *Data Access Layer*, all the according datasets and models for the current context (monitoring dataset). This collection of data is then transferred to the *Repository Parser* component to transform it into a generic data structure (*ReasoningInput*) that structures the retrieved monitoring dataset. The *ReasoningInput* will be used as input for the *Learning Module* whenever there is a need to perform a reasoning task. A reasoning task will exploit supervised machine learning classification

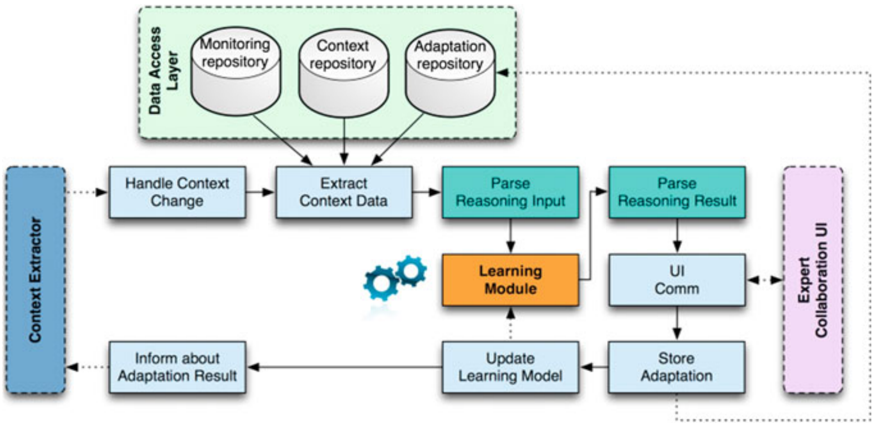


**Fig. 3** Adaptation process overview

techniques that are based on a learning model comprising the entire lifecycle behavior of the system that will breed new production system parameterization proposals.

Consequently, the *Learning Module* will deliver the reasoning task result to the *Learning Parser* component and create the *Adaptation* object instance. Specifically, at this moment, this object instance will include the current context dataset that has triggered the *Adaptation Process*, the adaptation proposal containing the result of the reasoning task, which is going to be shown to the system expert, and finally the adaptation result which is going to be filled with system expert final decision. This way, the *Adaptation* object instance will be transmitted through the *Comm UI* component to the *Expert Collaboration UI* that waits for the system expert to validate, modify, or refuse the original adaptation proposal. The system expert decision will be stored in the *Adaptation* object instance as adaptation result, and at the same time this adaptation result will be transferred to the real production system equipment. Finally, the *Adaptation* object instance will be distributed within the SLPS environment, i.e., notify the *Extractor* concerning the end of the *Adaptation Process*, save the *Adaptation* into the according repository and invoke the *Learning Module* service to update existing learning models with the related context information and adaptation result.

Since supervised machine learning techniques are used to adapt system behavior during its lifecycle, an externally supplied set of context instances are required to build a learning model for the particular application scenario. Once a learning model is available, an inductive machine learning process can be carried out representing the process of learning a set of rules from instances (examples in a training set), creating a classifier/estimator that can be used to generalize from new instances [10]. During the classification/regression task the choice of the specific learning algorithm is a critical step. The learning algorithm choice has been realized considering prediction accuracy and/or relative error. In this scenario several statistical comparisons were conducted between the learning algorithms coming to a final well-suited solution based on the nature of each application scenario.

## *3.3 Proactive Behavior*

Although triggered by the *Extractor* whenever a change in context is detected, the *Adapter* is also capable of monitoring its own state during system operation in order to identify instants in time to proactively launch new learning tasks (*Proactive Learning*). Therefore, when a learning task is launched, i.e., whenever a learn command is sent to the *Learning Module*, a new learning model referring to all the stored contexts information is inferred and a *Cross validation* [11] is performed to analyse the capability of the model to generalize in face of an independent data set. The result of the cross validation is then stored into an appropriate repository that can be queried by the user for retrieving statistical information useful for him to assess the quality of the adaptation proposals. Since

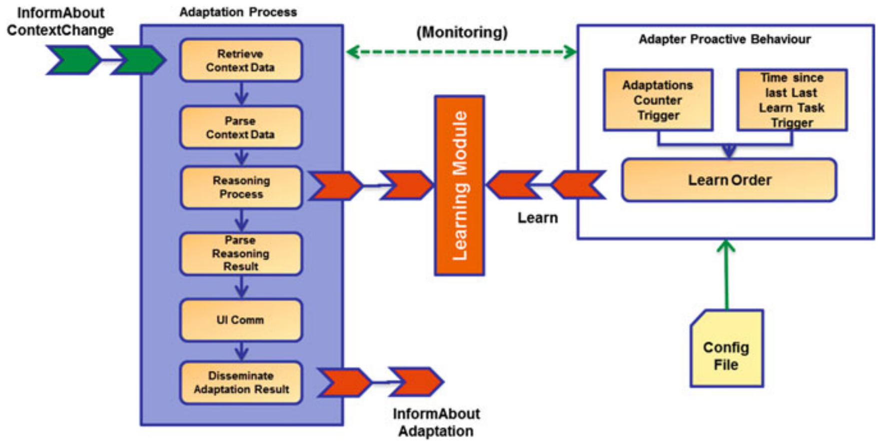


**Fig. 4** Adapter proactive behavior

the learning task is a time consuming activity, the proactive behavior should optimize this process identifying inactivity periods as well as obsolete learning models.

Figure 4 presents an overview of the *Adapter* proactive behavior.

Therefore, during production system operation, the *Adapter* will verify the number of performed adaptation processes and the elapsed time since last adaptation for detecting when a model can be considered out-dated and/or when the system is idle. The level of proactivity is defined through a configuration file, which can be configured by the user in order to specify the thresholds for triggering new learning tasks. The specification of the proactivity thresholds should be a good compromise between system accuracy and the processing time during the *Adaptation Processes*, since a large amount of context instances to learn implies time and processing power for building a new learning model.

## 4 Application Scenario

To validate the current proposal, three business cases from three industrial partners drove the current research work. Each business case is constituted by several application scenarios extracted form concrete industrial environment situations allowing experimental validation of the SLPS platform in order to assure that the proposed solution and Web-based communication infrastructure as well as the methodology is generic enough and valid to be applied at different levels of control & maintenance integration in distinct industrial environments. In this paper, the focus was put over one of the existing application scenarios to validate current infrastructure supported by early test results.

### 4.1 Self-Learning Scheduling and Dispatching for Flexible Manufacturing Systems (FMS) in Automotive Industry

Modeling and scheduling of Flexible Machine Systems (FMS) has been extensively studied and analyzed by several authors [12–15]. A FMS is constituted by several manufacturing high-specialized machines together with automated material handling systems enabling material transport from one machine to another. Each product can be manufactured via one of several available routes and tool implying that an high level controller have to decide how to allocate and/or control the available resources according to the production planning (scheduling and dispatching) to optimize a determinate performance criteria. The optimum management of FMS resources is fundamental in the field of industrial production for decreasing production costs. As stated in [14], the performance of a FMS not supported by an efficient scheduling and dispatching of the resources drastically reduce the advantages derived from its flexibility. Furthermore, the intrinsic heterogeneity of a FMS makes the identification and definition of a strategy for their management more difficult.

The third business case at Fastems is placed in this context, and grounds on the deeper use of a SLPS solution to improve and/or advance general performance of FMS cell by optimizing the machine scheduling and dispatching model according to the current context. Uncertainties in the production environment have to be considered: delays in part availability, machine breakdowns, tool failures, variable markets demands, and so on are only few aspects that make impossible the use on unreconfigurable scheduling and dispatching plans. These factors make the dynamic and/or reactive scheduling essential. Fastems intends to apply SLPS solution together with the existing monitoring and control platform for gathering all the necessary information about the manufacturing production process as well as input from human expert experience concerning the optimization criteria. The SLPS solution will process all the amount of gathered data to dynamically adapt the scheduling plans for avoiding loading stations starvation while improving maximum machines utilization.

### 4.2 Early Experimental Results

To validate current platform fitness and performance, Fastems *FPM DemoLite* simulator was used. This tool simulates the complete behavior of a FMS cell and offers an essential mean to test different production contexts. Common Fastems experts heuristics were followed to determine the appropriate behavior of the system for each context. The objective is to ensure that adaptation proposals converge to a level of accuracy that after some iterations will allow the system to run itself without any system expert intervention, learning from previous contextual decisions. The explicit process model has been dynamically constructed

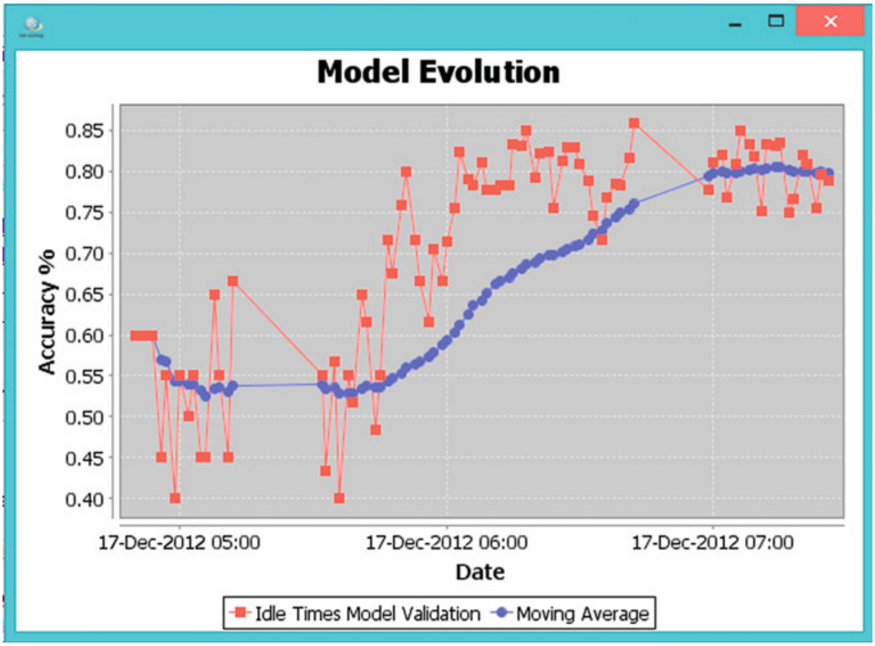


**Fig. 5** Early experimental cross validation results

applying a *Rule Induction* machine learning techniques (provided by the *Rapid-Miner 4.6*) to the following set of manufacturing process parameters provided by Fastems system expert: total loading and machining times, current priority mode, number of pallets, highest, lowest, and average priorities.

Figure 5 presents the early accuracy results obtained with 83 cross-validation tasks performed during system operation. It is visible in the graph that the accuracy improves over time (in proportion to the information added into the learning model coming from adaptations performed to the system) and tends to stabilize around an accuracy of 80 %. Further, tests will be performed on real equipment to confirm these values and, if necessary, correct and optimize some of the learning parameters.

## 5 Conclusions and Future Work

Current work presents an important contribution to the SLPS research domain by introducing a reference *Adapter* architecture as well as a detailed description of its components and behavior. The proposed solution addresses the need for adaptation of several process/control parameters envisioning the improvement of system overall performance and achieve a smoother integration of control and secondary processes along production system lifecycle. This approach relies on context awareness allied to machine learning approaches to enable the system to adapt to contextual changes through learning over previous system expert inputs and monitoring data.

Due to the architecture abstraction, the same implementation is able to cope with three distinct application scenarios although only one of them is presented. However, the data parsers need to be properly configured to face current system intricacies. This validated the solution as generic enough to adapt a wide range of distinct production contexts and goals. Moreover, the effectiveness of the SLPS solution as well as its capability to correctly identify contexts and suggest the best rule to apply has been shown by means of experimental evaluation, highlighting that the system is able to provide good suggestions to the system expert and during the initial phase adapt its own behavior according to optimum behavior provided by the system expert. However, the solution needs to be further integrated and tested to provide more extensive data to improve the reliability and the accuracy of the proposals produced by the *Adapter*. In a broader overview, it is still necessary to address aspects related to reliability, availability, security & trust of services, specifically real-time services in device space within the SLPS framework to then embed this technology in future production equipment.

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## References

1. Levitt T (1993) The globalization markets. The MIT Press, vol 249
2. Narula R (2003) Globalization and technology: interdependence, innovation systems and industrial policy. Wiley
3. Noble DF (2011) Forces of production: a social history of industrial automation. Transaction Publishers
4. Van Dyke Parunak H (1998) What can agents do in industry, and why? An overview on industrially-oriented R&D at CEC. In: Presented at the second international workshop on cooperative information agents II, learning, mobility and electronic commerce for information discovery on the internet
5. Rosiná F, Temperini S (2010) Advanced maintenance strategies for a sustainable manufacturing. In: 10th IFAC workshop on intelligent manufacturing systems (IMS'10), Lisbon
6. Jovane F, Westkämper E, Williams DJ (2009) The ManuFuture road: towards competitive and sustainable high-adding-value manufacturing. Springer
7. Cannata A, Gerosa M, Taisch M (2008) A technology roadmap on SOA for smart embedded devices: towards intelligent systems in manufacturing. In: IEEE international conference on industrial engineering and engineering management, 2008. IEEM 2008, pp 762–767

8. Candido G, Colombo AW, Barata J, Jammes F (2011) Service-oriented infrastructure to support the deployment of evolvable production systems. IEEE Trans Industr Inf 7(4):759–767
9. Uddin MK, Dvoryanchikova A, Lastra JLM, Scholze S, Stokic D, Candido G, Barata J (2011) Service oriented computing to self-learning production system. In: 2011 9th IEEE international conference on industrial informatics (INDIN), pp 212–217
10. Kotsiantis SB (2007) Supervised machine learning: a review of classification techniques. Informatica 31:249–268
11. Kohavi R, A study of cross-validation and bootstrap for accuracy estimation and model selection.
12. Stecke KE (1985) Design, planning, scheduling, and control problems of flexible manufacturing systems. Ann Oper Res 3(1):1–12
13. Jain AK, Elmaraghy HA (1997) Production scheduling/rescheduling in flexible manufacturing. Int J Prod Res 35(1):281–309
14. Rossi A, Dini G (2000) Dynamic scheduling of FMS using a real-time genetic algorithm. Int J Prod Res 38(1):1–20
15. Reyes A, Yu H, Kelleher G, Lloyd S (2002) Integrating petri nets and hybrid heuristic search for the scheduling of FMS. Comput Ind 47(1):123–138

# Forecasting Order Quantity for Treadmill Part by Comparison of Time Series Forecast Technologies and Artificial Intelligence Methods

**F. Michael Chang**

**Abstract** For an enterprise, the forecast of order quantity for a company affects the cost and the balance of production capacity. Many traditional time series forecasting technologies, such as Moving Average and Exponential Smoothing methods, are popular used to forecast order quantity in the field of Industrial Engineering and Management. Recently, machine learning methods in the field of Artificial Intelligence (AI) have also been used for prediction, among them including Artificial Neural Network (ANN) and Fuzzy Neural Networks (FNN) approaches. In this study, real treadmill part order quantity data are used to compare the forecasting efficiency of the above-mentioned four methods with methods which are combined time series and AI methods.

## 1 Introduction

The purpose of this study is to increase the order quantity forecast accuracy for a treadmill part manufacturing company. The price of treadmill part is high and the order quantity of which is low, hence the variation of demand affects the cost largely. The company is a hardware company that manufactures three kinds of treadmill parts by Computerized Numerical Control (CNC) punches and press brakes. These parts for a long-term customer comprise 70 % of the company's income. Actually, this company is the largest company to provide treadmill parts in Taiwan. However, the order quantity is usually unsteady and causes the unnecessary wastes of costs. Therefore, applying forecasting technology to predict the order quantity for this company for cost saving is an important issue.

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Some time series forecasting technologies based on moving average [1, 2] and exponential smoothing [3, 4] methods are applied often. They consider only previous order quantities to predict further demands without considering other affecting factors. Some factors such as season, price, and economic trend may affect product demands, and they can be calculated and adapted from the past data. However, more factors may affect demands also. This study uses real company's historical data processed by moving average, exponential smoothing, Artificial Neural network (ANN), and Fuzzy Neural Networks (FNN) methods to help control the production capacity and make a comparison of these methods.

## 2 Review

### 2.1 Moving Average Method

Moving average method averages the data values over a certain period of time of past and uses the average value to forecast the upcoming value. The benefit of this method is that the extreme datum with large difference from general data in the period of time will be offset and smoothed. Therefore, average data or forecast data values are renewed dynamically. When new datum arrives, the old forecast value is removed and the new predicted value is refreshed. The system always keeps the newest forecasting datum. The number of time units of the data affects the variation of the average values. If the length of time period is short, the variation among the average values is large. Otherwise, the variation is small but the prediction is not smart.

Moving average method takes average over all the data in $t$ period of time up until the current data. It could be calculated as:

$$MA_n = \frac{\sum_{t=1}^{n} A_t}{n}$$

where $MA_n$ is the moving average forecast value, $n$ is the number of period of time, and $A_t$ is the $t$th value.

### 2.2 Exponential Smoothing Method

Exponential smoothing method is a kind of moving average methods but needs simple information only. It is easy to calculate and is easy to change data weights, also it needs only small storage space in a computer. When there are many items for forecasting, it is special suitable for computerized implementations. Exponential smoothing method uses the value of an Alpha Factor to decide the degree of reaction for the previous forecast error. The range of Alpha Factor value is between 0 and 1, where a value in 0.2–0.5 is commonly used. It means that the current forecast value shall consider 20–50 % of the previous value. Exponential smoothing can be calculated as:

$$F_t = F_{t-1} + \alpha(A_{t-1} - F_{t-1})$$

where $F_t$ is the forecast value of the $t$th period of time, $F_{t-1}$ is the forecast value of the (t − 1)th period of time, $A_{t-1}$ is the actual value of the (t-1)th period of time, and $\alpha$ is Alpha Factor, $0 \leq \alpha \leq 1$.

## 2.3 Artificial Neural Network

There are many researches on neural network applications for manufacturing [5–10]. Artificial neural network was introduced in the era of 1940s inspired by biological neuron networks of human brains, and it was introduced a new paradigm parallel and distributed computing [11–20]. It was popularized by a simple family of two-layer neural networks called Perceptron [13–15], which is capable of learning solutions from training data to linearly separable classification problems. One important and useful feature of Perceptron is the convergence property, which says that if a linearly separable problem is solvable, then the solution can be found by a Perceptron in a finite amount of time [19]. However, for nonlinear problems as simple as the XOR problem, they cannot be solved by simple two-layer networks [13]. Multi-layer artificial neural networks with back-propagation learning procedure for solving nonlinear problems were introduced by [16–18]. However, in general, the convergence to a solution cannot be guaranteed for multi-layer networks. Another popular ANN was introduced in the form of learning associations from training data [20].

One example of multi-layer neural network is the Fuzzy neural network that will be reviewed in the following section. While applying ANN, we need two sets of data; one is used as training data set, the other is used as checking data set. Training data are used to train ANN in order to increase the forecast accuracy, and checking data are used to check the prediction accuracy.

## 2.4 Fuzzy Neural Network

Fuzzy Neural Networks, also known as Neuro-fuzzy systems, are multi-layer neural networks integrated with fuzzy inference systems. ANFIS (Adaptive Network-based Fuzzy Inference Systems) is a popular FNN tool proposed by Jang [11]. Given a set of input and output data, ANFIS can construct a fuzzy inference system with membership functions generated by adaptive back-propagation learning.

The basic model of ANFIS is the Sugeno fuzzy model [21, 22]. Let $x$ and $y$ be two input variables, let $z$ be the output variable, and the fuzzy if–then rules are formatted as:

$$\text{If } x = P \text{ and } y = Q \text{ then } z = f(x, y)$$

Consider two first-order rules of Sugeno fuzzy model, the if–then rules can be:

$$\text{Rule } A: \text{ If } x = P_1 \text{ and } y = Q_1, \text{ then}$$

$$f_1 = m_1 x + n_1 y + c_1$$

$$\text{Rule } B: \text{ If } x = P_2 \text{ and } y = Q_2, \text{ then}$$

$$f_2 = m_2 x + n_2 y + c_2$$

where $P_i$, and $Q_i$ are fuzzy sets, and $m_i$, $n_i$ and $c_i$ are constants for $i = 1, 2$. The Sugeno model is shown in Fig. 1a, and the corresponding ANFIS structure with a five-layer artificial neural network is shown in Fig. 1b.

The following is a brief description of the five layers in ANFIS. Let the output of the ith node of layer $l$ be $O_{l,i}$. In Layer 1 of ANFIS,

$$O_{1,i} = \mu_{M_i}(x), \quad i = 1, 2, \text{or}$$
$$O_{1,i} = \mu_{N_{i-2}}(y), \quad i = 3, 4$$

where $\mu_{M_i}$ and $\mu_{N_{i-2}}$ are arbitrary fuzzy membership functions of any types such as triangular or generalized bell function.

For nodes in Layer 2, the outputs $w_i$ are the products of the outputs of Layer 1, and they are used as the weights of Layer 3:

$$O_{2,i} = w_i = \mu_{M_i}(x)\mu_{N_i}(y), \quad i = 1, 2$$

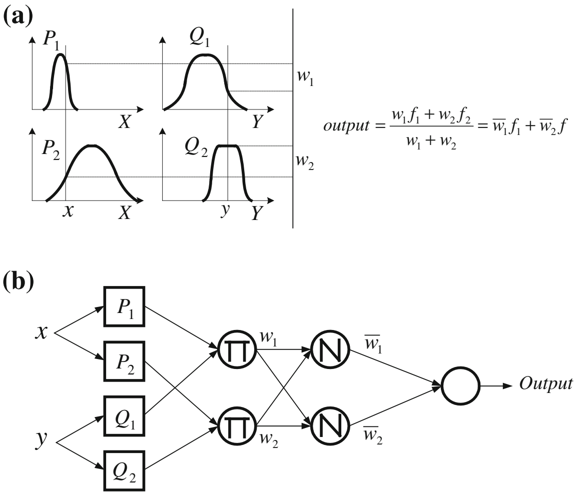


**Fig. 1** **a** The sugeno fuzzy mode. **b** The ANFIS structure

In Layer 3, the output of every node is normalized as follows:

$$O_{3,i} = \bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1, 2.$$

Next, Layer 4 is the defuzzification layer which adapts node values with the following equation:

$$O_{4,i} = \bar{w}_i f_i = \bar{w}_i (m_i x + n_i y + c_i), \text{ for } i = 1, 2$$

where $m_i$, $n_i$, and $c_i$ are parameters of the nodes.

Finally, the fifth layer is to compute the output from all the input signals using the equation:

$$O_{5,1} = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i}, \quad \text{for } i = 1, 2$$

### 2.5 Root Mean Squared Error

In this study, the measurement of errors used to compare the four different forecasting methods is based on the Root Mean Squared Error (RMSE). The RMSE is used to estimate the prediction error, and it is defined as:

$$RMSE = \sqrt{\frac{\sum_{t-1}^{n} (A_t - F_t)^2}{n}}$$

where $A_t$ is the actual value of the $t$th period to time, $F_t$ is the forecast value of the $t$th period to time, and $n$ is the total data number.

## 3 Experimental Data Sets

Experiments conducted in this study to compare the forecast efficiency of both time series and machine learning methods are based on data collected from a real treadmill company from 1998 to 2011. There are 570 records in total, including three products which are represented as T1, T2, and T3, respectively.

For the Moving average and the Exponential smoothing methods, monthly order quantities are used. Table 1 shows 11 data points from the monthly order data set.

For the ANN and FNN methods, the information used for training the learning methods and for predicting order quantities is different from time series methods. Each item in the data set consists of input and output attributes. The input

**Table 1** Part of the data for time serial methods

| No. | Quantity |
|---|---|
| 1 | 1,206 |
| 2 | 281 |
| 3 | 1,282 |
| 4 | 1,390 |
| 5 | 1,022 |
| 6 | 1,314 |
| 7 | 9,86 |
| 8 | 876 |
| 9 | 730 |
| 10 | 879 |
| 11 | 1,032 |

**Table 2** Part of the data for machine learning

| Years | Month | Price | Quantity |
|---|---|---|---|
| 2009 | 1 | 175 | 1,206 |
| 2009 | 2 | 175 | 281 |
| 2009 | 3 | 175 | 657 |
| 2009 | 4 | 175 | 879 |
| 2009 | 5 | 175 | 1,022 |
| 2009 | 6 | 180 | 1,390 |
| 2009 | 7 | 180 | 986 |
| 2009 | 8 | 180 | 1,314 |
| 2009 | 9 | 180 | 730 |
| 2009 | 10 | 180 | 876 |
| 2009 | 11 | 180 | 1,032 |
| 2009 | 12 | 180 | 1,282 |

attributes include year, month, and price, and the order quantity is the output attribute. Some of this data set is shown in Table 2. Data from 1998 to 2010 are used as training data sets, and data of 2011 are used as checking data.

# 4 Results

## *4.1 Moving Average Method*

The results of applying moving average method to the experimental data are shown in Table 3. The time series moving average method is applied with three different lengths of period of time N = 3, N = 5, and N = 7. The forecasting results are collected for the three different products T1, T2, and T3. Their RMSE values are as shown in Table 3. It indicates that N = 7 has the smallest RMSE.

**Table 3** RMSE of moving average method

| | N = 3 | N = 5 | N = 7 |
|---|---|---|---|
| **T1** | 361 | 348 | 342 |
| **T2** | 216 | 216 | 211 |
| **T3** | 65 | 64 | 63 |

## 4.2 Exponential Smoothing Method

Data used for the exponential smoothing method are the same as those used in the moving average method. The Alpha Factor $\alpha$ is set as 0.1, 0.3, 0.5, 0.7, and 0.9 to forecast the order quantities. The RMSE values are listed in Table 4. When $\alpha = 0.9$, the RMSE has the smallest value.

## 4.3 ANN-Moving Average

We use two kinds of data to predict order quantities by the ANN approach. In this subsection, following the different period of time concept in moving average method, we use the previous certain period of time data to forecast newest value by ANN. For example, when N = 3, three periods of time data $\{x_1, x_2, x_3\}$ are used as 3 input data to forecast $x_4$ the fourth value. When $\{x_2, x_3, x_4\}$ are used as 3 input data, $x_5$ is the value to be predicted. The RMSE results are shown in Table 5. It is clear that when N = 7, RMSE is the smallest. Comparing to Tables 3 and 4, the RMSE values in Table 5 are smaller

**Table 4** RMSE of exponential smoothing method

| | $\alpha$ | | | | |
|---|---|---|---|---|---|
| | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
| **T1** | 440 | 400 | 369 | 343 | 326 |
| **T2** | 243 | 227 | 215 | 213 | 205 |
| **T3** | 80 | 73 | 68 | 66 | 65 |

**Table 5** RMSE of ANN-moving average

| | N = 3 | N = 5 | N = 7 |
|---|---|---|---|
| **T1** | 326 | 315 | 303 |
| **T2** | 209 | 203 | 194 |
| **T3** | 63 | 63 | 62 |

**Table 6** RMSE of ANN-factor

| | |
|---|---|
| T1 | 309 |
| T2 | 197 |
| T3 | 63 |

### 4.4 ANN-Factor

Another way to apply ANN method for prediction is to use more attributes to represent data. In this section, data attributes year, month, and price are used as inputs and quantity is used as output. After training and checking, the RMSE for each product is presented in Table 6.

### 4.5 FNN-Moving Average

Following the ANN-Moving Average method, we use previous period of time values in moving average method for FNN learning to forecast order quantity. Their RMSE values are lower than those in ANN-Moving Average and are shown in Table 7.

### 4.6 FNN-Factor

Following the ANN-Factor method, we use FNN learning for the same data. Their RMSE values are listed in Table 8. They are lower than those in Table 6.

We compare the RMSE values of above methods in Fig. 2. For moving average, exponential smoothing, ANN-Moving, and FNN-Moving Average methods, the best results (N = 7 or $\alpha = 0.9$) are selected for the comparison in the figure. The results indicate that FNN-Moving Average and FNN-Factor methods have the best results. They are almost the same. However, in the ANN methods, ANN-Moving

**Table 7** RMSE of FNN-moving average

| | N = 3 | N = 5 | N = 7 |
|---|---|---|---|
| **T1** | 301 | 292 | 285 |
| **T2** | 174 | 184 | 178 |
| **T3** | 60 | 59 | 58 |

**Table 8** RMSE of FNN-factor

| | |
|---|---|
| **T1** | 286 |
| **T2** | 178 |
| **T3** | 58 |

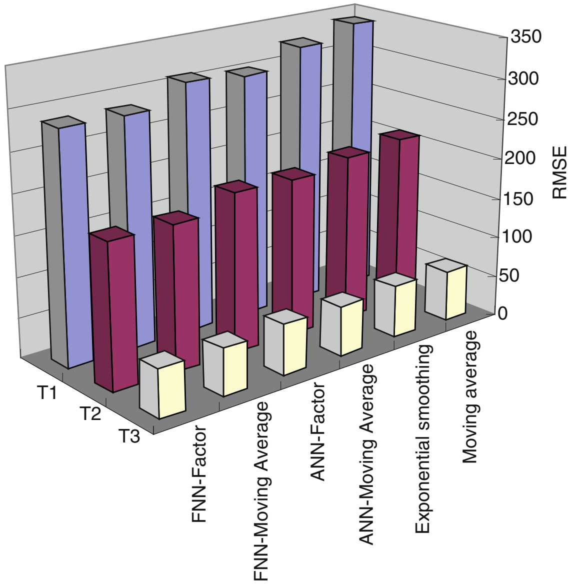


**Fig. 2** Comparison of forecast methods

Average method' RMSE values are a litter better than ANN-Factor'. From the other viewpoints, combining AI methods, FNN-Moving Average and ANN-Moving Average methods have better results than traditional moving average method.

## 5 Summary

It is very important for a company to balance its production capacity and required orders. However, it is challenging to predict order quantities, since order demanding patterns are unsteady in general. It is clear that production capacity may become insufficient when the quantity of orders jumps up abruptly, and it may lead to extra overtime labor costs, delay of finishing products, or losing customers. On the other hand, when the quantity of orders suddenly decreases, production capacity is wasted. Labors and machines are idle but the company still has to pay salaries and machine costs.

In this study, time series forecasting method and AI machine learning method are combined to improve order quantity prediction accuracy for a treadmill part company. The proposed methods are compared with traditional time series forecasting methods by historical data collected from the company. The results show that combining time series and AI methods indeed can improve the forecast accuracy, at least in this case.

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## References


1. Zhang NF (2006) The batched moving averages of measurement data and their applications in data treatment. Measurement 39(9):864–887
2. Moon YS, Kim J (2007) Efficient moving average transform-based subsequence matching algorithms in time-series databases. Inf Sci 177(23):5415–5431
3. Taylor JW (2004) Volatility forecasting with smooth transition exponential smoothing. Int J Forecast 20(2):273–286
4. Billah B, King ML, Snyder RD, Koehler AB (2006) Exponential smoothing model selection for forecast. Int J Forecast 22(2):239–247
5. Chryssolouris G, Lee M, Ramsey A (1996) Confidence internal prediction for neural network models. IEEE Trans Neural Netw 7(1):229–232
6. Chryssolouris G, Lee M, Domroese M (1991) The use of neural networks in determining operational policies for manufacturing systems. J Manuf Syst 10(2):166–175
7. Chryssolouris G, Lee M, Pierce J, Domroese M (1990) Use of neural networks for the design of manufacturing systems. Manuf Rev 3(3):187–194
8. Zhang G, Patuwo B, Hu M (1998) Forecasting with artificial neural networks: the state of the art. Int J Forecast 14(1):35–62
9. Maier HR, Dandy GC (2000) Neural networks for the prediction and forecasting of water resources variables: A review of modelling issues and applications. Environ Model Softw 15(1):101–124
10. Hippert HS, Pedreira CE, Souza RC (2001) Neural networks for short-term load forecasting: a review and evaluation. IEEE Trans Power Syst 16(1):44–55
11. Agatonovic-Kustrin S, Beresford R (2000) Basic concepts of artificial neural network (ANN) modeling and its application in pharmaceutical research. J Pharm Biomed Anal 22(5):717–727
12. McCulloch W, Pitts W (1943) A logical calculus of ideas immanent in nervous activity. Bull Math Biophys 5:115–133
13. Minsky ML, Papert SA (1969) Perceptrons. MIT Press, Cambridge
14. Rosenblatt F (1958) The perceptron: a probabilistic model for information storage and organization in the brain. Cornell Aeronaut Lab Psychol Rev 65(6):386–408
15. Rosenblatt F (1962) Principles of neurodynamics. Spartan, New York
16. Rumelhart DE, Hinton GE, Williams RJ (1986) Learning representations by back-propagating errors. Nature 323(6088):533–536
17. Rumelhart DF, McClelland JL, The PDP Research Group (1986) Parallel distributed processing: explorations in the microstructure of cognition, Vol 1: foundations. MIT Press, Cambridge
18. McClelland JL, Rumelhart DE, The PDP Research Group (1986) Parallel distributed processing: explorations in the microstructure of cognition, Vol 2: psychological and biological models. MIT Press, Cambridge
19. Novikoff AB (1962) On convergence proofs on perceptrons. In: Symposium on the mathematical theory of automata, Vol 12, pp 615–622
20. Kohonen T (1977) Associative memory: a system theoretical approach. Springer, New York
21. Sun ZL, Au KF, Choi TM (2007) A neuro-fuzzy inference system through integration of fuzzy logic and extreme learning machines. IEEE Trans Syst Man Cybern B Cybern 37(5):1321–1331
22. Huang YP, Hsu LW, Sandnes FE (2007) An intelligent subtitle detection model for locating television commercials. IEEE Trans Syst Man Cybern B Cybern 37(2):485–492
23. Jang JSR (1993) ANFIS: adaptive-network-based fuzzy inference systems. IEEE Trans Syst Man Cybern 23(3):665–685

# Analytical Method for Obtaining Cutter Workpiece Engagement in Five-Axis Milling. Part 3: Flat-End Cutter and Free-Form Workpiece Surface

**O. Hendriko, Emmanuel Duc and Gandjar Kiswanto**

**Abstract** In five-axis milling of 3D free form surface, determination of instantaneously changing cutter workpiece engagement for supporting force and surface quality prediction is still a challenge. In order to predict cutting force accurately, precise geometric information on cutter workpiece engagement is very important. Solid model and discrete model are the most common method used to predict the engagement region. Both methods give the result with the accuracy as the tolerance set in the beginning. However, the methods are suffering with the long computational time. This paper presents a new simple method to define Cutter Workpiece Engagement between flat-end cutter and free form workpiece surface. The engagement is calculated by using a combination of discretization and analytical method. Despite workpiece is discretized by normal vectors, but there is no calculation to check the intersection between cutter and normal vector. They are only used as the reference to define the shape of the surface at every Cl-point, mathematically. The engagement point is obtained based on predicted surface shape and tool orientation at instantaneous location. The formula were derived and implemented in a computer simulation. The program simulation can generate instantaneous cut shape and its size. To ensure the accuracy of the developed method, it was tested by compared the depth of cut generated by the program simulation with the depth of cut measured in Unigraphic. A test on sculptured part surface and workpiece surface was performed. The result indicates that the proposed method is very accurate.

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## 1 Introduction

In theory, the five-axis machining of sculptured surfaces with flat-end cutter offers many advantages over three-axis machining with ball end-mill, including faster material removal rate, improved surface finish and elimination of hand finish [1]. Nowadays, due to increasing competitiveness in the market, decreasing production time without sacrificing the part quality is becoming more vital. The new popular technique for advancing productivity and quality of machining processes is virtual machining. Manufacturing process include designing, testing and producing the parts is simulated in a virtual environment before it sent to the real machining. One of the main purposes of virtual machining is how to predict the instantaneous cutting force in milling operation, and hence the proper feedrate can be selected. Proper feedrate selection is always being very critical because it is directly influence the machining productivity and product quality. Selecting the most suitable feedrate values for free-form surface parts where the amount of material removal is constantly changing has the potential for great advantages. One of the optimization methods which have become popular in recently is feedrate scheduling. Process optimization is performed by adjusting feedrate.

In supporting the machining optimization, the precise geometrical information is very important especially in the modeling and calculating cutting force [2]. Various studies in geometric simulation strategy based on solid modeling include constructive solid geometry (CSG) and boundary representations (B-Rep) have been conducted. Altintas and Spence [3, 4] used CSG to identify cutter workpiece intersection to predict cutting forces. While El-Mounayri et al. [5] used a solid modeling system to compute the volume removed for a three-axis tool path. Other researchers who have contributed significantly are Jerard et al. [6–8]. They evaluated the conditions of cutter part engagement with computationally efficient algorithms called Z-map method. In this method, the workpiece was broken into a set of evenly distributed discrete z-direction vectors (ZDV). The Z-map or dexel can be thought of as a special type of discrete vector model, or also known as discrete vertical vector [9]. Another type of discrete vector model is discrete normal vector. This model represents the workpiece as a set of position and direction vectors where the directions are generally normal to the corresponding surface point. Solid modeling gives more accurate information, but computation time drastically increased. Meanwhile discrete vector model makes the calculation become faster than solid modeling. However, the computation time increases intensely as the precision and accuracy is to be improved.

Discretization method to obtain Cutter Workpiece Engagement (CWE) data is time consuming, especially for a simple surface like flat surface. To overcome such problem, Ozturk and Lazoglu [10] proposed an analytical method to determine chip load of ball-end mill during 3D free-form machining. In spite of the method is fast and accurate, but it is only applicable for 3-axis milling with flat workpiece surface. Another study was performed by Tunc and Budak [11]. When the surface is flat, a simple analytical method called bounding point coordinate was used. However, if the sculptured workpiece surface is machined, then they used faceted model to represent the workpiece surface. Analytical method was proven much faster and more accurate compared with the discrete approaches. However, study on CWE by using analytical method has not been well developed. Another limitation of the current analytical methods is they cannot provide Cutter Workpiece Engagement (CWE) data with respect to engagement angle. The instantaneous length of cut and cut thickness information are required to predict the instantaneous cutting force [12].

This paper presents a new analytical method for generating the instantaneous CWE in five-axis milling. The method is not only applicable for the workpiece with flat surface, but also for free form surfaces. The length of CWE can be determined by determining the coordinate of upper CWE (n) and cutter contact point (C) as shown in Fig. 1a. Upper CWE is end of engagement point that located on the workpiece surface. The workpiece surface is discretized by a number of normal vectors. Even though the normal vectors are applied in this model, but there is no calculation to check the contact between cutter and normal vector. The coordinate and orientation of the normal vector are used as the reference to define the shape of the surface at every tool position, mathematically. The predicted surface shape and the tool orientation will be employed to define the intersection of the tool and the workpiece surface. This paper is part of research project on analytical method for obtaining CWE in various stages of five-axis milling. The results are divided into three technical papers. Part 1 is focused on model development during semi-finish milling. Meanwhile free-form workpiece surface with toroidal cutting tool is discussed in Part 2.

## 2 Identifying Normal Vector and Surface Shape

In this study the workpiece surface is represented by a number of normal vectors. The vectors are distributed on the surface with $k_x$ and $k_y$ equal to half of cutter diameter. Where $k_x$ and $k_y$ are the distance between normal vector in *x-direction*

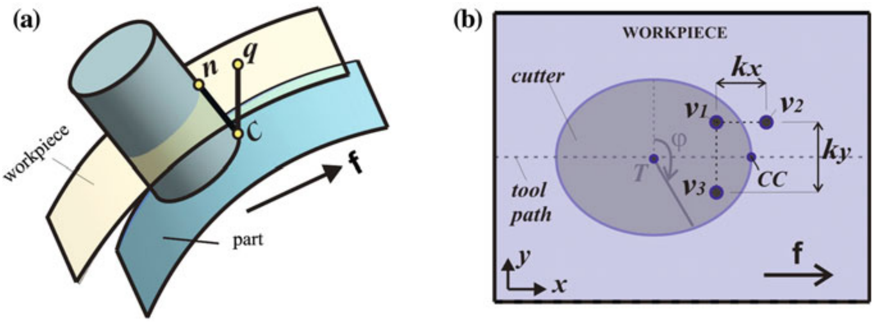


**Fig. 1** Workpiece surface representation, **a** projection line and upper CWE, **b** number and location of the reference vectors

and in *y-direction*, respectively. Three reference vectors are selected at every cutter location point (*T*) as shown in Fig. 1b. $v_1$ is a reference vector which is closest to point *C* at engagement angle ($\varphi$) equal to 90. It can be located inside or outside the tool. While $v_2$ and $v_3$ are two vectors which are located before $v_1$. The normal vectors can be defined as a point on the workpiece surface which has the orientation relative to surface in *x-axis* ($\varepsilon_x$) and the orientation of surface in *y-axis* ($\varepsilon_y$). Vector information is obtained by converting surface data generated from the CAM software $v_i(x_i, y_i, z_i, I_x, I_y, I_z)$ to become $v_i(x_i, y_i, z_i, \varepsilon_{xi}, \varepsilon_{yi})$. Their orientations are simply calculated by these equations,

$$\varepsilon_{xi} = \tan^{-1}(I_x/I_z);\ \varepsilon_{yi} = \tan^{-1}\left(I_y/I_z\right); \quad \text{where } (i = 1, 2, 3) \tag{1}$$

Based on the vector information, the shape of the surface at every cutter location (Cl) point can be defined. The radius of surface in *x-axis* ($R_x$) and surface in *y-axis* ($R_y$) can be determined by,

$$R_x = \frac{\sqrt{(x_2 - x_1)^2 + (z_2 - z_1)^2}}{2\sin(0.5(\varepsilon_{x2} - \varepsilon_{x1}))}; \quad R_y = \frac{\sqrt{(y_3 - y_1)^2 + (z_3 - z_1)^2}}{2\sin(0.5(\varepsilon_{y3} - \varepsilon_{y1}))} \tag{2}$$

After $R_x$ and $R_y$ are obtained, then some conclusions regarding the shape of the surface in *x-axis* ($S_x$) and *y-axis* ($S_y$) can be taken.

- Convex surface: if $R_x > 0$, $R_y > 0$
- Concave surface: if $R_x < 0$, $R_y < 0$
- Flat surface: if $R_x = 0$ and $\varepsilon_{x1} = 0$; or $R_y = 0$ and $\varepsilon_{y1} = 0$
- Slope surface: if $R_x = 0$ and $\varepsilon_{x1} \neq 0$, slope angle $(\gamma) = \varepsilon_{x1}$; or $R_x = 0$ and $\varepsilon_{y1} \neq 0$, $\gamma = \varepsilon_{y1}$

Some feasible surface shape from combination of $S_x$ and $S_y$ are illustrated in Fig. 2. When free-form surface is machined, the surface shape can be continuously changed at every tool location. However, some surfaces such as hemisphere surface, hemi cylinder surface and flat surface have constant curvature shape. And hence, they are only required three normal vectors to define the whole surface area. More complex surface needs more number of reference vectors.

## 3 Checking the Feasible Engagement Location

The generic flat-end cutter with respect to the tool coordinate system (TCS) can be described as,

$$S_C(\varphi; l_k) = [(r_m + r)\sin\varphi;\ (r_m + r)\cos\varphi;\ l_k] \tag{3}$$

where *R* is the major radius of cutter and $l_k$ is the height of cutter. Due to Cl-data and normal vector information are provided in Workpiece Coordinate System

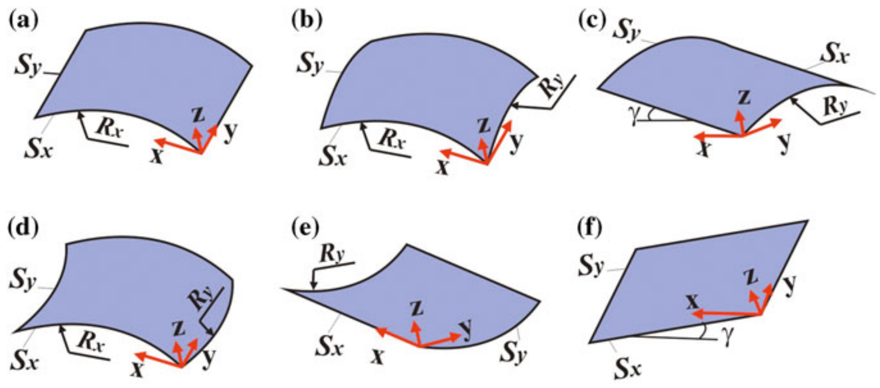


**Fig. 2** Feasible surface combinations, **a** convex-flat, **b** convex-convex, **c** slope-convex, **d** convex-concave, **e** concave-flat, **f** flat-slope

(WCS), then parametric equation of cutting tool in WCS can be expressed as follow,

$$S'_C(\varphi; l_k) = [\mathrm{M}]S_C(\varphi; l_k) \tag{4}$$

where [M] denotes an operator to map coordinate system from TCS to WCS. It is involving the tool rotation about *x-axis* ($\theta_A$) and *y-axis* ($\theta_B$), and also translation at $T$. Where $T$ is cutter location point (Cl-point) which is located at the bottom center of cutting tool. The mapping operator is given by:

$$[\mathrm{M}] = \begin{bmatrix} \cos\,\theta_{\mathrm{B}} & 0 & \sin\,\theta_{\mathrm{B}} & \mathrm{x_T} \\ \sin\,\theta_{\mathrm{A}}\sin\,\theta_{\mathrm{B}} & \cos\theta_{\mathrm{A}} & -\sin\,\theta_{\mathrm{A}}\cos\,\theta_{\mathrm{B}} & \mathrm{y_T} \\ \cos\,\theta_{\mathrm{A}}\sin\,\theta_{\mathrm{B}} & \sin\,\theta_{\mathrm{A}} & \cos\theta_{\mathrm{A}}\cos\theta_{\mathrm{B}} & \mathrm{z_T} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

At instantaneous tool position, it need to define whether the tool and workpiece engage or not. It can be defined by calculating the projecting point $q(x_q, y_q, z_q)$ as shown in Fig. 1a. Due to $q$ is projected point from $C(x_C, y_C, z_C)$ in *z-axis*, then $\{x_q, y_q\}$ is equal to $\{x_C, y_C\}$. While $z_q$ is obtained by calculating *z-axis* on $S_x$ with respect to $x_C$ ($\Delta \mathrm{Z_x}$), and *z-axis* on $S_y$ with respect to $y_C$ ($\Delta \mathrm{Z_y}$). First, by working on $S_x$, the *z-value* can be calculated by comparing $x_C$ with the coordinate and orientation of the reference vector $v_1$. The equations to obtain ($\Delta \mathrm{Z_x}$) and ($\Delta \mathrm{Z_y}$) for curved surface (concave or convex) can be expressed by,

$$\begin{aligned} \delta_x &= \sin^{-1}((R_x \sin \varepsilon_{x1} + (x_C - x_1))/R_x); \\ \delta_y &= \sin^{-1}\left(\left(R_y \sin \varepsilon_{y1} + (y_C - y_1)\right)/R_y\right) \end{aligned} \tag{6}$$

$$\Delta Z_x = R_x(\cos \delta_x - \cos \varepsilon_{x1}); \quad \Delta Z_y = R_y\left(\cos \delta_y - \cos \varepsilon_{y1}\right) \tag{7}$$

Meanwhile for flat surface and slope surface can be determined by Eq. 8 and Eq. 9 respectively.

$$\Delta Z_x = 0 \text{ and } \Delta Z_y = 0. \tag{8}$$

$$\Delta Z_x = (x_C - x_1)\tan\varepsilon_{x1}; \quad \Delta Z_y = (y_C - y_1)\tan\varepsilon_{y1} \tag{9}$$

Finally, $z_q$ is defined as follow,

$$z_q = z_1 + \Delta Z_x + \Delta Z_y \tag{10}$$

Since $z_q$ was obtained, thus the length of projection line from $C$ to $q$ can be calculated by $\overline{Cq} = z_q - z_C$. The projection line $\overline{Cq}$ will be used as the initial reference line for further calculation to get upper CWE. The engagement occurred if $\overline{Cq}$ is positive. Otherwise, there is no engagement between tool and workpiece.

# 4 Obtaining CWE and Cut Geometry

There are two types of tool path topologies that are mostly used in sculptured surface machining, parallel pattern and spiral pattern. Normally, parallel pattern is used for milling area of sculptured surface. Cutting tool moves at fixed *x-axis* or fixed *y-axis*. Parallel pattern is a simple and the easiest pattern to generate. Therefore, machining direction along *x-axis* is selected in this study.

After the projection line is obtained, then it will be rotated by the tool rotation about $\theta_B$ and $\theta_A$. These two rotation procedures must be performed sequent except for certain conditions it can be skipped and then jump to the next procedure. In this section the detail procedure to obtain $n$ will be derived.

## 4.1 Rotating the Projection Line by $\theta_B$

In the first rotation procedure, the perpendicular line is rotated by $\theta_B$ on the first surface $(S_x)$ as shown in Fig. 3. The projection line is then rotated about point $C$ to get line $\overline{Cs}$. If $\theta_B$ is equal to zero then line $\overline{Cs}$ is equal to line $\overline{Cq}$. Equations to define the rotated line for every surface shape can be expressed below.

The same method can be applied for convex and concave surface. By employing trigonometry equations, the length of the lines and angles in Fig. 3a can be determined.

$$\overline{CO}_x = \sqrt{\overline{Cq}^2 + R_x^2 - 2\overline{Cq}R_x\cos\delta_x} \tag{11}$$

$$\phi_b = 180 - |\theta_B - \delta_x| + \phi_a; \text{ or } \phi_b = 180 - |\theta_B| - |\delta_x + \phi_a| \quad \text{if } (\theta_B < 0 \text{ and } \delta_x > 0) \tag{12}$$

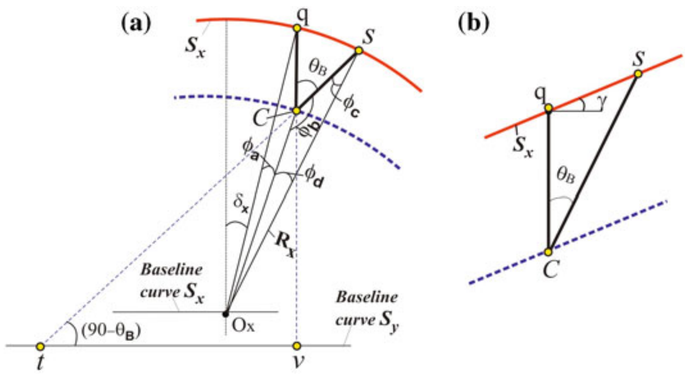


**Fig. 3** Rotation of projection line on $S_x$, **a** convex surface, **b** slope surface

$$\phi_a = \cos^{-1}\left(\frac{\overline{CO_x}^2 + R_x^2 - \overline{Cq}^2}{2\,\overline{CO_x}\,R_x}\right);$$
$$\phi_c = \sin\left(\frac{\overline{CO_x}\sin\phi_b}{R_x}\right); \tag{13}$$
$$\phi_d = 180 - (\phi_b + \phi_c)$$

$$\overline{Cs} = \sqrt{R_x^2 + \overline{CO_x}^2 - 2R_x\overline{CO_x}\cos\phi_d} \rightarrow \ (curved\ surface) \tag{14}$$

Meanwhile $\overline{Cs}$ for flat surface or slope surface (Fig. 3b) can be defined by Eq. 15.

$$\overline{Cs} = \overline{Cq}/\cos\theta_B \rightarrow flat\ surface;\ \text{or}\ \overline{Cs} = \frac{\overline{Cq}\sin(90+\gamma)}{\sin(90-\gamma-\theta_B)} \rightarrow slope\ surface \tag{15}$$

## 4.2 Inclined Surface

If $\theta_B$ is not equal to zero, it means that the projecting line was rotated in the first procedure. Due to this rotation, the projecting line is not perpendicular to the second surface $(S_y)$. Consequently, when $S_y$ is curved surface, the line $\overline{C}$s cannot be mapped to $S_y$ because the line and the surface are not aligned anymore. It can be analogous to Fig. 5 where the inclined curved surface $(S_i)$ is obtained by sliced the workpiece material with plane B. Plane B is a plane A which is rotated by $\theta_B$. The radius of $S_i$ $(R_i)$ is dependent on $S_x$. When $S_x$ is a curved surface, it can be

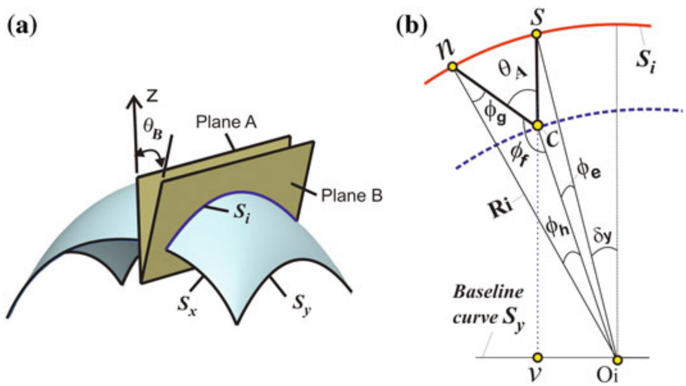


**Fig. 4** Rotation of projection line on $S_i$, **a** inclined surface, **b** rotation of the rotated projection line on $S_i$

calculated by referring back to Fig. 3a. Line $\overline{qv}$ denotes the projected distance in *z-axis* from projected point $q$ on workpiece surface to baseline of curved surface $S_y$.

$$\overline{s\,t} = \left(\frac{(R_y \cos\delta_y - \overline{C\,q})}{\cos\theta_B}\right) + \overline{C\,s} \tag{16}$$

$$R_i = \sqrt{\overline{s\,t}^2 + \left(R_y\ \sin\delta_y\right)^2} \rightarrow \textit{curved surface} \tag{17}$$

Meanwhile $R_i$ when $S_x$ is flat surface or slope surface can be determined by Eq. 18 below.

$$R_i = R_y/\cos\theta_B \rightarrow \textit{flat surface}; \quad R_i = \frac{R_y \sin(90+\gamma)}{\sin(90-\gamma-\theta_B)} \rightarrow \textit{slope surface} \tag{18}$$

However, when $\theta_B = 0$, then $R_i = R_y$.

## *4.3 Rotating the Rotated Line by $\theta_A$*

$n$ can be defined after the length of $\overline{C\,n}$ as shown in Fig. 4b was obtained. $\overline{C\,n}$ is the rotated projecting line after the second rotation. And it represents the length of contact between tool and workpiece or normally called as *cut width*. For the curved surface it can be expressed as follow,

$$\overline{C\,O_i} = \sqrt{\overline{C\,s}^2 + R_i^2 - 2\overline{C\,s}R_i\cos\delta_y} \tag{19}$$

$$\phi_e = \cos^{-1}\left(\frac{\overline{CO_3}^2 + R_i^2 - \overline{Cs}^2}{2\,\overline{CO_3}\,R_i}\right); \quad \phi_f = 180 - |\theta_A| + |\delta_y| + \phi_e \tag{20}$$

$$\phi_g = \sin\left(\frac{\overline{CO_i}\sin\phi_f}{R_i}\right); \quad \phi_h = 180 - (\phi_f + \phi_g) \tag{21}$$

$$\overline{Cn} = \sqrt{R_i^2 + \overline{CO_i}^2 - 2R_i\overline{CO_i}\cos\phi_h} \rightarrow \ (\mathit{curved\ surface}) \tag{22}$$

Meanwhile for flat surface and slope surface it can be determined by Eq. 22.

$$\overline{Cn} = \overline{Cs}/\cos\theta_A \rightarrow \mathit{flat\ surface};\ \overline{Cn} = \frac{\overline{Cs}\sin(90+\gamma)}{\sin(90-\varepsilon_{\mathrm{n}}-\theta_B)} \rightarrow \mathit{slope\ surface} \tag{23}$$

Finally, coordinate of $n$ can be determined by mapping the parametric equation of cylinder (Eq. 4) with $l_k$ is equal to $\overline{Cn}$. And it yields to,

$$n\,(x_n, y_n, z_n) = [\mathrm{M}].\ S_C(\varphi; l_k). \tag{24}$$

If $n$ located out of the workpiece block, then it should be cut. And hence the length of CWE fall into,

$$\overline{Cn} = \frac{\Delta s}{\cos\vartheta} \rightarrow \vartheta = \cos^{-1}(\cos\theta_A\cos\theta_B) \tag{25}$$

where $\Delta s$ and $\vartheta$ denote the distance from CC-point to the block limit and the tool orientation angle relative to *z-axis* in WCS, respectively. Then coordinate of upper CWE can be obtained by using Eq. 24.

## 5 Simulation and Test Result

Based on the formula derived in the previous sections, a simulation program using MATLAB has been developed, enabling the calculation of CWE at instantaneous tool location. Two free-form workpiece and part surface models as shown in Fig. 5a and b were tested. Machining conditions used in the test were feedrate 2,500 mm/min and cutting speed 5,000 rpm. Two teeth flat-end cutter with diameter 20 mm was employed as cutting tool. By using the simulation developed, the shape of cut geometry can be generated. The graph as depicted in Fig. 5c and d are cut shapes at every Cl-point for one strip tool path. From these graphs can be seen that the shapes of cut resemble the shape of workpiece removed. It is an indication that the proposed method is accurate. The size of cut width at every Cl-

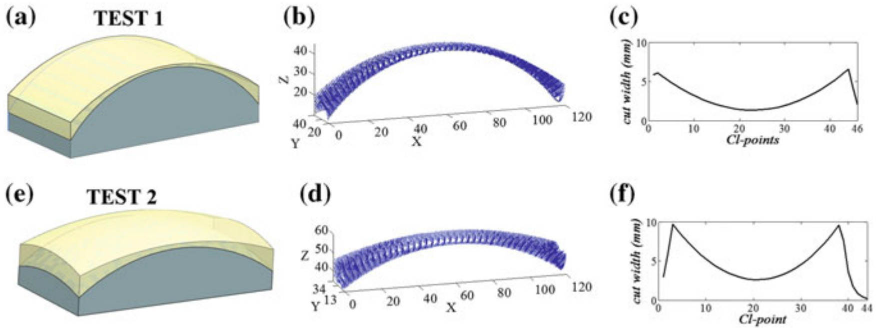


**Fig. 5** Model tests, **a**, **b** part and workpiece surface models, **c**, **d** cut shape, **e**, **f** cut width progression

point can be seen in Fig. 5e and f. Lower cut width as shown by the initial and final tool path are due to some part of the cutting edge is out of the workpiece block.

Even though the shape of cut resemble the shape of material removed, but the accuracy of the proposed method should be examined. Therefore, to verify the accuracy of the proposed method, width of cut obtained from the simulation program was compared to the width of cut measured by using Unigraphic. The width of cut was measured in Unigraphic by putting the cutter model at the Cl-point and adjusts its orientation based on Cl-data. After that, the workpiece model is subtracted by the cutter model. Then the width of cut between cutter can be measured.

Verifications were conducted by calculating the error of the developed method. This error is the difference between the result generated by the program simulation and that is measured by Unigraphic. Verification performed for the width of cut at $\varphi = 90$ for every Cl-point. From the results show in Fig. 6 can be seen that both model tests produce relatively small error.

The shapes and width of cut as a function of engagement angle for four selected Cl-points from Test 1 shown in Fig. 7. When the tool located at Cl-1 (Fig. 7a, b), only some part of the cutting tool engages with workpiece. It is due to Cl-point located out of the workpiece block. CWE start at $\varphi = 20$ which is called as entry angle. Complete CWE showed by Cl-8 (Fig. 7c, d). Another case depicted by

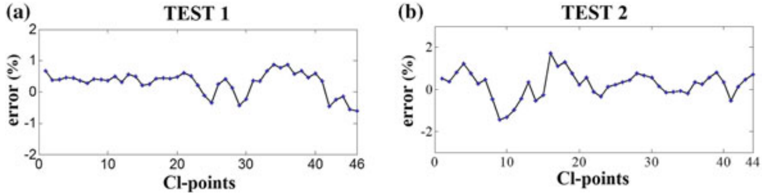


**Fig. 6** Cut width error for every Cl points at $\varphi = 90$

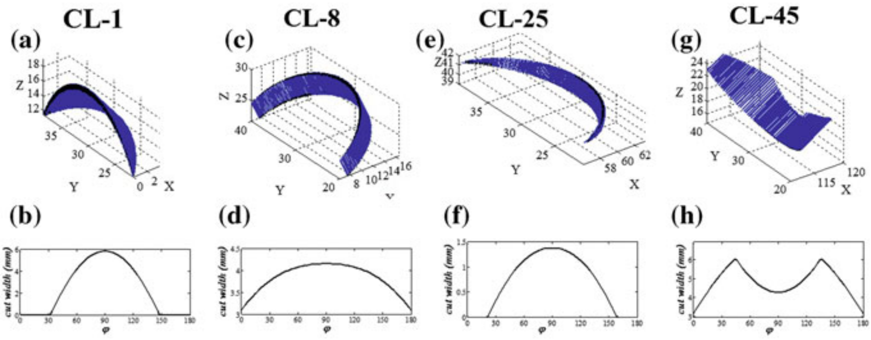


**Fig. 7** Cut shape and cut width at $\varphi \in [0, 180]$ for selected Cl-points from Test 1

CWE at Cl-25 (Fig. 7e, f). In this case, inclination angle and small depth of cut make CWE starts at $\varphi = 20$. Meanwhile CWE at Cl-45 (Fig. 7g, h) shows a complete engagement. However, some CWE at the front side were cut due to the workpiece block limit.

## 6 Conclusion

In this paper, a new analytical method to generate CWE for flat-end cutter was presented. The proposed method is not only applicable for flat workpiece surface, but also for free form workpiece surface. It is an important advantage over the existing analytical method in the literature. The test has been performed to compare the geometry obtained by the proposed method to that measured by Unigraphic. The result shows that it produces relatively small error. It proves the accuracy of the proposed method. Moreover, the method was eliminating the need for large number of vector to define the workpiece surface. It indicates that the method is computationally more efficient as compared to Z-map.

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## References

1. Xiong WL (1995) "Five-axis NC cylindrical milling of sculptured surfaces. Comput Aided Des 27:887–894
2. Kurt M, Bagci E (2011) Feedrate optimisation/scheduling on sculptured surface machining: a comprehensive review, applications and future directions. Int J Adv Manuf Technol 55:1037–1067

3. Altintas Y, Spence AD (1991) End milling force algorithms for CAD systems. Manuf Technol CIRP Ann 40:31–34
4. Spence AD, Altintas Y (1994) A solid modeler based milling process simulation and planning system. Trans ASME J Eng Ind 116(1):61–69
5. El-Mounayri H, Spence AD, Elbestawi MA (1998) Milling process simulation-A generic solid modeller based paradigm. J Manuf Sci Eng 120(2):213–221
6. Fussel BK, Ersoy C, Jerard RB (1992) Computer generated CNC machining feedrates. ASME Jpn/USA Symp Flex Autom 1:377–384
7. Hemmett JG, Fussell BK, Jerard RB (2000) A robust and efficient approach to feedrate selection for 3-axis milling. In: Proceedings of IMECE symposium on dynamics and control of material removal processes, DSC, vol 2, pp 729–736
8. Jerard RB, Drysdale RL, Hauck K, Schaudt B, Magewick J (1989) Methods for detecting errors in sculptured surface machining. IEEE Comput Graphical Appl 9:26–39
9. Park JW, Shin YH, Chung YC (2005) Hybrid cutting simulation via discrete vector model. Comput Aided Des 37(4):419–430
10. Ozturk B, Lazoglu I (2006) Machining of free-form surfaces. Part I: analytical chip load. Int J Mach Tools Manuf 46(7–8):728–735
11. Tunc LT, Budak E (2009) Extraction of 5 axis milling conditions from CAM data for process simulation. Int J Adv Manuf Technol 43:538–550
12. Wan M, Zhang WH, Qin GH, Tan G (2007) Efficient calibration of instantaneous cutting force coefficients and run out parameters for general end mills. Int J Mach Tools Manuf 47:1767–1776

# Building a Case Base for the Non-Conformance Problem Solving in the Aluminum Extrusion Process

**N. O. Pacheco, J. C. E. Ferreira and W. L. Mikos**

**Abstract** This work proposes the application of Case-Based Reasoning (CBR) to build a knowledge base system for seeking and providing solutions for non-conformances that take place in the aluminum extrusion process. CBR is an important area of Artificial Intelligence (AI) that is used to solve problems based on the knowledge accumulated previously from known scenarios, providing a solution to both recurrent and new problems. The CBR cycle is characterized by having four stages known as: retrieval, reuse, revision, and retention. These stages interact with the knowledge base in order to seek one or more solutions to the problem. The steps for the development of the relational model of the knowledge base according to CBR are as follows: (a) identification and classification of the non-conformances, (b) information gathering of situations that result in non-conformances, which include: records of non-conformances, experience of operators with non-conformances, literature on non-conformances in the aluminum extrusion process, and (c) the structure definition for the diagnosis of cases of non-conformance and support in decision-making. The final step consists in storing the cases in a relational database, which will correspond to a knowledge base. New cases may be added in the knowledge base, as they occur. The structure of the cases in the knowledge base will be important for its provision for decision-making in the aluminum extrusion process. In a further work it is intended to implement a web-based distributed system to support the inclusion of new cases (that may occur in different geographic locations and company conditions) as well as a fast search for solutions to non-conformances that occur in the aluminum extrusion process.

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## 1 Introduction

Due to globalization and increased competition, an increasing amount of manufacturing companies are seeking to produce high quality products efficiently with lower costs, and such quality must meet the expectations of increasingly demanding customers. An important issue in manufacturing industries, which has hindered the achievement of these goals, is the occurrence of non-conformances in parts and products that undergo manufacturing processes. When non-conformances occur, often production stops, and the people involved in the process attempt to solve the problem, typically performing the following steps: (a) identify precisely the nonconformance, (b) search for possible causes, and (c) establish possible solutions to prevent the occurrence of the nonconformance. The duration of these steps can be long, resulting in delays in the delivery of parts, and potential problems with customers.

However, similar problems related to non-conformances may have occurred previously in the factory, or in other plants of the same company, and it is very likely that they were already solved. But the knowledge about the nonconformance and its solution may have remained hidden in the memory of the few professionals who were involved with solving the problem, or such knowledge may have been stored on paper or in digital format somewhere in the company, but not easily available.

Given this scenario, in order to provide a means to store and enable easy and quick access to information about non-conformances, we conceived Intelligent System to Support Aluminum Extrusion (ISSAE), which is a methodology to support the process of aluminum extrusion through Artificial Intelligence (AI). It is based on a computer system that encompasses multi agent systems (MAS) and case-based reasoning (CBR) to solve non-conformances in the process of aluminum extrusion. ISSAE is developed in the Java programming language, and it seeks to quickly generate suggestions to solve those nonconformance problems. ISSAE is a result of meetings between academia and industry in order to make the process faster and more efficient. The case study is focused on non-conformances of the aluminum extrusion process in a company located in the state of Santa Catarina, southern Brazil.

This application is based on concepts of CBR for knowledge representation and reasoning. The basic concepts of CBR are presented below, as well as the steps for obtaining a generic case focused on the diagnosis of non-conformances and the corresponding decision making, and a relational database model that will be used according to the CBR technique.

## 2 Case-Based Reasoning

Case-based Reasoning (CBR) is an application of AI that, for engineering environments, is becoming an important tool to support the user, which can be used in systems that assist the user in troubleshooting and support for decision-making in industry [1–3].

The CBR approach provides a solution to new problems from previous situations. A similarity measure allows the definition of a similarity between the cases, enabling the reuse or adaptation of the most similar solution(s) of the case(s) to the new case in question [4, 5].

According to Aamodt and Plaza [4], a CBR cycle has four stages known as 4R: retrieve, reuse, revise, and retain. If a new situation or problem is detected, a CBR-based computer system starts searching for similar cases within its knowledge base in the retrieve phase. Once found, the solution can be reused or adapted to solve similar processes in order to establish a solution for the problem during the reuse phase. The solution obtained by the system may undergo correction in the review stage, and finally the new experience is stored in the case-base in the retention phase.

An important feature of a CBR system is the possibility of learning. When a new problem is solved, corrected, or modified, it is retained in the database, remaining available to solve similar problems in the future. This allows the knowledge in a CBR system to remain constantly updated, and learning can take place from new cases [5].

According to the CBR approach, one case is a unit of knowledge that stores all the information of the situations or problems occurring with the solution. Thus, a case represents a problematic situation already identified and solved.

## 3 Proposed Method

The objective of the proposed system is to support the decision making regarding the aluminum extrusion process when a nonconformance is detected. The proposed method is based on the following:

- Build a case format that stores the information on the situations of nonconformance, and the action taken to remedy the nonconformance.
- Obtain a relational database model that is suitable for the knowledge base.

The proposal to build the CBR-based system is shown in Fig. 1. In the module for generating knowledge in Fig. 1 the steps for the relational model of the case-base are shown, which are detailed below (see Fig. 2):

- Identification and classification of the equipment: classification of non-conformances that occur in the aluminum extrusion process.
- History of cases: capturing and collecting historical information about the non-conformances in the aluminum extrusion process.
- Knowledge extraction and representation: definition of the format and construction of the cases.
- Case-base: construction of the case-base in accordance with the relational model.

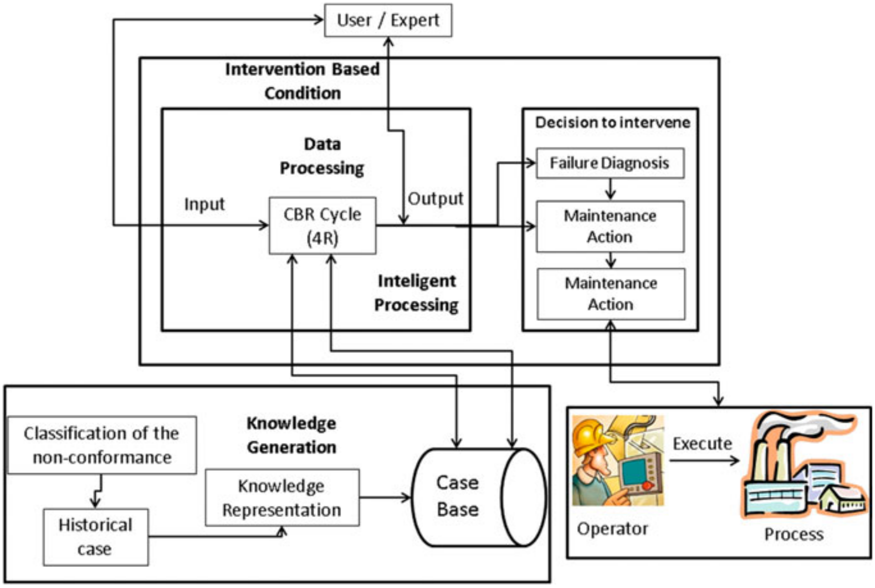


**Fig. 1** System for the support to aluminum extrusion based on the CBR approach

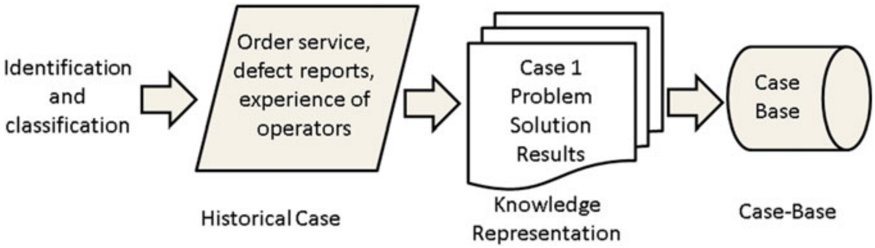


**Fig. 2** Steps for the construction of the case-base

## *3.1 Identification and Classification of the Non-conformance*

The identification and classification of non-conformance in the aluminum extrusion process seeks to collect all the available and sufficient information to represent a specific type of non-conformance. Each specific type of non-conformance will have a unique identification code, and it contains all information and cases that occurred previously in the extrusion process, according to a particular family or class.

For example, if a piece of information regarding a particular non-conformance is found, this information will form a historical record concerning a subdomain called "bubble." Then, each piece of information found referring to a family of non-conformances will compose a small knowledge base related to the subdomain

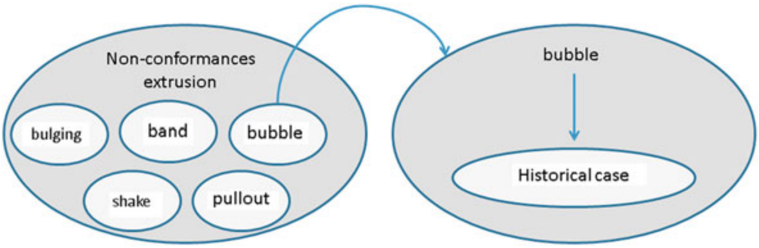


**Fig. 3** Identification and classification of the non-conformance

mentioned. Consequently, the various subdomains of the application area must be identified according to the family of each non-conformance, as illustrated in Fig. 3.

## *3.2 History of Cases*

According to Kim et al. [1], a system for fault diagnosis requires the information systematization, diagnostic, and solution procedures. He et al. [6] propose an intelligent system that requires a large amount of information, such as operational data, maintenance data, fault data, decision data correction, etc., reflecting the status of the non-conformance, then use this information to develop the case-base.

In the case of non-conformance, the information about the defects in the aluminum extrusion process is directly accessible through reports of nonconformities, which include the types of defects, location of defects in the extruded profile, and the possible causes and solutions found to solve the non-conformances. Besides this information, manuals, books, and notes on best extrusion practices are important for obtaining knowledge.

## *3.3 Knowledge Representation*

A case can have different contents and representations, depending on the application area and purpose of reasoning with the information. These pieces of information should be specific to its implementation, but the minimum structure that a case should have is the description of the problem and its solution [5]. The cases can be represented in different ways, which include: semantic networks, frames, object-oriented, and trees. Whatever the representation used, the encoding scheme should also include information about the condition of non-conformance and corrective actions [7]. Figure 4 shows a frame format that can be used in case of non-conformance in a manufacturing process.

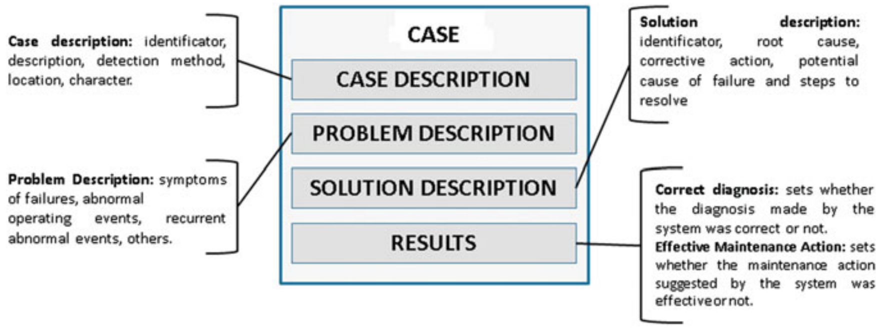


**Fig. 4** Structure of a case describing a non-conformance in a process

### 3.3.1 Description of the Case

This field specifies a unique identification code, date of occurrence of the event, the description of the non-conformance (type, location, date of occurrence, etc.), and some additional information like the user who identified/accomplished the task of correcting the process. The identification code of each case is essential, and is related to the recovery phase and to the concept of indexing, in order to facilitate or accelerate the search for the case-base of similar situations.

### 3.3.2 Description of the Problem

In this field each of the elements that allow describing the non-conformance are specified: problems encountered by operators/specialists, recurring problems, etc. The elements must contain a very accurate description of the problem, with enough detail of its description, and the concept of abstraction is usually important. The abstraction helps to "reduce" the problem so that the most relevant aspects can be identified, and should include sufficient detail to identify the problem. The capacity for abstraction operator/specialist helps to determine how many details need to be represented in order to describe the problem [8].

The abstraction leads to a concept that the authors in [5] define as "information entity," which is an atomic part of the case. Some examples are: name of non-conformance, the date of the event, the system, the cause of failure, etc. Therefore, the description of the problem should be represented according to these information units.

### 3.3.3 Description of the Solution

The solution for the application domain considered in this paper corresponds to the suggestions of possible actions to be performed on the process, given the diagnosis of the non-conformance [5]. The identification of non-conformance is very important because it lets you decide what kind of actions should be taken to avoid or minimize its consequences. In the solution is also common to add the cause of the problem.

#### 3.3.4 Results

The field of results contains an assessment of the diagnosis suggested by the CBR system, that is, if it is correct, and if the corrective action is effective or not. This field contains the information about what occurred during the execution of the suggested solution, and whether this solution was successful or not. With this information the specialist can anticipate potential problems and foresee the consequences of a solution. This field is part of the knowledge of the system [5].

The evaluation of the outcome of a process can take some time, but if it is appropriate, it can be stored and reused for new situations.

### *3.4 Case-Base*

After the process of knowledge acquisition, a set of relevant attributes are identified to describe the problem as well as to describe the solution of non-conformances and their results. A CBR system can be used to identify significant attributes [3]. Accordingly, the information set of cases can be organized and maintained in a database according to the relational model of the case-base, and any database can be used [9]. Considering that a case is a structure containing fields detailing specific situations through different attributes, this information can be organized in tables and linked by indexes, as represented by relational databases. The representation of data through tables of relational data provides the following advantages [7, 10]:

- Representation of information by using tables (rows and columns), wherein the lines represent a case and the columns represent fields or attributes of the case.
- The databases provide advanced techniques for managing large volumes of historical cases. The indexing, for example, is a method used by the CBR system that allows fast, efficient cases from attributes identified as indexes in the database. An index is a body of information that is a key attribute and that is not necessarily a primary key, which is essential for the identification of similar cases.
- Redundancy of information is avoided. The minimum amount of storage space is used to store information.
- The database and organization of information, as well as its maintenance, are more understandable and easy to implement, since they are organized in tables and their relationship with the primary or foreign keys.

# 4 Case Study

The case study to implement the proposed method is called the “bubble” non-conformance, which correspond to the occurrence of hydrogen bubbles in the extruded profile. This type of defect is related to lubrication points of the knife, billet, among others [11]. In the company where this study was carried out, there are three direct presses for aluminum extrusion. The same mechanisms are used in each press.

According to the proposed strategy, the first step is to identify and classify the non-conformance, given the family or the type of equipment to which it belongs.

## *4.1 Case-Base*

The information about the cases can be represented in a relational database model, as shown in Fig. 5. In this model, information is represented in tables and interconnected according to the relational model [10].

The case-base should have a few features essential to a case recovery process in a CBR cycle. Some of them are as follows:

- Avoids data redundancy.
- In the description of the non-conformance, information can be easily added without the need to change complete records.
- There are key fields that cannot be null. Each non-conformance belongs to the family of defect type. Any non-conformance is isolated.

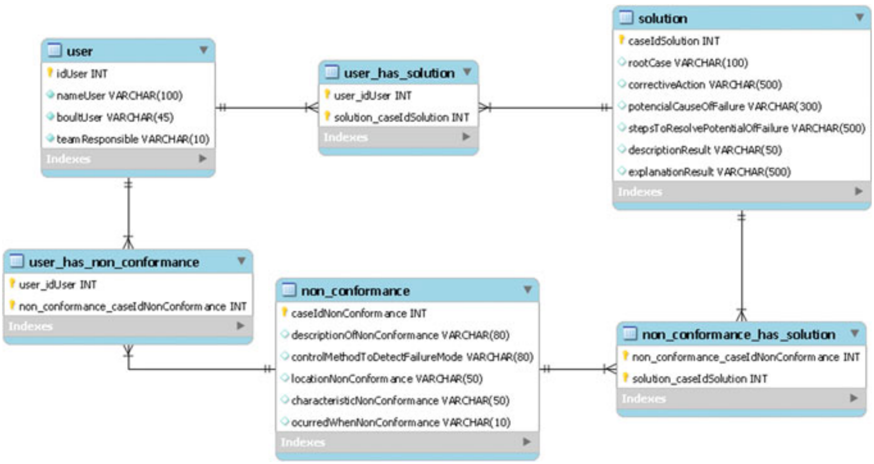


**Fig. 5** Representation of the knowledge base in a relational model for information regarding the non-conformances of the aluminum extrusion process

- In the tables of “non-conformance,” “solution,” and “user” indices are used to make the search for a case by the database manager more efficient in the recovery stage in the CBR cycle. The concept of indexing is crucial in this stage of reasoning.

## *4.2 CBR Implementation*

To implement the CBR-based system, the COLIBRI platform was used, which is an academic software whose main goal is to provide the infrastructure necessary to develop CBR systems and their associated software components. COLIBRI is designed to provide a collaborative environment where users can share their efforts in the implementation of CBR applications [12].

COLIBRI provides a well-defined architecture to design CBR systems, and contains the jCOLIBRI framework, besides several development tools that assist users in sharing CBR components.

COLIBRI Studio is the implementation of the upper layer of the COLIBRI platform. It provides graphical tools needed to generate CBR systems without dealing directly with the source code, allowing the composition of its CBR components. COLIBRI Studio is integrated with the popular Eclipse IDE, and therefore it uses the facilities for running and managing projects in Java, as shown in Fig. 6.

Through the CBR system modeling tool COLIBRI Studio a CBR model is created, which can be used in other applications on the same field of knowledge, making only minor changes [12].

The process of identifying similar cases, adaptation of solutions and learning from experience, can be driven and supported by generic knowledge about the

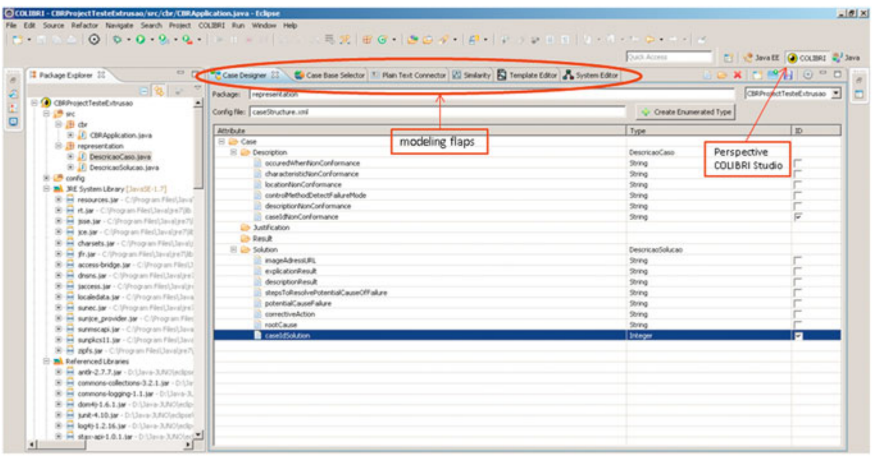


**Fig. 6** COLIBRI Studio’s plug-in in the Java eclipse IDE

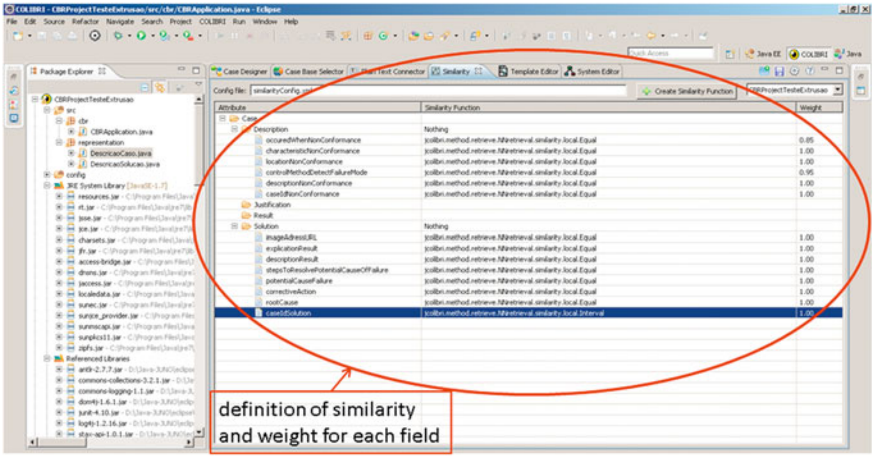


**Fig. 7** Specifying the similarity and weight for each field

domain, through deep, superficial or compiled knowledge models, or based on an apparent similarity that is illustrated in Fig. 7, in which is defined the type of similarity and its associated weight. To implement this technique the nearest neighbor was used to measure similarity, which considers the importance of each index for determining the nearest neighbor. For example, the parameter characteristic non-conformance is considered more important than location non-conformance, and their values are usually normalized between 0 and 1, where 0 corresponds to complete dissimilarity, whereas 1 is the complete equality, calculated for each case in the base according to the values assigned in the "weight" column in Fig. 7. Equation (1) shows how the calculation is carried out to reach the results. Figure 8 shows the interface with the response given by the system developed using COLIBRI Studio through a query about the extrusion non-conformance "bubble."

$$sim\,(Q,C) = \sum_{i=1}^{n} f(Q_i, C_i)\ *\ W_i \qquad (1)$$

where:

$Q$ query

$C$ case

$f$ measure of local similarity

$i$ index

$W$ weight factor that represents the importance of each index for calculating the similarity

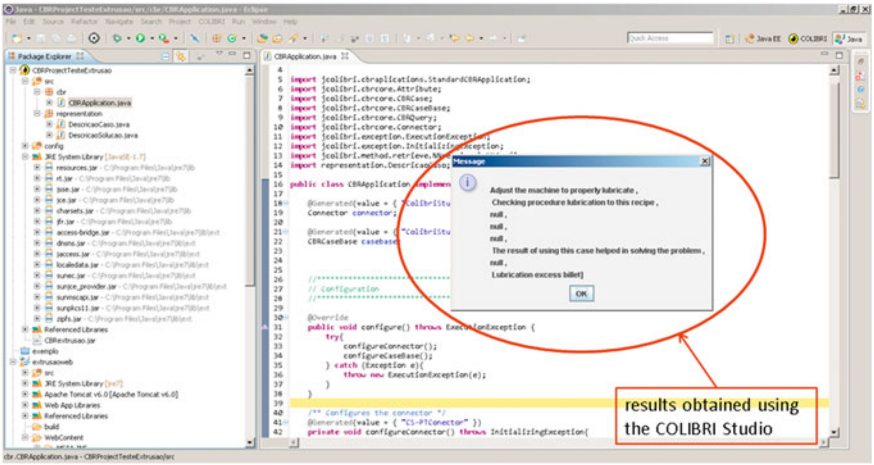


**Fig. 8** Result obtained using COLIBRI studio after querying the database

# 5 Conclusion

This paper presented a method for generating a knowledge base model for a system to support the decision making in the aluminum extrusion process according to the CBR approach. The proposed method is based on the cases approach, and is a technique similar to the one used by Mikos et al. [13] for solving problems related to the thermoplastic injection molding process.

The amount of cases correspond to the domain knowledge in which the relational database model is ideal for their representation. A model for the organization of processes in a relational database format is also presented in this paper, seeking to obtain the knowledge base of the CBR system, which is adapted to the jCOLIBRI framework [12].

The results obtained with the information input to the present version of the system were adequate, considering the number of cases recorded in the database. As additional solutions are built from old cases, we believe the database will tend to provide even better results.

# References

1. Kim HJ, Bae CH, Kim SH, Lee HY, Park KJ, Suh MW (2009) Development of a knowledge-based hybrid failure diagnosis system for urban transit. Int J Automot Technol 10(1):123–129
2. Yee PS, Kiong LC, Soong LW (2009) Adaptive case based reasoning for fault diagnosis. Soft Computing and Pattern Recognition, SOCPAR'09. International Conference, 2009
3. Gao N, Zhao S, Xu H (2008) Research of fault diagnosis technology based on BOM and CBR. In: Proceedings of the wireless communications, networking and mobile computing, WiCOM 2008

4. Aamodt A, Plaza E (1994) Case-based reasoning: foundational issues, methodological variations, and system approaches. AI Commun 7(1):39–59
5. Wangenheim AV, Wangenheim CGV (2003) Case-based reasoning, 1st edn. Manole (in Portuguese)
6. He Z, Wang H, Wang M, Li G (2012) Simulation of extrusion process of complicated aluminium profile and die trial. Trans Nonferrous Met Soc China 22(7):1732–1737
7. Vachtsevanos G, Lewis F, Roemer M, Hess A, Wu B (2006) Intelligent fault diagnosis and prognosis for engineering systems. Wiley, New York
8. Zhou M, Chen Z, He W, Chen X (2010) Representing and matching simulation cases: a case-based reasoning approach. Comput Ind Eng 59(1):115–125
9. Waheed A, Adeli H (2005) Case-based reasoning in steel bridge engineering. Knowl-Based Syst 18(1):37–46
10. Elmasri R, Navathe SB (2011) Database systems, 6 edn. Pearson, London (in Portuguese)
11. ABAL (2008) Technical guide of aluminum: extrusion, São Paulo, Brazil (in Portuguese)
12. Recio-García JA, Díaz-Agudo B, González-Calero PA (2009) Boosting the performance of CBR applications with jCOLIBRI, 21st IEEE international conference on tools with artificial intelligence, Newark, NJ
13. Mikos WL, Ferreira JCE, Gomes FGC, Lorenzo RM (2010) A combined multi-agent and case-based reasoning approach to support collaborative non-conformance problem solving in the thermoplastic injection moulding process. Int J Comput Integr Manuf 23(2):177–194

# Framework of Optimization of Transport Process with Use of Intelligent Hybrid System

**Kubiak Natalia and Agnieszka Stachowiak**

**Abstract** Many definitions of logistic management exist, but some of them are connected with the transport-warehouse chain, that includes obtaining raw materials, their processing, and selling. The environment, in which the company exists is also important. This is the reason why the optimization in a company should be made having in mind those aspects. The modification and optimization process in a company should include changes in its environment. The question is how long it takes for the company to adapt. Changes can be not significant in certain moment, but with the time they can have large influence on the company. It is not easy to recognize the size of the impact while consequences can be serious for the company. If the changes are recognized quickly, the company can conquer the difficulties by adaptation or can make changes in their processes. Sometimes the situation is not so simple, for example when the changes are detected too late or they require changes in management system. Improvement of the system can take a lot of time, i.e., year or more. This time would be shorter, if the system would change from itself, then the improvement of the system could be not so tedious and so consumptive of time. This is possible by implementation of elements of artificial intelligence in the system. Therefore the authors suggest a new concept of transport management, with use of an intelligent hybrid system, which adjusts to the current economic situation without updating or changing the management system and thanks to it the company can quickly replay with no outlay. The hybrid system consists of a neural network and three expert systems. It will influence the transport time by optimization of loading processes. In this manner the time and money will be spared. The loading surface and the number of trucks needed to transport the goods will be also optimized by continuous adaptation to the current economic situation.

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**Keywords** Supply logistic · Hybrid system · Neural network · Transport · Expert system

# 1 Introduction

## *1.1 Transport in Logistics*

One of the main task of the management in a company is to offer a product on the market [1], i.e., deliver it on time, to a proper price and conditions, to places, where the customer wants to buy it [2, 3]. This task is related directly with transport, which is why the rating of the delivery service is important in logistics. The following assessment criteria are usually considered is time (speed of the order realization), punctuality, reliability, quality of the deliveries [4].

The qualities of the deliveries influence the costs of maintenance and level of the stock. When the delivery time is longer, then the size of stocks must be bigger to avoid running out of stocks while waiting for arrival of the next delivery [5].

The necessity of the transport optimization is also important, because nowadays the average distance, on which the goods have to be transported is longer than it used to be, since manufacturing facilities are moved to distant places in the world due to labor cost reduction [6].

The optimization in the framework solution developed will influence the time, punctuality and quality of the deliveries and their travel costs through optimization of the total length of the pick-up collection.

## *1.2 Informatics System in Logistics*

The economy, which is based on knowledge, depends on the ability of using the modern technologies and informatics systems [7]. The reason for this is, that in a company a lot of data has to be collected, transformed and transmitted and only computer software can manage that amount of data and guarantee safe and error-free data processing giving managers coherent and full information on company's performance [See 5].

A good and adapted to the circumstances IT system influences the success of the company in a large degree [8]. The systems becomes inseparable and integral part of the logistic systems [4], therefore they are one of the most important, abundant and growing PC software [9]. The framework includes parts of artificial intelligence and thus the system can adjust itself to the current economic situation. This is the reason why this system is so promising.

## 1.3 Time as a Crucial Factor in Transport Process

Time is considered as one of the main sources of advantage in the competitive economy. The curtailment of time between the order and the delivery can cause the reduction of stock and of the costs of its storage [5]. The easiest way to achieve the reduction of time is faster and more efficient transport process.

From the authors' experience in management these two factors—short transport time and optimal utilization of the loading surface are often opposite to each other resulting in trade-off decisions. Often the addendum of the surface is achieved by adding new pick-up (or unloading) point, which causes longer transport time. Because of that this factor will be considered in the framework.

Additionally often the truck waits a long for unloading. This is a waste of time and it depends individually on the infrastructure and processed in company, where the truck is. This is an important aspect and it will be considered in this paper and in the hybrid system.

## 1.4 Artificial Intelligence

One of the first applications of artificial intelligence (AI) is to support the activity of human in data base management systems [10, 11] and now AI is also applied in many other fields [5, 8, see 12]. AI is defined as a field in informatics studies that causes, that machines perform actions, which would require intelligence, if a human would do it [5]. That means AI is computer programs, which actions are similar to human actions [13].

AI is based on biology, psychology, statistic, mathematic, logic, and other disciplines [14].

In the paper two elements of AI are applied, one of the elements is a self-learning program which adapts to changes in the reality in a dynamic way without modification of the program code. The other element explains the actions of the system and checks if there are any mistakes made.

This approach to programs (hybrid constructions of different technologies of AI) seem to be more efficient than traditional programs [15].

The choice which AI solutions are used in the hybrid system is a choice based on best practices, because neural networks are applied very often in science, as they easily adapt to solving different computational problems in science and technics and because they can transform information effectively and in a reliable way and such approach is required in the concept [16]. They have the ability to generalize gained knowledge, to learn and adapt to changes in environment [17]. Thanks to the expansion of informatics and development of faster and more efficient computers the application of neural networks is possible in many areas [18, see 19].

Using neural networks brings numerous benefits, but the main, according to literature on the subject, are the following [20, 21]:

- they are comfortable and cheap systems with many elements, processing information in a parallel way
- they do not require extra informatics system.

The applications of neural network generally refer to optimization problems, for classifications and to forecast (for example request of electric energy or rate of Swiss Francs in short period of time—see, i.e., [22]). Despite of the large amount of applications, the capabilities of their utilization is not explored yet and it seems, that they will affect the progress in IT [17].

Expert systems are often used in many fields [11, 19, 23, 24] and they are one of the most popular system of AI in applications. They will be used in the analyzed approach to receive better indication with respect to quality [25], because they can solve problems, predict, suggest the possibilities, give advises (comparable with consuls of human experts), to win, improve or increase management skills in practice [5].

An expert system basing on the knowledge base transmitted from an expert, can be in economic in an effective way used, because during its work the presence of an expert is not required [12] and then the company can share the knowledge with many employees. This influences the regularity, accuracy, and efficiency of actions made in the whole logistic network. It also allows to manage knowledge, which is the most important asset of the organization [5].

The implementation has to be considered as long time project, because the knowledge obtainment and its structuring are very labor-consuming [12].

Expert systems are divided in three categories consulting, decision making without employee control and criticizing [12].

The hybrid system will be of the first type, consulting, because all the effects will be transmitted and they have to be accepted or modified.

In many articles hybrid systems, that includes expert system and neural networks, are described, but their applications in logistic focus on forecasting the trend and cycle or the cargo flow in the logistics park, evaluation and selection of suppliers, money flow management, measures of distribution of the production plan track, urban logistics park modeling and planning or predicting the traffic flow in urban streets network. This applications are very interesting, but any application, similar to the one described in the paper was not found.[1] The major applications refer to water or power flows, to classification or recognition of patterns. In this paper the application described focuses on transport, pick-up order, optimization of time transport and length of transport route. The use of neural network does not guarantee the optimal solution, but a solution close to the optimum, obtained in short time, which makes it acceptable.

[1] The application source was made in Scopus base (date: 03.03.2013).

## 2 Framework

The optimization in transport is based on setting the pick-up order of goods in a logistic system, which can be described as follows:

1. Few days before the planned shipment of the goods the supplier will notify the shipment with weigh and the quantity of pallet places (we assume that every cargo is palatable).
2. Neural network will group the suppliers with each other to maximize the loading space including the location of the suppliers and their *logistic coefficient*.

The coefficient will describe the how fast a truck is loaded—from the moment when it will arrive to the supplier until it will leave the company; and the suppliers logistic infrastructure. It will be set individually for each supplier based on the previous experience with the supplier. The existence of this confidence is important, because the transport time is often so long, because the truck often waits for loading. This time is not effective and depends on the processes performed by the enterprise and that means it will start the tour to the final receiver later.

The group of suppliers means, that the suppliers in one group will denote, that these suppliers will be handled by one truck.

3. Expert system ES1 will randomly change the suppliers in groups twice, creating new groups. When the new solution is better (the sum of the coefficients or/and used loading surface is bigger) then the new groups will be given to the neural network as pattern. The purpose is to avoid mistakes made by the neural network.
4. Expert system ES2 will check the groups from the utilization of loading surface point of view. If the utilization is less than 85 %, then the proposition will be rejected. The system after verification of all of the propositions will give the number of trucks needed to pick up the goods, followed with the utilization of each truck.
5. In case if in one group includes more than one city, the expert system ES3 will designate the exact tour of reception of goods. We assume that the end point is the final recipient. This system will be connected with the GPS system, which will be a main part of ES3. Additionally basing on the number of kilometers of the optimal tour (a number of kilometers will be agreed with the truck company) the cost of each tour will be given by the ES3. Moreover the system will give an estimation of arriving time to each supplier. Thanks to it the supplier can be prepared to quickly handle the truck.

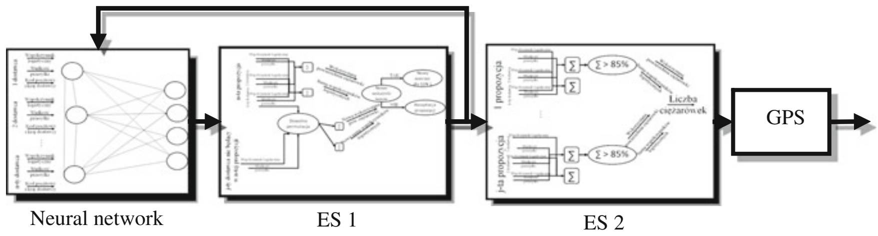


**Fig. 1** Framework of the hybrid system (own work)

## 3 Future Work and Summary

The presented approach is the first step in building such software in a company. Every software must be fitted into a reality of the company and other components of their management system. The authors are convinced that such a framework can be also applied in a distribution company, but at first it has to be adapted to it. Only after implementing this framework it can be tested, if it is useful and profitable (Fig. 1).

Each component of the framework has to be created, tested, and then the elements can be combined. Additionally the neural system has to be created from the beginning. Such problem is not defined yet, but it can be brought from another problem already solved. ES3 can try to build new groups from the suppliers that remained. After testing the assumption of 85 % accepted can be updated.

The results can be different for different companies; therefore conclusions can be made only after the system will be implemented.

## References


1. Gołembska E (2010) (red nauk) Kompendium wiedzy o logistyce Nowe wydanie, Wydawnictwo Naukowe PWN
2. Maćkowiak N, Pawłyszyn I, Stachowiak A (2010) The concept of use of artificial neural networks in process of selection of JIT-suppliers. In: Pawłowski E (red), Operations and logistics management, Wydawnictwo Politechniki Poznańskiej
3. Pomykalski A (2008) Zarządzanie i planowanie marketingowe, Wydawnictwo Naukowe PWN
4. Golińska P (2010) (red) Nowoczesne rozwiązania technologiczne w logistyce, Politechnika Poznańska
5. Bubnicki Z (2005) Teoria i algorytmy sterowania, Wydawnictwo Naukowe PWN
6. Flasiński M (2011) Wstęp do sztucznej inteligencji, Wydawnictwo Naukowe PWN
7. Kwiatkowska AM (2007) Systemy wspomagania decyzji Jak korzystać z WIEDZY i informacji, Wydawnictwo Naukowe PWN/MIKOM
8. Tarczyński G (2011) Algorytm Kohonena w analizie danych ekonomicznych, Wydawnictwo Uniwersytetu Ekonomicznego we Wrocławiu
9. Bendkowski J, Radziejowska G (2005) Logistyka zaopatrzenia w przedsiębiorstwie, Wydawnictwo Politechniki Śląskiej

10. Bach M Wybrane zagadnienia związane z automatycznym tłumaczeniem zadań
11. Grzegorczyk W (2011) Strategie marketingowe przedsiębiorstw na rynku Międzynarodowym, Wydawnictwo Uniwersytetu Łódzkiego
12. Lenart A (2010) Uwarunkowania pozyskiwania zintegrowanych systemów informatycznych zarządzania. In: Nowicki A, Chomiak-Orsa I, Sroka H (red), Informatyka ekonomiczna 17. Systemy informacyjne w zarządzaniu. Przegląd naukowo-dydaktyczny, Wydawnictwo Uniwersytetu Ekonomicznego we Wrocławiu
13. Korbicz J, Obumowicz A, Uciński D (1994) Sztuczne sieci neuronowe. Podstawy i zastosowania, Akademicka Oficyna Wydawnicza PLJ
14. Barzykowski J (2004) (opr) Współczesna metrologia zagadnienia wybrane, Wydawnictwa Naukowo—Techniczne
15. Sławińska M (2008) (red), Kompendium wiedzy o handlu, Wydawnictwo Naukowe PWN
16. Knosola R (2007) i zespół, Zastosowania metod sztucznej inteligencji w inżynierii produkcji, Wydawnictwo Naukowo-Techniczne
17. Mulawka JJ (1996) Systemy ekspertowe, Wydawnictwo Naukowo-Techniczne
18. Tadeusiewicz R (1993) Sieci neuronowe, Akademicka Oficyna Wydawnicza RM
19. Pawłyszyn I, Maćkowiak N, Stachowiak A, Jańczak T (2011) An expert system as a tool for optimization of warehousing process. In: Conference Proceeding of ICPR21, Stuttgart
20. Baczyński D, Bielecki S, Parol M, Piotrowski P, Wasilewski J (2008) Sztuczna inteligencja w praktyce, Labolatorium, Oficyna Wydawnicza Politechniki Warszawskiej
21. Szczerbicki E, Reidsema C (1999) Modelling design planning in concerrent engineering, Intelligent processing $\phi$ manufacturing of materials, IPMM '99, Vol 2
22. (2006) wyszukiwania danych sformułowanych w języku polskim na język formalny SQL. In: Grzech A (red.) Inżynieria wiedzy i systemy ekspertowe Tom 1, Oficyna Wydawnicza Politechniki Wrocławskiej
23. Pająk E (2006) Zarządzanie produkcją: produkt, technologia, organizacja, Wydawnictwo Naukowe PWN
24. Pawłyszyn I, Maćkowiak N, Stachowiak A, Jańczak T, Elements of artificial intelligence applied in warehousing. In: Fertsch M, Grzybowska K (red), Logistics in the enterprises—selected aspects, Wydawnictwo Politechniki Poznańskiej
25. Osowski St (2006) Sieci neuronowe do przetwarzania informacji, Oficyna Wydawnicza Politechniki Warszawskiej
26. Bednarek J (2006) Multimedia w kształceniu, Wydawnictwo Naukowe PWN/MIKOM
27. Coyle JJ, Bardi EJ, Langley CJ (2007) Zarządzanie logistyczne, Polskie Wydawnictwo Ekonomiczne
28. Pawłyszyn I, Maćkowiak N, Stachowiak A, Pacholski L (2011) Completation of items in high storage warehouse with the expert system, Logistyka i Transport, Issue 2(13)
29. Zieliński JS (2000) (red), Inteligentne systemy w zarządzaniu, Wydawnictwo Naukowe PWN

# A New Collaborative Filtering-Based Recommender System for Manufacturing AppStore: Which Applications Would be Useful to Your Business?

**C.-S. Ok, H.-Y. Kang and B.-H. Kim**

**Abstract** In this work, a recommender system is proposed for a manufacturing appstore which is designed and built to revitalize online application trades among application developers and small size manufacturing companies. The aim of the recommender system is to create and provide each website user an effective application recommendation list. The list for a user might include items which are not bought by the user but useful. To build the recommendation list the proposed system makes a list of users having similar purchasing pattern to the given user. To construct the user list every user is represented by a *k*-dimensional vector of categories which are predetermined according to industry and business area. Based on the vectors user similarities are calculated for every pair of users. With the user list the system figures out recommendation candidate items which are purchased by users in the list but by the target user. To rank items in the candidate list an item similarity metric is utilized. The metric for a given item implies how close the item is to the applications which the target user purchased. Finally, candidate items are ranked by this metric and first *r* items are recommended to the target user. To demonstrate the effectiveness of the proposed algorithm the proposed system is applied the manufacturing appstore (www.mfg-app.co.kr) and a numerical analysis has conducted with real data from the appstore.

**Keywords** Recommender system · Collaborative filtering · Manufacturing application · Appstore

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## 1 Introduction

Most online shopping mall companies consider recommender system as an essential business tool to enhance their competiveness [1]. Recommender system is an information filtering system which predicts the 'rating' and 'preference' of a user for an item which the user had not yet considered, using a model built from the characteristics of the item [2]. Generally recommender systems improve online business with the following three aspects. First, recommender systems reduce leaving customers without buying by recommending some items which the customers might be interested. Second, they recommend additional items, which are related to the items purchased by a user, to the users for increase of sales. Last, the recommender systems increase customers' loyalties for the online company by helping customers find useful items. With these three aspects recommender systems give online shopping mall companies a sustainable profit model [1].

A collaborative filtering approach is one of the most typical recommender systems. This approach firstly finds a similar user group for a user by utilizing user information and purchasing history [3]. Then, it recommends some items purchased by similar user group and not considered by the user. Although the collaborative filtering is widely used due to its simplicity, this approach does not consider any similarity or correlation between two items [4]. To overcome this weakness we upgrade the collaborative filtering by considering correlations among items. One way to consider correlation among items is the item-to-item filtering [5, 6]. The item-to-item filtering calculates item correlation for every pair of items and creates a recommendation list based on the correlation. This approach has an advantage on the quantity of calculation, but the quality of recommendation is relatively low. Therefore, this work proposes a hybrid recommender system combining the collaborative filtering with the item-to-item approach. In addition, we apply the proposed recommender system to a real manufacturing appstore which is built to revitalize online application trades among application developers and small size manufacturing companies. With this case study we will discuss the effectiveness of our approach.

The remainder of this paper is organized as follows. Section 2 describes the proposed recommender system. Section 3 provides a case study and finally we conclude our work in Sect. 4.

## 2 Proposed Recommender System

This section explains the proposed recommender system. First, a user vector is defined to calculate user similarity between given two users. The user vector is a $N$-dimensional vector where $N$ is the number of items or predetermined categories. Each element of the vector indicates how many items from the corresponding category purchased by the users. Suppose that 3 categories are available and a user have purchased 3, 2, and 0 items from A, B, C categories. Then, the vector of the user would be (3, 2, 0). The user vector for user $i$ is generally defined as follow:

$$\begin{aligned} \mathrm{U_i} = (&\#\text{ of purchased items from 1 categories},\\ &\#\text{ of purchased items from category } 2, \ldots,\\ &\#\text{ of purchased items from category } N) \end{aligned} \tag{1}$$

User similarity ($US$) for given two users $i$ and $j$ are calculated by (2) [3].

$$US(i,j) = \frac{U_i \cdot U_j}{U_i U_j} \tag{2}$$

where $U_i$ and $U_j$ are user vectors of user $i$ and $j$ respectively. This metric is designed to have a high value if two users purchased items from the same category and low otherwise.

Now, our recommender system identifies a similar user group for a given client based on the user similarity. To this end any clustering algorithm can be used. This work adopts the simplest rule which selects users having similarity value over a certain value ($q_0$). Then, a recommendation candidate list is drawn up by selecting items which are purchased by users of the similar user group and not by the target user. This recommendation candidate list is calculated as follow:

Step 1: Create a list of items purchased by user $i$ ($PL_i$).

Step 2: Create a list of items purchased by similar user group of user $i$ ($PLG_i$).

Step 3: Calculate a list of a recommendation candidate list using (3) ($RL_i$).

This process can be represented by (3).

$$RL_i = PL_i - PLG_i \tag{3}$$

However, this list contains too many items for recommendation. Therefore, the proposed system ranks items in the list based on a closeness metric and recommends a part of items in the list. The closeness metric measures how close the items in the candidate lists are to the items purchased by the target user. To calculate the closeness the system requires a business area relationship matrix. This matrix is shown as (4).

$$closeness(i,\ j) = \frac{\sum_{j \in PL_i} BR_{ij}}{n(PL_i)},\ \text{for } i \in RL_i \tag{4}$$

Finally items in the candidate list are ranked with the closeness values and a part or all of them are recommended to users.

**Table 1** Business area and abbreviations in mfg-app.co.kr

| Business area | Abbreviation | Business area | Abbreviation |
|---|---|---|---|
| Product design | PDD | Quality management | QCM |
| Production plan | PRP | Equipment management | EQM |
| Material management | MPM | Inventory management | INM |
| Process control | PRC | Factory operation | FAM |

# 3 Case Study

This chapter explains how our system works in real applications. Our recommender system has been applied a real manufacturing appstore (mfg-app.co.kr) which is designed and built to revitalize online application trades among application developers and small size manufacturing companies. The website classifies applications into eight categories shown in Table 1. Every application is fallen into one of categories.

Table 2 shows purchasing application lists of 15 users registered to the mfg-app.co.kr and their user vectors. In the case of user 1, user 1 has purchased one, two, one and one application from the Product Design, the Process Control, the Quality Management and the Inventory Management category respectively. The subscription of the business area abbreviation indicates the application id in the corresponding category. For example, PPD5 implies the fifth application in the Product Design category. Based on the information the user vector of user 1 becomes (1, 0, 0, 2, 1, 0, 1, 0).

**Table 2** Purchasing lists of 15 users

| User | Purchasing applications | User vector |
|---|---|---|
| 1 | $PDD_5$, $PRC_2$, $PRC_3$, $QCM_2$, $INM_2$ | $U_1 = (1,0,0,2,1,0,1,0)$ |
| 2 | $PRP_1$, $MPM_1$, $PRC_2$, $PRC_3$, $INM_1$ | $U_2 = (0,1,1,2,0,0,1,0)$ |
| 3 | $PDD_1$, $PDD_2$, $PDD_3$, $PDD_4$, $PDD_5$, $PRP_1$, $FAM_1$ | $U_3 = (5,1,0,0,0,0,0,1)$ |
| 4 | $PDD_1$, $PDD_2$, $PDD_4$, $PRC_1$, $PRC_3$, $INM_2$, $FAM_1$ | $U_4 = (3,0,0,2,0,0,1,1)$ |
| 5 | $PDD_2$, $PDD_4$, $PDD_5$, $MPM_1$, $MPM_2$, $PRC_1$, $PRC_2$, $PRC_3$, $ECM_1$, $INM_2$ | $U_5 = (3,0,2,3,0,1,1,0)$ |
| 6 | $MPM_1$, $PRC_1$, $PRC_2$, $PRC_3$, $ECM_1$, $INM_1$, $INM_2$ | $U_6 = (0,0,1,3,0,1,2,0)$ |
| 7 | $PDD_1$, $PDD_2$, $PDD_3$, $PDD_5$, $MPM_1$, $MPM_2$, $PRC_2$, $PRC_3$, $QCM_1$, $QCM_2$, $ECM_1$, $FAM_1$ | $U_7 = (4,0,2,2,2,1,0,1)$ |
| 8 | $PDD_1$, $PDD_2$, $PDD_3$, $PDD_4$ | $U_8 = (4,0,0,0,0,0,0,0)$ |
| 9 | $PDD_3$ | $U_9 = (1,0,0,0,0,0,0,0)$ |
| 10 | $PRC_1$, $PRC_2$, $QCM_1$ | $U_{10} = (0,0,0,2,1,0,0,0)$ |
| 11 | $PDD_1$, $PDD_2$, $PRC_2$, $INM_2$ | $U_{11} = (2,0,2,0,1,0,0,0)$ |
| 12 | $PDD_1$, $PDD_2$, $PRC_2$, $INM_2$ | $U_{12} = (2,0,0,1,0,0,1,0)$ |
| 13 | $PDD_1$, $PDD_2$, $PDD_3$, $PDD_4$, $MPM_1$, $MPM_2$, $PRC_2$, $QCM_1$, $ECM_1$, $INM_2$ | $U_{13} = (4,0,2,1,1,1,1,0)$ |
| 14 | $PDD_1$, $PDD_3$, $PDD_5$, $PRP_1$, $MPM_1$, $MPM_2$, $PRC_3$, $INM_1$, $FAM_1$ | $U_{14} = (3,1,2,1,0,0,1,1)$ |
| 15 | $PDD_1$, $PDD_4$, $QCM_1$, $FAM_1$ | $U_{15} = (2,0,0,0,1,0,0,1)$ |

**Table 3** User similarities between two users

| User | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | – | 0.71 | 0.36 | 0.78 | 0.77 | 0.78 | 0.69 | 0.38 | 0.38 | 0.85 | 0.38 | 0.72 | 0.62 | 0.55 | 0.46 |
| 2 | | – | 0.07 | 0.49 | 0.69 | 0.88 | 0.41 | 0.00 | 0.00 | 0.68 | 0.25 | 0.46 | 0.39 | 0.56 | 0.00 |
| 3 | | | – | 0.80 | 0.59 | 0.00 | 0.74 | 0.96 | 0.96 | 0.00 | 0.64 | 0.79 | 0.79 | 0.79 | 0.86 |
| 4 | | | | – | 0.84 | 0.53 | 0.80 | 0.78 | 0.78 | 0.46 | 0.52 | 0.95 | 0.79 | 0.81 | 0.74 |
| 5 | | | | | – | 0.74 | 0.86 | 0.61 | 0.61 | 0.55 | 0.68 | 0.83 | 0.88 | 0.86 | 0.50 |
| 6 | | | | | | – | 0.42 | 0.00 | 0.00 | 0.69 | 0.71 | 0.53 | 0.422 | 0.44 | 0.00 |
| 7 | | | | | | | – | 0.73 | 0.73 | 0.49 | 0.85 | 0.75 | 0.93 | 0.84 | 0.82 |
| 8 | | | | | | | | – | 1.00 | 0.00 | 0.67 | 0.82 | 0.82 | 0.73 | 0.82 |
| 9 | | | | | | | | | – | 0.00 | 0.67 | 0.82 | 0.82 | 0.73 | 0.82 |
| 10 | | | | | | | | | | – | 0.15 | 0.37 | 0.27 | 0.22 | 0.18 |
| 11 | | | | | | | | | | | – | 0.54 | 0.89 | 0.81 | 0.68 |
| 12 | | | | | | | | | | | | – | 0.83 | 0.79 | 0.67 |
| 13 | | | | | | | | | | | | | – | 0.89 | 0.75 |
| 14 | | | | | | | | | | | | | | – | 0.69 |

**Table 4** Similar user group

| User | Similar users |
|---|---|
| 1 | User 4, user 5, user 6, user 10, user 12 |
| 2 | User 1, user 5, user 6, user 10, user 14 |
| 3 | User 4, user 8, user 9, user 14, user 15 |
| 4 | User 3, user 5, user 7, user 12, user 14 |
| 5 | User 4, user 7, user 12, user 13, user 14 |
| 6 | User 1, user 2, user 4, user 5, user 10 |
| 7 | User 5, user 11, user 13, user 14, user 15 |
| 8 | User 3, user 9, user 12, user 13, user 15 |
| 9 | User 3, user 8, user 12, user 13, user 15 |
| 10 | User 1, user 2, user 5, user 6, user 7 |
| 11 | User 5, user 7, user 13, user 14, user 15 |
| 12 | User 4, user 5, user 8, user 9, user 13 |
| 13 | User 5, user 7, user 11, user 12, user 14 |
| 14 | User 4, user 5, user 7, user 11, user 13 |
| 15 | User 3, user 7, user 8, user 9, user 13 |

Now, user similarities are calculated by Eq. (2) based on user vectors shown in Table 2. Table 3 lists user similarity for every pair of users.

According to Table 3 similar user groups can be identified for every single user. To determine the similar group for a given user several methods can be used. The methods include top-$k$, predetermined threshold, and other approaches. This example utilizes the top 5 method which selects five users having high similarity values. Table 4 shows similar user group for each user.

**Table 5** Candidate items for each user

| User | Candidate items |
|---|---|
| 1 | $PDD_1$, $PDD_2$, $PDD_4$, $MPM_1$, $MPM_2$, $PRC_1$, $QCM_1$, $ECM_1$, $INM_1$, $PEM_1$ |
| 2 | $PDD_1$, $PDD_2$, $PDD_3$, $PDD_4$, $PDD_5$, $MPM_2$, $PRC_1$, $QCM_1$, $QCM_2$, $ECM_1$, $INM_2$, $PFM_1$ |
| 3 | $MPM_1$, $MPM_2$, $PRC_1$, $PRC_3$, $QCM_1$, $INM_1$, $INM_2$ |
| 4 | $PDD_3$, $PDD_5$, $PRP_1$, $MPM_1$, $MPM_2$, $PRC_2$, $QCM_1$, $QCM_2$, $ECM_1$, $INM_1$ |
| 5 | $PDD_1$, $PDD_3$, $PRP_1$, $QCM_1$, $QCM_2$, $INM_1$, $PEM_1$ |
| 6 | $PDD_1$, $PDD_3$, $PDD_4$, $PDD_5$, $PRP_1$, $MPM_2$, $QCM_1$, $QCM_2$, $PFM_1$ |
| 7 | $PDD_4$, $PRP_1$, $PRC_1$, $INM_1$, $INM_2$ |
| 8 | $PDD_5$, $PRP_1$, $MPM_1$, $MPM_2$, $PRC_2$, $QCM_1$, $ECM_1$, $INM_2$, $PFM_1$ |
| 9 | $PDD_1$, $PDD_2$, $PDD_4$, $PDD_5$, $PRP_1$, $MPM_1$, $MPM_2$, $PRC_2$, $QCM_1$, $ECM_1$, $INM_2$, $PFM_1$ |
| 10 | $PDD_1$, $PDD_2$, $PDD_3$, $PDD_4$, $PDD_5$, $PRP_1$, $MPM_1$, $MPM_2$, $PRC_3$, $QCM_2$, $ECM_1$, $INM_1$, $INM_2$, $PFM_1$ |
| 11 | $PDD_2$, $PDD_4$, $PDD_5$, $PRP_1$, $MPM_1$, $MPM_2$, $PRC_3$, $QCM_2$, $ECM_1$, $INM_1$, $INM_2$, $PFM_1$ |
| 12 | $PDD_3$, $PDD_4$, $PDD_5$, $MPM_1$, $MPM_2$, $PRC_1$, $PRC_2$, $PRC_3$, $QCM_1$, $ECM_1$, $INM_2$, $PFM_1$ |
| 13 | $PDD_5$, $PRP_1$, $PRC_1$, $PRC_3$, $QCM_2$, $INM_1$, $PEM_1$ |
| 14 | $PDD_2$, $PDD_4$, $PRC_1$, $PRC_2$, $QCM_1$, $QCM_2$, $ECM_1$, $INM_2$ |
| 15 | $PDD_2$, $PDD_3$, $PDD_5$, $PRP_1$, $MPM_1$, $MPM_2$, $PRC_2$, $PRC_3$, $QCM_2$, $ECM_1$, $INM_2$ |

Based on the similar user group, candidate items for recommendation to a user are listed up in Table 5. The list for a user includes items which are purchased by the similar user group of the given user and not by the given user. For example, candidate items for user 1 are applications purchased by user 4, 5, 6, 10, and 12 and not by user 1.

Since these lists include too many items to recommend, the items in those lists are needed to be ranked. The items in the list are ranked with a new metric, closeness, calculated by a relatedness. We define the relatedness between two items as the number of users who buy the two items together. This metric has a higher value, more users purchase two items together. Table 6 shows the relatedness for every pair of users.

Now, for every item in the candidate list the closeness is calculated by using Eq. (4). The closeness measures how much related a given item to items purchased by a given user and implies how much helpful the given item is to the given user. Table 7 shows all closeness values of all items for 15 users.

Now, top 5 items can be chosen for every single user based on the closeness value and Table 8 lists those items to be recommended.

We demonstrate the effectiveness of our approach by comparing with a simple collaborative filtering method which recommends the most items purchased by similar users. To evaluation these recommender systems an evaluation method proposed by Sarwarn et al. has adopted [4]. The evaluation method is as follow:

**Table 6** Relatedness for every pairs of applications

| | $PDD_1$ | $PDD_2$ | $PDD_3$ | $PDD_4$ | $PDD_5$ | $PRP_1$ | $MPM_1$ | $MPM_2$ | $PRC_1$ | $PRC_2$ | $PRC_3$ | $QCM_1$ | $QCM_2$ | $ECM_1$ | $INM_1$ | $INM_2$ | $PFM_1$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $PDD_1$ | – | 6 | 6 | 5 | 3 | 2 | 4 | 4 | 1 | 3 | 3 | 3 | 2 | 2 | 1 | 3 | 5 |
| $PDD_2$ | | – | 4 | 5 | 3 | 1 | 3 | 3 | 2 | 4 | 3 | 2 | 1 | 3 | 0 | 4 | 3 |
| $PDD_3$ | | | – | 3 | 3 | 2 | 4 | 4 | 0 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 3 |
| $PDD_4$ | | | | – | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 0 | 3 | 3 |
| $PDD_5$ | | | | | – | 2 | 3 | 3 | 1 | 3 | 4 | 1 | 2 | 2 | 1 | 2 | 3 |
| $PRP_1$ | | | | | | – | 2 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 2 | 0 | 2 |
| $MPM_1$ | | | | | | | – | 5 | 2 | 5 | 5 | 2 | 2 | 4 | 3 | 3 | 2 |
| $MPM_2$ | | | | | | | | – | 1 | 3 | 3 | 2 | 2 | 3 | 1 | 2 | 2 |
| $PRC_1$ | | | | | | | | | – | 3 | 3 | 1 | 0 | 2 | 1 | 3 | 1 |
| $PRC_2$ | | | | | | | | | | – | 5 | 3 | 2 | 4 | 2 | 5 | 1 |
| $PRC_3$ | | | | | | | | | | | – | 1 | 2 | 3 | 3 | 4 | 3 |
| $QCM_1$ | | | | | | | | | | | | – | 1 | 2 | 0 | 1 | 2 |
| $QCM_2$ | | | | | | | | | | | | | – | 1 | 0 | 1 | 1 |
| $ECM_1$ | | | | | | | | | | | | | | – | 1 | 3 | 1 |
| $INM_1$ | | | | | | | | | | | | | | | – | 1 | 1 |
| $INM_2$ | | | | | | | | | | | | | | | | – | 1 |

**Table 7** The closenesses of items to every user

| User | $PDD_1$ | $PDD_2$ | $PDD_3$ | $PDD_4$ | $PDD_5$ | $PRP_1$ | $MPM_1$ | $MPM_2$ | $PRC_1$ | $PRC_2$ | $PRC_3$ | $QCM_1$ | $QCM_2$ | $ECM_1$ | $INM_1$ | $INM_2$ | $PFM_1$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.8 | 3.0 | 0.0 | 1.8 | 0.0 | 0.0 | 3.6 | 2.6 | 2.0 | 0.0 | 0.0 | 1.4 | 0.0 | 2.6 | 1.4 | 0.0 | 1.8 |
| 2 | 2.6 | 2.2 | 2.2 | 1.4 | 2.6 | 0.0 | 0.0 | 2.6 | 1.8 | 0.0 | 0.0 | 1.2 | 1.2 | 2.4 | 0.0 | 2.6 | 1.8 |
| 3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.9 | 2.7 | 1.0 | 0.0 | 2.7 | 1.7 | 0.0 | 0.0 | 0.9 | 2.0 | 0.0 |
| 4 | 0.0 | 0.0 | 2.7 | 0.0 | 2.6 | 1.1 | 3.0 | 2.4 | 0.0 | 3.3 | 0.0 | 1.7 | 1.0 | 2.3 | 1.0 | 0.0 | 0.0 |
| 5 | 3.4 | 0.0 | 2.5 | 0.0 | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 1.3 | 0.0 | 1.3 | 0.0 | 2.0 |
| 6 | 2.4 | 2.7 | 0.0 | 1.9 | 2.3 | 1.0 | 0.0 | 2.6 | 0.0 | 0.0 | 0.0 | 1.4 | 1.1 | 0.0 | 0.0 | 0.0 | 1.4 |
| 7 | 0.0 | 0.0 | 0.0 | 2.5 | 0.0 | 1.3 | 0.0 | 0.0 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.2 | 2.5 | 0.0 |
| 8 | 0.0 | 0.0 | 0.0 | 0.0 | 2.8 | 1.5 | 3.3 | 3.3 | 0.0 | 2.8 | 0.0 | 2.3 | 0.0 | 2.3 | 0.0 | 2.8 | 3.5 |
| 9 | 6.0 | 4.0 | 0.0 | 3.0 | 3.0 | 2.0 | 4.0 | 4.0 | 0.0 | 2.0 | 0.0 | 2.0 | 0.0 | 2.0 | 0.0 | 1.0 | 3.0 |
| 10 | 2.3 | 2.7 | 1.3 | 2.0 | 1.7 | 0.3 | 3.0 | 2.0 | 0.0 | 0.0 | 3.0 | 0.0 | 1.0 | 2.7 | 1.0 | 3.0 | 1.3 |
| 11 | 0.0 | 3.4 | 0.0 | 2.4 | 2.8 | 1.4 | 0.0 | 0.0 | 0.8 | 3.0 | 3.0 | 2.0 | 0.0 | 2.4 | 1.2 | 2.0 | 2.6 |
| 12 | 0.0 | 0.0 | 3.3 | 3.8 | 2.8 | 0.0 | 3.8 | 3.0 | 2.3 | 0.0 | 3.8 | 2.3 | 0.0 | 3.0 | 0.0 | 0.0 | 2.5 |
| 13 | 0.0 | 0.0 | 0.0 | 0.0 | 2.5 | 1.0 | 0.0 | 0.0 | 1.7 | 0.0 | 3.1 | 0.0 | 1.4 | 0.0 | 1.0 | 0.0 | 2.3 |
| 14 | 0.0 | 2.9 | 0.0 | 2.2 | 0.0 | 0.0 | 0.0 | 0.0 | 1.1 | 2.8 | 0.0 | 1.4 | 1.4 | 2.0 | 0.0 | 1.9 | 0.0 |
| 15 | 0.0 | 4.0 | 3.5 | 0.0 | 2.3 | 1.3 | 2.5 | 2.5 | 0.0 | 2.3 | 2.3 | 0.0 | 1.0 | 1.8 | 0.0 | 2.0 | 0.0 |

**Table 8** Ranking of recommendation items

| User | Ranking | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | $MPM_1$ | $PDD_2$ | $PDD_1$ | $MPM_2$ | $ECM_1$ |
| 2 | $PDD_1$ | $INM_2$ | $PDD_5$ | $MPM_2$ | $ECM_1$ |
| 3 | $MPM_1$ | $PRC_3$ | $MPM_2$ | $INM_2$ | $QCM_1$ |
| 4 | $PRC_2$ | $MPM_1$ | $PDD_3$ | $PDD_5$ | $MPM_2$ |
| 5 | $PDD_1$ | $PDD_3$ | $PFM_1$ | $QCM_1$ | $INM_1$ |
| 6 | $PDD_2$ | $MPM_2$ | $PDD_1$ | $PDD_5$ | $PDD_4$ |
| 7 | $PDD_4$ | $INM_2$ | $PRC_1$ | $PRP_1$ | $INM_1$ |
| 8 | $PFM_1$ | $MPM_1$ | $MPM_2$ | $PRC_2$ | $INM_2$ |
| 9 | $PDD_1$ | $PDD_2$ | $MPM_1$ | $MPM_2$ | $PDD_4$ |
| 10 | $MPM_1$ | $PRC_3$ | $INM_2$ | $PDD_2$ | $ECM_1$ |
| 11 | $PDD_2$ | $PRC_2$ | $PRC_3$ | $PDD_5$ | $PFM_1$ |
| 12 | $MPM_1$ | $PRC_3$ | $PDD_4$ | $PDD_3$ | $MPM_2$ |
| 13 | $PRC_3$ | $PDD_5$ | $PFM_1$ | $PRC_1$ | $QCM_2$ |
| 14 | $PDD_2$ | $PRC_2$ | $PDD_4$ | $ECM_1$ | $INM_2$ |
| 15 | $PDD_2$ | $PDD_3$ | $MPM_1$ | $MPM_2$ | $PRC_2$ |

Step 1: For a given user, create a new purchasing list by deleting of the items from the purchasing list of the user.

Step 2: Build a new recommendation list by applying a recommender system with the new purchasing list.

Step 3: Count how many deleted items are contained by the recommendation list.

Step 4: Evaluate the recommender system with *F1* [4].

*F1* has been proposed by by B. M. Sarwarn et al. to consider two metrics, *recall* and *precision* [7] which are critical for quality judgment of recommender system, simultaneously. *F1* is defined as follows:

$$F1 = \frac{2 \times recall \times precision}{recall + precision}$$
$$\text{where } recall = \frac{|test \cap Top\_N|}{|test|} \text{ and } precision = \frac{|test \cap Top\_N|}{|N|} \tag{5}$$

where *test* is the set of items deleted from the original recommendation list in **Step 1**, *Top_N* is the new recommendation list in **Step 2**, and *N* is the number of items recommended.

Table 9 shows the *F1* values of the collaborative filtering-based and the proposed systems. These values are the average of 15 *F1* values for 15 users. Although our system gives a little better performance than the existing system, the

**Table 9** The evaluation results for the collaborative filtering and the proposed systems

| | Collaborative filtering-based system | Proposed system |
|---|---|---|
| *F1* | 0.360572 | 0.366647 |

gap of *F1* values is too small to conclude that our system is superior to the collaborative filtering-based system. To show the effectiveness of the proposed system more experiments are required with more users and items.

## 4 Conclusions

This paper proposed a new recommender system which upgrades a collaborative filtering-based recommender system with item-to-item collaborative filtering. This system firstly builds a list of candidate items to be recommended to a user by finding a similar user group and selecting items purchased by the group and not by the user. Then, candidate items in the list are ranked by the proposed metric and first *r* items are recommended to the target user. We demonstrated the effectiveness of the proposed system by applying the real manufacturing appstore (www.mfg-app.co.kr) and performing some experiments. Even though our system gives a little better performance, we failed to have a solid evidence to conclude that our system is superior to the existing recommender system. One possible reason of this situation is that the manufacturing website is very early stage and, consequently, the registered users and items are not enough for the experiments. Therefore, in future, we plan to conduct more experiments as the numbers of users and items of website increase.

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## References

1. Schafer JB, Konstan J, Riedi J (1999) Recommender systems in e-commerce. In: Proceedings of the 1st ACM conference on electric commerce, pp 158–166
2. Ricci F, Rokach L, Shapira B (2011) Introduction to recommender systems handbook. Recomm Syst Handbook, Springer pp 1–35
3. Sarwarm BM et al (2000) Analysis of recommendation algorithms for e-commerce, ACM conference of electronic commerce, ACM Press, New York, pp 158–167
4. Cho Y, Gu M, Ryu K (2012) Development of personalized recommendation system using RFM method and k-means clustering, J Korea Soc Comput Inf, 17(6)
5. Linden GD, Jacobi JA, Benson EA (2001) Collaborative recommendations using item-to-item similarity mappings, Patent $\pi\pi$ Trademark Office

6. Linden G, Smith B, York J (2003) Amazon.com recommendations: item-to-item collaborative filtering, Industry Report, Jan-Feb 2003
7. Kowalski G (1997) Information retrieval systems: theory and implementation. Kluwer Academic Publishers, Norwell

# Real-Time Tracking System for a Moored Oil Tanker: A Kalman Filter Approach

**Paulo Malheiros, Paulo Rosa-Santos, José Gonçalves, Paulo Costa, António Paulo Moreira, Fernando Veloso-Gomes and Francisco Taveira-Pinto**

**Abstract** This paper presents a tracking system developed to study the behavior of an oil tanker moored at the Berth "A" of the Leixões Oil Terminal, Porto, Portugal. A brief description of the local environmental conditions and the existing operational conditions at that oil terminal are presented. Due to extreme outdoor working conditions a Kalman filter was implemented to ensure the robustness and reliability of the obtained measurements. Tests were performed in laboratory on a physical model of a moored oil tanker at a scale 1/100. The results were compared with a commercial motion capture system installed in laboratory. The presented measurement system was developed as part of the DOLPHIN project that aims to study the behavior of moored ships in harbors.

## 1 Introduction

Downtime at ocean facing ports is closely related with excessive moored ship motions caused by wave action. Reducing the amplitude of the moored ships' motions is therefore crucial to increase the on and off-loading operations efficiency, to minimize port operational costs, as well as to reduce security and environmental risks, especially when dealing with dangerous cargoes.

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The study of the behavior of moored ships in harbors can be justified in the initial design stage of a new port or terminal to assess the effects of some interventions on a particular berth, and also to try to improve operation and security conditions at existing berths. Usually there are three tools to deal with this issue: experience with previous and related projects, numerical modeling, and physical modeling [1]. Despite its importance for port engineering research, prototype measurements of ship motion amplitude and mooring lines and fender forces are usually scarce. Sometimes available data is not very accurate or is limited, in order to provide qualitative information. Prototype measurements are not affected by scale or laboratory effects and test conditions are realistic, although limited.

This paper presents a developed tracking system based on a physical model and stereoscopic vision data fusion, merging the data resorting to a Kalman Filter approach. The oil tanker maintains a set of hypotheses with regard to its position and the position of different objects around them. The input for updating these beliefs comes from poses belief and various sensors. An optimal estimation can be applied in order to update its beliefs as accurately as possible. After one action the pose belief is updated based on data collected up to that point in time, by a process called filtering. Kalman filtering is a standard approach for reducing the error in a least squares sense, using measurements from different sources [2–5]. The filter has two steps that are common to all localization probabilistic algorithms, which are predicted and corrected [6, 7]. Initially it is calculated the state update based on the oil tanker model (relative measurements) and the propagation of the state covariance. Then it is included data from the developed stereoscopic vision system (absolute measurements) and the state covariance is updated.

A Butterworth linear low-pass filter was also added to the obtained data due to the knowledge that a maximum frequency of oscillation exists in the ships movements. The ship absolute position at the port terminal is measured by stereoscopic computer vision system composed of two or more synchronized cameras that can capture and record ship images from different locations from a safe distance, consequently determining its position.

The presented results are objectives of the DOLPHIN project which aims to study the behavior of moored ships in harbors and oil terminals, shown in Fig. 1. This paper focuses on the results of a simplified model of an oil terminal and surrounding area, built with the aim of analyzing the influence of an increase of the breast line pretension on the behavior of a moored oil tanker, namely on the ship motion amplitude as well as on the forces on the mooring lines and fenders.

## 2 Dolphin Project

The DOLPHIN project aims to study the behavior of moored ships in harbors and, in particular, at Berth “A” of Leixões Oil Terminal, trying to deal with its operational problems. The Port of Leixões, located in the Northwest coast of Portugal and facing the North Atlantic, has an oil terminal composed by 3 berths,


**Fig. 1** Leixões Oil Terminal, Porto, Portugal

shown in Fig. 1. Berth "A", located at the harbor entrance, does not assure in average the operational and security conditions during about 20 % of the time, despite the protection offered by the Leixões north breakwater [8]. In this berth the breakage of ship mooring lines can occur and moored ships sometimes have excessive movements.

The Berth "A" jetty structure consists of two breasting dolphins and a loading platform. Each breasting dolphin is equipped with a pneumatic fender and double mooring hooks. The remaining terminal mooring hooks are located on the north breakwater superstructure. Alongside this berth the bottom is about-16 mCD, which allows receiving oil tankers of up to 105,000 dwt. In the vicinity of the Port of Leixões tides are of the semidiurnal type, reaching amplitudes that range between 2 and 4 m. The wave climate is highly energetic, the main storms come from the North Atlantic, mainly between the months of October and March. During storms significant wave heights may exceed 8 m and wave periods can be on the order of 16–18 s with the storm persisting for up to 5 days. Wave directions between West and Northwest prevail, also with some occurrences from Southwest.

The behaviour of an oil tanker moored at the Berth "A" is being studied within the scope of the R&D project—DOLPHIN, in order to better clarify the contribution of some of the identified critical issues on Berth "A" downtime and to analyze the effectiveness of some intervention alternatives proposed in previous studies. This project includes physical model tests, numerical simulations and prototype measurement systems at Berth "A".

## 3 Experimental Setup

The physical model study was carried out at the Hydraulics Laboratory of the Hydraulics, Water Resources and Environment Division of the Faculty of Engineering of the University of Porto, on a geometric scale of 1/100. The existing wave tank is 28 m long, 12 m wide, and 1.2 m in depth. The setup of the physical

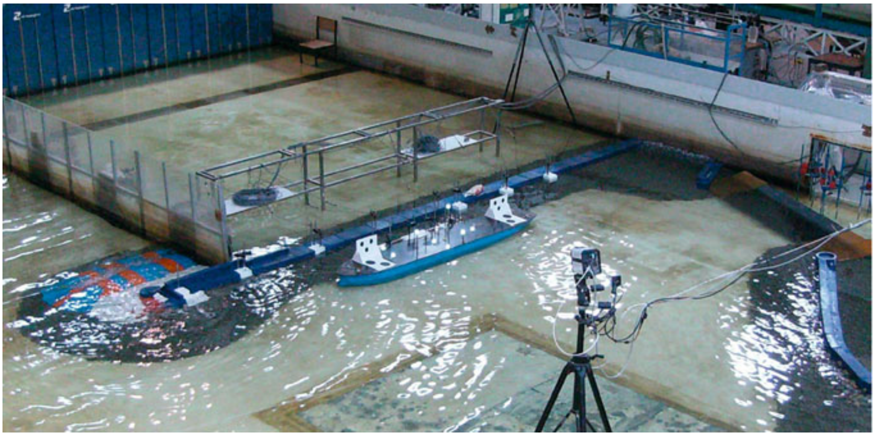

**Fig. 2** The physical model in the wave tank

model in the wave tank is shown in Fig. 2. The ship selected for the study intends to represent the biggest class of oil tankers that regularly demand Berth “A” and corresponds to a 105,000 dwt oil tanker, with 245 m overall length, 43 m of breath, and a maximum draft of 14.1 m. The load-elongation curves of the ship mooring lines were simulated using a combination of precision springs, taking also into account the stiffness of the corresponding force transducer. Their non-linear behavior was linearized. This way the stiffness of each one of the mooring lines (which depends of the mooring line elongation) was replaced by the constant stiffness of an equivalent linear mooring line having the same energy absorption capacity of the non-linear mooring line. Precision springs were carefully selected to furnish the appropriate elasticity for each mooring line. The non-linear behavior of the two fenders installed was reproduced in the same way. The elasticity of each mooring element was confirmed, by calibration, prior to testing. Forces on the mooring lines and fenders were measured with suitable force transducers. The moored oil tanker motions, in the 6 degrees of freedom (surge, sway, heave, roll, pitch, and yaw), were measured using a Qualisys—Motion Capture System, composed by 3 infrared cameras [9].

One array of four wave probes was installed in the water tank parallel to the water movement, to record the water surface elevations for reflection analysis. A dissipation beach was created at the end of the wave tank to reduce wave reflections.

## *3.1 Stereoscopic Vision System*

The presented system was developed to provide the absolute localization of moored ships. Carrying out measurements (in prototype) during severe environmental conditions can be very difficult or even impossible. Ideally, prototype measurements should also include data about wave conditions (short and long period waves) at some locations, forces on the mooring lines and fenders as well as wind and current characteristics [1].

Furthermore the restrictions imposed in such a volatile environment require the use of a passive measurement system. The development of a computer vision system to determine the ship position at the Berth "A" (Fig. 1) was based on stereoscopic vision with two or more cameras. From a safe distance, two or more synchronized cameras can capture and record ship images from different locations. With multiple cameras and choosing some ship features as natural landmarks it is possible, after a calibration process, to map the landmark pixels into points in the 3D space. The next step is to recover the ship's position and orientation from the landmark positions.

A commercial stereoscopic vision solution with three cameras provided by Qualisys was already installed in the wave tank. The developed system's cameras were installed in the vicinity of the Qualisys cameras, as shown in Fig. 3, in order to work in similar conditions. The cameras were positioned approximately at 5 m distance in a 45° view angle. The Qualisys system consists of three infrared cameras which emit infrared light. Reflective sphere markers are placed in the ship model which allows an easy detection by the cameras. The detection of the markers is done by the cameras which mean they have internal processing. All three are connected by a cable to a personal computer (PC) and at the same time they synchronize through that same connection.

The PC records the movement through the duration of the test, a final processing is done after the end of the test presenting graphically the animated positions of the markers, as shown in Fig. 3. This system can also show the results in real-time. The position of the markers is then translated to a mathematical model of the ship which allows the calculation of the translation and orientation of the ship. The acquisition rate used for the Qualisys system during the tests was of 24 Hz. However this system can measure up to 120 Hz.

The developed stereoscopic system consists of two synchronized cameras, as highlighted by circles in Fig. 3, looking at the target from different positions. The

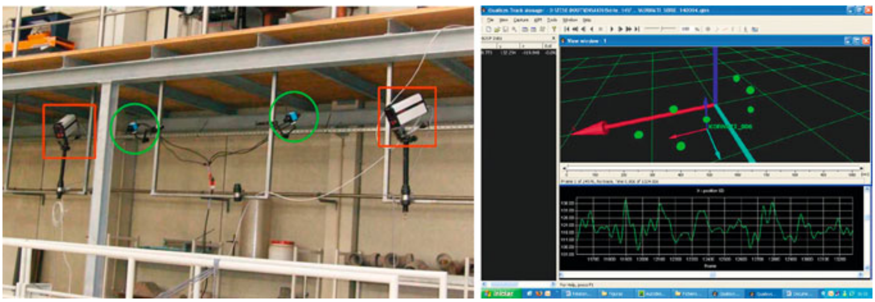

**Fig. 3** Cameras installed in the Hydraulics Laboratory (on the *left*). Qualisys cameras shown inside *squares* (only two pictured), presented system cameras shown inside *circles*. Qualisys software markers reconstruction (on the *right*)

problem consists in determining the structure of the scene from the two views, and for that two algorithms were used, the Normalized Eight-Point Algorithm [10] for the initial estimation followed by minimizing a function for fine fitting using the Levenberg–Marquardt Algorithm. The eight-point algorithm is the simplest method of computing the fundamental matrix, involving no more than the construction and (least-squares) solution of a set of linear equations [11]. If a point X in space is $x$ in one image and its match $x'$ in the second image then the fundamental matrix $F$ satisfies the condition $x'Fx = 0$ (the X and $x$ vectors are expressed in homogeneous coordinates).

The calibration process consists of determining the cameras geometry by computing the matrix $F$. With the focal length of both views known the intrinsic parameters can be written using a $3 \times 3$ matrix $A$ and $A'$ and assuming that the pixel in the first image is $x = A[I0]$X where $[I0]$ is a $3 \times 4$ matrix composed by a $3 \times 3$ identity matrix and a column of zeros. An estimate of the rotation matrix $R$ and the translation matrix $T$ can be determined as $x = A' [RT]$X. A minimization function is then applied to achieve a metric reconstruction.

1. *Solution Structure:* Two FireWire CCD Bayer industrial cameras were used in this application, and an interface board with an 8-bit microcontroller was used to control the acquisition rate. Using the measurements by the Qualisys cameras a 10 Hz acquisition rate was found acceptable for our tests. Both visual systems work in real-time so it was ensured that the laptop had enough time to process all data in 100 ms. Using a standard industrial camera allows to benefit from lower costs, when compared with the use of purpose built cameras.

The presented solution was developed in Object Pascal using Lazarus which is open source and runs in many operating systems. A virtual graphical representation of the scene was implemented using the GLScene components which are very useful for a fast validation of the results. The main set of components used in this application was the 5 dpo Component Library [12] developed by the 5 dpo Team for robotic applications. This library contains components for image acquisition (Firewire and USB Cameras), video display, and serial communication and is also open source.

2. *The Calibration Process:* The calibration of the cameras system consisted in recording a set of point matches in each image. Then with several matches (eight or more) the eight-point algorithm can determine the structure of the two views. A specific marker was designed to place on the model as shown in Fig. 4. This has circles which are easier to detect in a perspective view, and they are positioned in different planes to determine with better accuracy the various motion directions. Since these tests took several weeks this calibration process was done several times, normally more than 100 matches were used in the calibration process although the eight-point reconstruction algorithm only needed eight matches [10].
3. *The Marker Detection:* Two markers were placed on the bow and stern of the ship respectively as shown in Fig. 4. This was the chosen configuration because

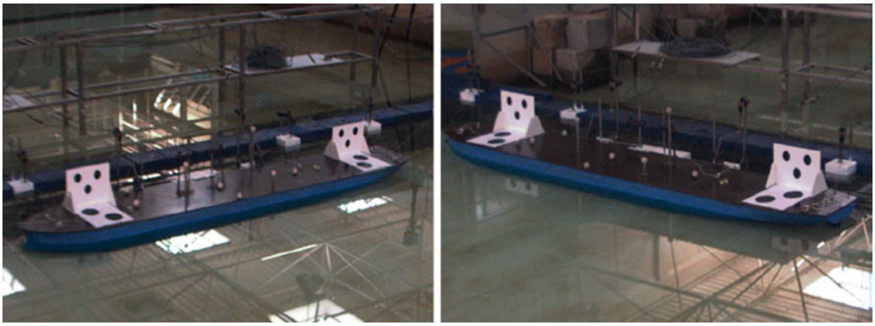

**Fig. 4** Stereo images from the developed system of the physical model with markers

the remaining available space in the model was very reduced and these markers could not interfere with the markers used by the Qualisys system. These were A4 pages with a dotted pattern printed on. The markers design was chosen to achieve a precise and robust measurement, the detection of the marker consisted in two steps. The first step was to find all white rectangles in the scene and the second step was to find five black circles inside each white area. The circle centers give a very stable result. Once the markers were found each circle was classified, resulting in a match in both images.

## 4 Absolute and Relative Measurements

Having both markers 3D positions detected the final task was to determine the global position of the moored ship, in its six degrees of freedom. These are referred to its center of mass, which is approximately amidships and 100 mm below main deck level.

Determining the equation of the plane

$$ax + by + cz + d = 0 \tag{1}$$

that is the best fit of both markers gives us the "Deck" and the vector ($a$; $b$; $c$) is the normal to that plane. Going to the middle of the deck and moving in the normal direction 100 mm to the interior of the ship we can obtain its center of mass. This point gives us the three degrees of translation. Using the vector that unites both markers in combination with the previously obtained normal vector we can compute all three degrees of rotation.

The presented models were used to execute the first step of the Kalman filter algorithm (the state update). Different models were applied for rotation and for translation movements, as shown in the next subsections.

## 4.1 Translation Model

The moored oil tanker when performing a translation presents a physical behavior close to a mass-spring system. Using a classical linear system the model of an object with one-dimensional movement and attached to a wall with a spring is

$$ma = -k_{st}x \tag{2}$$

where $m$ is the mass of the object, $a$ is its acceleration, $k_{st}$ is the spring constant and $x$ is the object position. The state equation would then become

$$\begin{bmatrix} \dot{x}(t) \\ \dot{v}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k_{st}}{m} & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ v(t) \end{bmatrix} \tag{3}$$

where the acceleration is $a(t) = \dot{v}(t)$ and the velocity is $v(t) = \dot{x}(t)$. Difference equation in discrete form of Eq. 2 is found to be

$$x[k] = \frac{2}{1 + \frac{k_{st}}{m}\Delta t^2} x[k-1] - \frac{1}{1 + \frac{k_{st}}{m}\Delta t^2} x[k-2]. \tag{4}$$

The least-squares solution of Eq. 4 in the form $x[k] = ax[k–1]–bx[k–2]$ should yield $a \approx 2b$ if this system model approximation was correct. Using a sample of one movement direction it was possible to determine $a = 1.89$ and $b = 0.89$ which was the expected result. The Kalman Filter can be implemented using the state model matrix

$$e^{At} = \begin{bmatrix} \cos\left(\sqrt{\frac{k_{st}}{m}}t\right) & \frac{\sin\left(\sqrt{\frac{k_{st}}{m}}t\right)}{\sqrt{\frac{k_{st}}{m}}t} \\ -\sqrt{\frac{k_{st}}{m}}\sin\left(\sqrt{\frac{k_{st}}{m}}t\right) & \cos\left(\sqrt{\frac{k_{st}}{m}}t\right) \end{bmatrix}. \tag{5}$$

In Eq. 5 it is clear that the use of a Kalman filter allows the compensation of the system model considering the ship mass and the tension placed in the breast lines. This is one of the main reasons for using this filter for this specific outdoor application.

## 4.2 Rotation Model

A mass-spring model was also used for filtering the rotation measurements. Since these movements consist of rotations along the axes the model should depend on the moment of inertia of the ship. Assuming its shape as a cuboid one can determine the three inertial components as

$$J_h = \frac{1}{12}m\left(w^2 + d^2\right),\ J_w = \frac{1}{12}m\left(h^2 + d^2\right),\ J_d = \frac{1}{12}m\left(h^2 + w^2\right). \tag{6}$$

where the cuboid of mass $m$ has height $h$, width $w$ and depth $d$. The corresponding model is achieved identically to the translation model, shown in the previous section. The rotation state equation is

$$\begin{bmatrix} \dot{\theta}(t) \\ \dot{\omega}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k_{sr}}{J} & 0 \end{bmatrix} \begin{bmatrix} \theta(t) \\ \omega(t) \end{bmatrix} \tag{7}$$

where $k_{sr}$ is the rotation spring constant and $J$ the corresponding moment of inertia. The value of $k_{sr}$ depends on the distance between ships center of mass and its center of buoyancy.

## 5 Real-Time Tracking System Resorting to a Kalman Filter

The used filtering system consisted of two linear filters in series, a Butterworth filter and a Kalman filter. The first was used to remove the high frequency noise from the measurements followed by a Kalman filter for real-time tracking. Observing the behavior of the moored ship (through Qualisys software) one can determine its oscillation frequency to be lower than 2 Hz, thus the noise presence can be reduced using a low-pass filter. A fifth order Butterworth filter was implemented with the previously specified cut-off frequency.

Physical model tests were carried out with irregular long crested waves characterized by significant wave heights (Hs) of 1.5 and 2.0 m (on a geometric scale of 1/100), and peak wave periods (T) ranging from 10 to 18 s. The test program included two water levels (d), namely: high tide (corresponding to a water depth, d, equal to 20 m) and mean sea level (d = 18 m). Tests were carried out with about 600 waves with the same temporal sequence for the tests having the same peak wave period. To analyze the effect of an increase of the breast line pretension two conditions were considered: "base condition", with the initial tension in all of the ship mooring lines set between 10 and 12 t; and "extra pretension condition", corresponding to a situation where the initial tension on the breast lines was increased to a value between 25 and 27 t.

The results obtained by the developed Stereoscopic Vision System (SVS) are presented in Figs. 5, 6 alongside the results from the Qualisys—Motion Capture System (QS) to allow comparison. In order to have a more clear perception of the ship motions time series, the results obtained with each of the systems were vertically shifted with QS results in the top line and SVS in the bottom line.

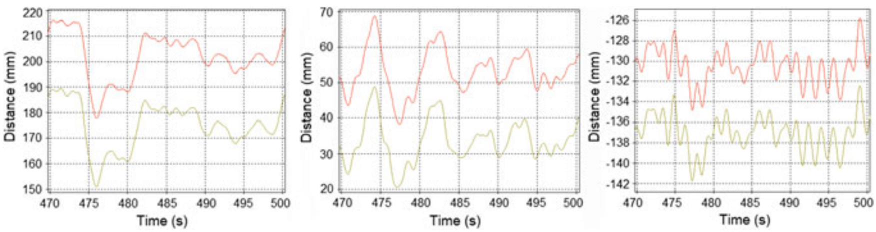


**Fig. 5** Time sample of the model translation motions (surge, sway, and heave, respectively) in a test. *Top line* with QS results and *bottom line* with SVS results

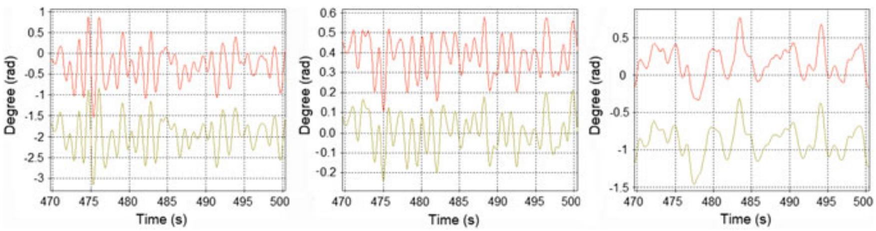


**Fig. 6** Time sample of the model rotation motions (roll, pitch, and yaw, respectively) in a test. *Top line* with QS results and *bottom line* with SVS results

## *5.1 Translation Motions*

The translation motions a ship can experience are the heave (up/down), the sway (side-to-side) and the surge (front/back) [13]. In Fig. 5 is represented a time sample of this ships motions. Based on Fig. 5 analysis, it can be observed that the SVS results follow correctly the values obtained with the QS and with identical magnitude.

Table 1 illustrates the maximum (Max) and significant (Signf) amplitude of the ship translation motions measured with the SVS and QS systems during the physical model test, as well as, the differences (Diff) between both systems in percentage. Significant wave height is the average wave height (trough to crest) of the one-third largest waves in a record. The SVS raw data was also added to Table 1 for analysis of the filters performance. The developed system showed consistency in all tests performed in which the sway results showed a bigger difference from the QS system. Using the filter results in better results especially in the Significant Wave, where this last one is the main characteristic in the analysis of the ship movement.

**Table 1** Translation (in meters) and rotation (in degrees) measurements

| Motion category | | Translation motion | | | Rotation motion | | |
|---|---|---|---|---|---|---|---|
| | | Surge (m) | Sway (m) | Heave (m) | Roll (deg) | Pitch (deg) | Yaw (deg) |
| | QS | 9.74 | 4.11 | 0.95 | 0.24 | 0.07 | 0.20 |
| Max | Raw SVS | 9.73 | 4.10 | 1.00 | 0.24 | 0.07 | 0.20 |
| | Diff (%) | **– 0.1** | **0.0** | **5.5** | **1.6** | **– 5.6** | **2.2** |
| | QS | 2.65 | 1.92 | 0.47 | 0.11 | 0.04 | 0.09 |
| Signf | Raw SVS | 2.53 | 1.87 | 0.47 | 0.11 | 0.03 | 0.08 |
| | Diff (%) | **−4.7** | **−2.7** | **−0.9** | **0.9** | **−4.7** | **−2.3** |
| | QS | 9.74 | 4.11 | 0.95 | 0.24 | 0.07 | 0.20 |
| Max | Filtered SVS | 9.74 | 4.11 | 1.00 | 0.24 | 0.07 | 0.20 |
| | Diff (%) | **0.0** | **0.1** | **5.6** | **– 2.2** | **– 6.6** | **1.7** |
| | QS | 2.65 | 1.92 | 0.47 | 0.11 | 0.04 | 0.09 |
| Signf | Filtered SVS | 2.66 | 1.91 | 0.48 | 0.11 | 0.04 | 0.08 |
| | Diff (%) | **0.2** | **−0.5** | **0.6** | **0.9** | **−3.8** | **−0.6** |

### *5.2 Rotation Motions*

The rotation motions a ship can experience are the roll (rotation about the longitudinal axis), the pitch (rotation about the transverse axis) and the yaw (rotation about the vertical axis) [13]. In Fig. 6 is represented a time sample of this ship motions. As with the translation motions these also follow correctly and with similar amplitude the results from the QS. Table 1 shows the differences (Diff) between both systems in percentage for the rotation motions where is also possible to compare the SVS raw data and the filtered tracking system. Once again the developed system showed consistency in all tests performed and the Significant Wave measurements improved with the filter approach.

## 6 Conclusions

The developed stereoscopic system was able to measure with high precision all six degrees of freedom of the model ship. All tests were developed in laboratory, resorting to a physical model of a moored oil tanker at a scale 1/100. The tests show a good agreement with the results obtained with the Qualisys system. With the cameras positioned approximately at 5 m distance from the target body it was possible to measure a few millimeters variations. The presented system presented a high level of scalability since it doesn't rely on personalized exterior markers since it will use the ship features to track its movement. Also the Qualisys system uses an exterior light source while the developed system works under normal ambient light. The openness of the system was one of the main concerns during the development of this system, using standard and easily accessible equipment and also with little software restrictions.

The presented system has as future work the goal of being applied to track an oil tanker moored at the Berth "A" of the Leixões Oil Terminal, Porto, Portugal. Due to the extreme outdoor working conditions the reliability of the absolute measurements provided by the stereoscopic vision system will, inevitably, decrease. In order to minimize tracking errors, that might emerge while working outside the laboratory, a Kalman filter was implemented to ensure the robustness and reliability of the obtained measurements. It is also important, as future work, to quantify the how outdoor conditions affect the absolute measurements confidence in the measurements in order to obtain an optimal sensor fusion.

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## References

1. Taveira Pinto F et al (2008) Analysis of the behavior of moored tankers, Proceedings of the 27th international conference on offshore mechanics and arctic engineering—OMAE2008 (ASME). Estoril, Portugal, pp 15–20
2. Thrun S, Burgard W, Fox D (2005) Probabilistic robotics, MIT Press, Cambridge
3. Choset H, Lynch K, Hutchinson S, Kantor G, Burgard W, Kavrak L, Thrun S (2005) Principles of robot motion: theory, algorithms, and implementations, MIT Press, Cambridge
4. Ribeiro M (2004) Kalman and extended Kalman filters: concept, derivation and properties, technical report, IST
5. Welch G, Bishop G (2001) An introduction to the Kalman filter, Technical Report, University of North Carolina, US
6. Bravo F et al (2006) Particle-filter approach and motion strategy for cooperative localization, ICINCO
7. Rekleitis I (2003) A particle filter tutorial for mobile robot localization, International conference on robotics and automation
8. IHRH-FEUP/IST (2005) Operational conditions on the oil terminal at Leix̃oes Harbour—Porto—Portugal, Technical Report, vol 6(in Portuguese)
9. Qualisys http://www.qualisys.com
10. Hartley RI (1997) In defense of the eight-point algorithm, in pattern analysis and machine intelligence, IEEE Transactions
11. Hartley RI, Zisserman A (2004) Multiple view geometry in computer vision, Cambridge University Press, Cambridge
12. 5dpo Component Library http://wiki.lazarus.freepascal.org/5dpo
13. Triantafyllou MS, Bodson M, Athans M (1983) Real time estimation of ship motions using Kalman filtering techniques, IEEE J Ocean Eng, OE-8(1):9–20

# Managing Automation Development Projects: A Comparison of Industrial Needs and Existing Theoretical Support

**A. Granlund and M. Jackson**

**Abstract** The use of automation can increase competitiveness but does not guarantee advantageous results. The right choice of technology and correct implementation and use is the key to a successful outcome. This in turn puts great demands on how automation development projects are managed. The aim of this paper is to make a comparison between industrial needs and existing theoretical support associated with managing automation development projects. Through a multiple case study, challenges and success factors related to managing automation projects have been identified. The empirical findings are compared with automation development support found in literature. The results from the empirical study indicate the need for improved process models and clear strategy connected to automation development. The importance of an overall view and planning during automation projects is highlighted as a success factor while difficulties in collaborating with third parties is identified as existing challenges. It is concluded that the support in literature deals with many of the identified challenges and success factors and offers some support for specific parts of the automation development project. There is however still need for an overall framework connecting existing theoretical support, and suggesting how strategy can be connected to the process of developing automation.

## 1 Introduction

Productivity is one of the most fundamental business principles and companies are constantly striving for productivity improvements within operations to sustain competitiveness. The use of automation technology is one proven tool to improve

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productivity [1, 2] and hence stay competitive in the global market. But the use of automation does not per se guarantee advantageous results. The key to a successful use of automated equipment lies in finding the right type and level of automation that best suits the company's needs, goals, and prerequisites. Baines [3] point out the importance of selecting the right type of technology as well as the correct implementation for a successful outcome and correct use of technology. This in turn puts great demands on the companies' way of working with automation since it requires that automation development projects, and its adherent processes, are well structured and supported. However, existing research on technology acquisition practices highlight the lack of a formal structure to technology acquisition activities, as well as lack of mechanisms to support decision making [4]. Previous studies have also shown that companies struggle during automation projects and find them hard to manage, often to the extent that they resist to automate [5] and hence also miss out on the many potential benefits that automation can bring. Therefore, there is a need for research that address how companies can be supported to better manage automation development projects, giving them the prerequisites to invest in automation and making use of its potential competitive gains.

The aim of this paper is to make a comparison between industrial needs and challenges, and existing theoretical support associated with managing automation development projects. This is done from the perspective of the company that will actually use the automation.

The following research questions have been stated and will be addressed in the paper:

- What challenges and success factors are there in industry related to the management of automation projects?
- Does existing literature within automation development offer proper support?

Through a multiple case study with 12 industrial cases, existing challenges and success factors, related to the management of automation projects, has been explored and analyzed. The empirical findings have been compared to support for automation development projects found in literature. This is to identify suitable existing theories as well as to identify knowledge gaps.

The remainder of this paper is structured in a theoretical overview as well as in an empirical study. In the next section research on automation development and literature related to managing automation development projects is introduced. Then the research design is presented, followed by the empirical findings concerning challenges and success factors related to automation development and management of automation projects. Thereafter, the empirical findings are analyzed and discussed, based on and compared to, identified theoretical support on automation development. Finally, the paper is ended with a summary and conclusions.

## 2 Theoretical Framework

Automation can be defined as the technology by which a process or procedure is accomplished without human assistance [1]. It can further be divided into mechanization and computerization [6] where mechanization mainly relates to the automation of and in the physical flow of goods and computerization refers to the automation of and in the flow of information. The use of technology, such as automation, affects competitive advantage and can worsen as well as improve a firm's competitive position [7]. It is hence of outmost importance that it is used correctly to ensure a positive effect. According to [8], a company must therefore, before investing in advanced manufacturing technology such as automation, first reassess its direction, strengths and weaknesses, and develop a strategy for successful implementation accordingly. This however rarely seems to be the case since automation related decisions often are made through ad hoc nature and based on other issues than solid facts and a well-defined strategy [9]. Previous research of current technology acquisition practices has highlighted the lack of formal structure to technology acquisition activities, as well as lack of mechanisms to support decision making and concluded the a need for an structured approach [4].

There exist in literature a number of frameworks, processes and other types of support models connected to, and relevant for, management of automation projects. A large part of the literature come from area of advanced manufacturing technology and covers especially the acquisition process. Table 1 presents a selection of identified literature and its main content and characteristic.

## 3 Research Design

In order to fulfill the aim of the study, which was presented in the introduction, and to answer the specified research questions, empirical data has been gathered through a multiple case study. The case study approach was chosen for this study since it is an empirical inquiry that closely investigates a contemporary phenomenon within its real-life context [10]. Between the years 2008 and 2011 data from 12 case companies has been gathered through interviews, observations, surveys and collected documentation. More information about the case companies and adherent data collection methods can be found in Table 2.

The overall unit of analysis in the empirical study was the companies' automation development process. Previous, current as well as desired future way of working with automation development was investigated. Special focus was put on the management of automation development projects and experiences from past automation projects, but also other aspects associated with automation development were covered such as desire to automate as well as reasons for not automating. As part of developing and testing a supportive framework, suggested ways of working with automation development was also tested in collaboration with the

**Table 1** Identified theoretical support on managing automation development projects

| Source | Type of support | Description |
|---|---|---|
| Baines [3] | Technology acquisition process | Stage-gate process with nine steps and five gates. The steps are: Technology profiling, Establish requirements of technology, Find technological solution, Form outline business case, Choose technological source, Demonstrate technology, Confirm business strategy, Implement technology, Post-investment audit |
| Durrani et al. [4] | Technology acquisition process | Five stages: Establish market-place requirements, Identify technology solutions, Classify the technology solutions, Assess sources of technology acquisition, Make the technology acquisition decision |
| Trudel and Goodwin [14] | Automation project process | Five key phases/decisions points: Development strategy, Establishing system architecture, Systems design and specification, and Communications and start-up support. Focus on computer integrated manufacturing |
| Archibald [15] | Approach to handle technology projects | Specific focus on project management issues during large scale technology projects |
| Meredith [17] | Framework for managing automation projects | Four primary phases: Initiation, planning, implementation and control. Focus on useful project management concepts and techniques |
| Langley and Truax [28] | Technology adoption process | Three sub-process: The strategic commitment process, the technology choice process and the financial justification process |
| Sambasivarao and Deshmukh [8] | Approach for implementation of advanced manufacturing technology | Lists 14 issues involved in technology implementation procedures |
| Hax and Majluf [27] | Strategic decisions linked to technology management | Eight categories of decisions linked to technology selection, acquisition, strategy, planning etc |

case company in two of the cases. During those two tests an automated cell for each company was collaboratively developed. These development processes made it possible to in real life examples apply and test process support and identified important aspects for automation development projects.

Since the study was a multiple case study, there were two stages of analysis, the within-case and the cross-case analysis. The within-case analysis data consisted of coding the data [11] and identifying challenges and success factors for automation

**Table 2** Information about the case companies and data collection methods

| Case no. | Line of business | Size (est.) | Interviews | Observations | Survey | Documents | Test |
|---|---|---|---|---|---|---|---|
| Case 1 | Producing industry | M | X | X | X | | |
| Case 2 | Producing industry | S | X | X | X | | |
| Case 3 | Producing industry | S | X | X | X | | |
| Case 4 | Producing industry | M | X | X | X | | |
| Case 5 | Producing industry | L | X | X | X | | |
| Case 6 | Warehousing and distribution | M | X | X | X | | |
| Case 7 | Distribution | M | X | X | X | | |
| Case 8 | Hospital | M | X | X | | X | |
| Case 9 | Hospital | L | X | X | | X | |
| Case 10 | Hospital | L | X | X | | X | |
| Case 11 | Food manufacturing | S | X | X | | X | X |
| Case 12 | Producing industry | M | X | X | | X | X |

development work. Theses challenges and success factors were then compared between the cases during the cross-case analysis to find similarities and differences [12] and thereafter clustered using categories [13]. Finally the results of the analysis were compared with the findings from the literature review.

## 4 Empirical Findings

This section presents the findings from the case study. The section is divided in two main parts: (1) the identified difficulties and challenges during automation development and (2) the identified success factors related to automation development. The findings are under each heading presented connected to different themes.

### *4.1 Difficulties and Challenges During Automation Development*

#### 4.1.1 Base for Improvement Work

During the within-case analysis, when comparing the answers from interviews regarding current problem or potential improvement areas with the findings from the observations of the company's operations, it became clear that in many of the cases several possible improvements areas were unknown to the company. A few of the case companies could also themselves express a lack of insight in existing problems and insufficient knowledge regarding improvement potentials.

When asked what stopped the company from not improving (possibly automating) known problems and improvement areas many case companies (e.g., Case 2, 4, 5, 6, and 12) gave the same short explanation: *Lack of time and/or resources*.

### 4.1.2 Resistance Toward Automation Technology

Both Case company 2 and 12 gave examples of previous automation installations, often including new technology, where the technology often had failed and caused downtime and other problems. A production manager in Case 2 pointed out that *This made a deep mark, creating high resistance to robots a long time to come.* Case 12 had similar experiences but also found that due to previous bad experiences also the management became reluctant to approve future automation investments. At the production development department, where the cause of the problems were better understood, these problems had not created the same resistance but instead an understanding such as a clearer view of what type and level of automation was preferred and how they in the future could better specify requirements.

Also without previous bad experiences of failing automation, several of the case companies told of a resistance toward automation especially among staff at lower levels. In Case 1, the operators' lack of knowledge/unwillingness to learn to handle computers and robot cells was even perceived as an obstacle for automating.

### 4.1.3 Lack of Knowing the Possible Applications of Automation

Case companies 3, 7, 8, and 11 expressed a lack of automation competence which mainly reflected in a poor understanding of what is possible to solve with automation and how automation could be of use in their organization. One interviewee explained that *there probably are automation solutions that we would benefit from, we just don't know what they are.*

### 4.1.4 Lack of Process Structure for Automation Development Projects

When it comes to the actual process of developing automation many of the inexperienced companies expressed that one of the main difficulties during automation projects was to know what to do. Many felt insecure on what steps and actions to take and when, some to the degree that they hence refrained from automating.

But even in the companies with experience in developing automation there were often a lack of structured, suitable, and well supported process for the development projects. Most companies did not have a defined process at all. In Case 12, a defined process existed but it originated from product development and was therefore not fully suitable for the undertaking and consequently most often not followed. Further, routines and adherent support documents were often lacking, were outdated or not followed. Automation development was also not always considered and handled as a project with set deadlines, defined resources, etc. instead often of more ad hoc nature and part of the daily work.

A specific part often missing in the automation development project was the important follow up of both the investment in itself but also of the actual development project. In several of the cases it was admitted that the company had poorly evaluated investments and their returns. Even more seldom was however evaluation of the projects made, something that in Case 12 resulted in them making the same mistakes over and over again.

### 4.1.5 Difficult Steps

Many of the companies considered especially the early steps in the process of developing automation as difficult. The most difficult steps were according to the majority to:

- Identify/find/develop possible solutions
- Evaluate solutions and decide on most appropriate solution

Other steps considered difficult was to:

- Identify problems/possible improvements (addressed above)
- Develop the specification of requirements
- Draw up investment calculations (addressed below)

### 4.1.6 Finance

Above, one of the steps considered difficult in the automation development process was to draw up investment calculations. For some case companies this related to difficulties in the actual writing of the content in the calculation, that is was hard to know what to include, to estimate costs, return of investments, etc. In Case 12 there were extensive, complicated routines for investment calculations which were considered time-consuming and difficult to perform. Others referred to the outcome of the calculation, i.e., the difficulty of achieve a return on automation investments due to the large cost associated. Some, like Case 8 also had difficulties with the long investment horizon that automation investments require, that it made it difficult to internally get funds for automation investments.

### 4.1.7 Dependency on and Cooperation with Third Party

The companies studied did all, at least in some steps of the automation projects, engage system suppliers or integrators often due to lack of time or competence. They were also, but to varying extent, strongly dependent on third parties when conducting automation development. Some hired third parties for entire projects, while others only for a few steps. It was however considered difficult to find an appropriate level of cooperation with systems suppliers. Companies witnessed that the third party could take too much control over the project, risking ending up with a "black-box" solution that did not fit into the rest of the system or that the company could not handle after the implementation.

In Case 1, where the company had experience from several automation projects, the site manager expressed that *the hardest step during automation development is to find good suppliers that can help with small portions of a solution.* He felt that most suppliers only provide complete solutions and then the case company lost their influence. Those turn-key solutions were also considered very expensive and not always appropriate for their business. Others, such as in Case 4 preferred, turn-key solutions since they felt that it then where no discussion as to who was responsible for what, for example connected to warranties.

Case company 12 expressed a desire to work more closely together with the suppliers, but that required a lot of trust and often long previous relationships. Case company 7 found it hard when several suppliers were involved in the same project and preferred that only one-third party was to be involved in future projects.

The most reoccurring steps in improvement work, that the companies chose to do themselves and not involve a third party, were to identify problems or possible areas of improvements. This was however one of the steps considered most difficult in the improvement process.

### 4.1.8 Ownership and Responsibility

The lack of, or unclear ownership and responsibility of automation equipment, in different aspects and in different cases, emerged as a challenge during the study. In Case 8, which had outsourced parts of the operations on 1–2 year contracts, neither the hospital nor the service provider wanted to take the ownership of automation equipment and hence had refrained from making investments that in the long run would be profitable for both parties.

Several other case companies witnessed that lack of ownership and responsibility, not only for the automated equipment but also the operation/process that it was included in, led to problems. In Case 7 there had during previous automation development projects been discussions and disagreement between the different parties regarding who was responsible for what part in the development process. In Case 2 there instead had been disagreement between the company and the systems supplier where both claimed ownership of the developed equipment. In Case 12 the maintenance department were often reluctant to take over the responsibility for automated equipment after it was installed.

#### 4.1.9 Education of Staff

In Case 10, where a new, highly automated facility had been developed and inaugurated, the experience from the implementation and start up was that the actual technology in itself worked well from start. Most problems were instead created by faulty handling. This was often contacted to the operator's poor experience and knowledge of automation combined with insufficient education and training. The new facility and systems also placed higher demands on the competence and skill of the staff responsible for maintaining the automation equipment.

#### 4.1.10 Dependency on Individuals

In Cases 2, 3, 4, 11, and 12 the dependency on individuals, from different aspects, emerged as an issue and potential problem. In some of the cases there were extreme pressure and responsibility (for example connected to initiating automation development, providing automation knowledge, handling automation projects or equipment) solely lying on one person. In other cases the there were a lot of automation knowledge, experience, well established contacts, etc. in the company but only connected to a few individuals and it was often their know-how and gut feeling that contributed to the success of previous automation projects.

### *4.2 Identified Success Factors During Automation Development*

In practice can several of the identified challenges presented above be turned to a success factors in the cases they are overcome and handled correctly. The focus under this heading is however on, compared to the previous discussed issued, supplementing aspects that clearly emerged as success factors in the case study.

#### 4.2.1 Overall View of Operations

When analyzing automation projects that were considered successful by the company, in for example Case 9 and 10, a good overall view of the current situation of operations emerged as a key to provide the necessary base for successful projects. This involved having current operations thoroughly mapped and analyzed before conducting changes and having a clear view of the company's overall goals and strategy. This approach, with careful attention to current state analysis and the company's overall goals was also tested in Case 11 and 12. Doing this helped specify the requirements for the project, provided a clear base for solution/concept evaluation and decision as for the follow up and evaluation of the project and investment.

### 4.2.2 Plan Ahead

Having clear responsibilities and roles in general and connected to automation specifically (both including the equipment and development projects), is one aspect of planning ahead. This also involves to, early in the automation development process, asses needs and plan for education and training of staff, maintenance, etc. In many of the cases the company chose to outsource for example maintenance due to lack of knowledge or time while others preferred to handle everything to have a complete view of the operations. Regardless of how, the important thing is considered to make an active choices, understand the implications of your actions and have a plan for them.

### 4.2.3 Specification of Requirements

The specification of requirement was considered both difficult to develop but also appeared to strongly influence the success of automation projects, especially when third parties were involved. Case 1, 2, and 12 mentioned poor support for writing the specifications but had learnt much from previous projects when problems and discussions had emerged due to poorly formulated requirements (aspects missing or unclear, to loosely or strictly formulated, etc.) and that they now understood the importance of a well formulated specification of requirements.

### 4.2.4 Involvement and Cross Functional Teams

Cross functional project teams and/or involvement of different functions and levels of staff such as operators, maintenance, etc. early in the process, was considered to be a success factor. This since it both contributed to better solutions (since different types of issues and aspects were lifted by the different team members) and also that it increased the acceptance of the new equipment when people had been involved in the process of developing it.

### 4.2.5 Benchmarking

Benchmarking was several times lifted as a good way to find potential solutions to specific problems, to get general inspiration for possible improvements or information and help from others. Many benchmarked for automation solutions both within and outside their own line of business. Case company 6 was one of the companies using benchmarking. They had collaboration with two other companies specifically for benchmarking purposes and were also member of a network to get more contacts and benchmarking opportunities. The company had even specified benchmarking as an activity in their strategy to reach their business vision.

### 4.2.6 Automation Strategy

An overall and general key to successful automation investments is to find a solution that is suitable for the company's needs and prerequisites. And this is not only in terms of the solution fulfilling the specified requirements but also that is a type and level of automation that suits the company. Case companies 1 and 12 for example preferred industrial robots due to their flexibility, that they well fitted into the rest of the company and the company had knowledge to handle them. Case company 9 and 10 strove for an overall high level of automation but preferred mature and well tested technology. All these companies, whether it was explicit or not, had an overall idea or strategy connected how they wanted to automate and this most often paid of in terms of successful implementations.

## 5 Discussion

The empirical findings support previous research that show that the main problems during automation projects is not associated with the level, or the lack of technology, but rather with its implementation and the difficulties in choosing and incorporating it [4, 8].

The findings showed a clear need for process models giving support for working with automation development projects. Of the in Table 1 presented support models, [3] is considered to offer the most structured and detailed description of automation development and the acquisition process with specified tasks (including motivations to them) and adherent outcomes. It also, compared to for example [4, 14], covers how the project can be initiated as well as include follow up and evaluation of the investment, something identified as important but often forgotten. None of the listed support models however thoroughly cover how support documents for automation development can be created although [15] deal with typical documents for project planning, controlling, and reporting.

The need for overall understanding of the processes and to plan ahead was identified in the study and also lifted in the literature. For example [16] points out the need to structure the processes to be automated before automating them. Reference [17] emphasizes that it in automation projects it is worthwhile to spend extra time in the planning phase. Different aspects identified as important to address in the planning such as plans for maintenance, education, and training of staff were addressed by, e.g., [8, 14, 17]. Reference [3] also addresses different roles and responsibilities during automation development.

Reference [15] covers many of the project management aspects of automation projects addressed in several themes in the findings such as project planning, different roles and responsibilities (special focus on the project manager), and project teams. Also much of the other sources [e.g., 3, 4, 20] discusses the importance of a multidisciplinary team when it comes to automation development projects and also addresses it as one possible way to secure the, in the empirical studies identified necessary commitment and overcome or get around the identified resistance toward automation.

In the findings, benchmarking was lifted as a success factor for finding appropriate automation solutions which is supported by [18] who identified it as one of the most determining factors for the adoption of advanced technology. Reference [4] has incorporated benchmarking as one of the pre-steps before the suggested automation acquisition process since it *facilitates decision making*.

One of the main results from the empirical findings is the significance and importance of strategy connected to the automation development process (as well as vice versa) and this is a view supported in litterateur (e.g., [8, 14, 18–20]). As support, [21 and 22] suggest different models for developing a generic technology strategy while [23] suggest an eighth step audit for its formulation. Reference [24] present a five step method for formulating an strategy specifically for the use of automation. Reference [9, 25] suggest two different approaches to automation strategy but also points out the need for more research on the content of the automation strategy. An automation strategy was hence developed for the case company as part of the test phase in Case 12. The automation strategy (described in [26]) covered aspects related to organization, technology, process, and economy and aimed at helping the company achieve their goal with automation and provided structure for the way of working with automation. The strategy and its content were, by the case company, found helpful during automation development and was assessed to aid the company making better use of automation investments and their resources in general.

One specific aspect which the above mentioned automation strategy covers is to specify preferred way of working with third parties during automation development. The involvement of, and collaboration with, third parties was in the empirical studies lifted as a challenge. Reference [27] also addresses the extent to which the firm will rely on third parties as one of the strategic decisions that is linked to technology and [3] emphasizes a rigorous supplier selection.

## 6 Summary and Conclusions

This paper has presented challenges and success factors related to the management of automation projects, identified during a multiple case study with 12 companies. The main findings show:

- The need for process models for automation development projects.
- Difficulties in finding an appropriate way, and level of, collaborating with third parties.
- The importance of overall view and planning during automation projects.
- The need for strategy connected to automation development and vice versa.

The support identified in literature deals with many of the identified challenges and success factors and offers support for different parts of automation development projects such as acquisition, implementation, project management or strategy formulation. Some gaps still exist such as support on how to develop a company specific process model with adherent support documentation, routines, etc. But most importantly does little of the existing theoretical support cover all aspects of managing automation development projects, and instead only focuses on one specific part. There is hence still need for an overall framework connecting these different parts, and for example deal with the difficulty of how to actually connect strategy to the process of developing automation and vice versa.

The research presented in this paper contributes to the theory connected to management of automation development by identifying knowledge gaps. The findings also offer support to practitioners in the field working with automation development.

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## References

1. Groover MP (2008) Automation, production systems, and computer-integrated manufacturing, Pearson Education
2. Chen IJ, Small MH (1996) Planning for advanced manufacturing technology: a research framework. Int J Oper Prod Manage 16(5):4–24
3. Baines T (2004) An integrated process for forming manufacturing technology acquisition decisions. Int J Oper Prod Manage 24(5):447–467
4. Durrani TS, Forbes SM, Broadfoot C, Carrie AS (1998) Managing the technology acquisition process. Technovation 18(8/9):523–528
5. Jackson M, Hedelind M, Hellström E, Granlund A, Friedler N (2011) Lean automation: requirements and solutions for efficient use of robot automation in the swedish manufacturing industry. Int J Eng Res Innov 3(2):36–43
6. Frazelle EH (2001) World-class warehousing and materials handling, McGraw-Hill, New York
7. Porter M (2004) Competitive advantage—creating and sustaining superior performance, Free Press, Simon & Schuster

8. Sambasivarao KV, Deshmukh SG (1995) Selection and implementation of advanced manufacturing technologies: classification and literature review of issues. Int J Oper Prod Manage 15(10):43–62
9. Winroth M, Säfsten K (2007) Automation strategies: existing theory or ad hoc decisions? Int J Manuf Technol Manage 11(1):98–114
10. Yin RK (1994) Case study research—design and methods, Sage Publications, California
11. Maxwell JA (2005) Qualitative research design, Sage Publications, California
12. Stake RE (2006) Multiple case study analysis, Guildford Publications, Guildford
13. Merriam SB (1998) Qualitative research and case study applications in education 2nd ed Jossey-Bass
14. Trudel D, Goodwin C (1990) How to manage automation projects. InTech 37(5):38–41
15. Arcibald RD (2003) Managing high-technology programs and projects, John Wiley & Sons, New Jersey
16. Hammer M (1990) Reengineering work: don't automate, obliterate. Harvard Bus Rev 68(4):104–112
17. Meredith JR (1987) Managing factory automation projects. J Manuf Syst 6(2):75–91
18. Arvanitis S, Hollenstein H (2001) The determinants of the adoption of advanced manufacturing technology. Econ Innov New Technol 10(5):377–414
19. Greenfield D (2003) Automation strategy increases volume, in Control Engineering, pp 57–58
20. Kotha S, Swamidass PM (2000) Strategy, advanced manufacturing technology and performance: empirical evidence from US manufacturing firms. J Oper Manage 18(3):257–277
21. Chiesa V, Manzini R (1998) Towards a framework for dynamic technology strategy. Technol Anal Strat Manage 10(1):111–129
22. Hax AC, No M (1992) Linking technology and business strategies: a methodological approach and an illustration, Working paper 3383-92BPS, Sloan School of Management, MIT Boston
23. Ford D (1988) Develop your technology strategy. Long Range Plan 21(5):85–95
24. Lindström V, Winroth M (2010) Aligning manufacturing strategy and levels of automation: A case study. J Eng Tech Manage 27(3–4):148–159
25. Säfsten K, Winroth M, Stahre J (2007) The content and process of automation strategies. Int J Prod Econ 110(1–2):25–38
26. Granlund A, Friedler N (2012) A model for the formulation of an automation strategy, The 4th world conference production & operations management, Amsterdam, The Netherlands
27. Hax AC, Majluf NS (1991) The strategy concept and process: a pragmatic approach, Prentice Hall, New Jersey
28. Langley A, Traux J (1994) A process study of new technology adaption in smaller manufacturing firms. J Manage Stud 31(5):619–652

# Issues Affecting Advanced Manufacturing Technology Projects

**Josef Hynek and Václav Janeček**

**Abstract** Manufacturing industry in economically developed countries is undergoing a major change. Vast demands on quality, price cutting and increased throughput together with deepening globalization, put a lot of pressure on manufacturing companies and their management. Efficient utilization of advanced manufacturing technology (AMT) seems to be a convenient tool to address the challenges we have to face. However, it is not easy to select the most appropriate technology, purchase it, implement it successfully, and to reach the stage of its routine operation. Especially small and middle-sized companies lack relevant experience and an unsuccessful attempt to adopt AMT can easily lead to serious problems. This paper brings out selected results of several surveys that were carried out in the Czech Republic. We will focus especially on the problems related to AMT benefits expectations, management attitudes toward AMT, and methods used during the appropriate decision making processes.

## 1 Introduction

Manufacturing companies in economically developed countries operate under immense and ever increasing pressure. Huge demands on quality, cost savings, increased productivity, and higher flexibility together with the necessity to compete with product that were manufactured by competitors from emerging economies in contemporary globalized world create altogether very tough conditions for

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manufacturing companies and their management. It is obvious that these companies cannot rely on cheap labor force and efficient utilization of advanced manufacturing technology (AMT) seems to be a convenient tool to address the challenges they have to face. These computer-based technologies include a great variety of tools, machines, and devices ranging from isolated systems like computer-aided design (CAD), computer-aided manufacturing (CAM), numerically controlled machines, robots, etc. up to the fully integrated systems like computer-integrated manufacturing (CIM) or flexible manufacturing systems (FMS).

At the first glance this answer to the above mentioned pressures looks very simple and straightforward. It is the twenty-first century, we can see a lot of different pieces of technology all around us and so it is quite natural to expect that manufacturing companies in economically developed countries would rely on latest technology. Nevertheless, it is not easy to select the most appropriate technology, purchase it, implement it successfully, and to reach the stage of its routine operation. We have to keep in our mind that advanced manufacturing technology is usually quite expensive and long-term nature, which means that the company needs some time to accommodate it, to integrate it within existing environment, to get used to it in order to derive its full potential, and even more time is needed to repay the money invested into that piece of technology. And of course, there is always some degree of risk associated with any technology project and this degree is higher especially if the particular company lacks experience with the specific type of technology. Altogether, it is obvious that the relevant processes starting from technology planning up to its implementation are not easy and effortless. And we have to take into account that especially small and middle-sized companies do not possesses relevant experience and an unsuccessful attempt to adopt AMT can easily lead to serious problems that could easily destabilize and even put in jeopardy the whole company.

This paper brings out selected results of several surveys that were carried out in the Czech Republic in order to learn more about problems associated with AMT projects. We will focus especially on the problems related to AMT benefits expectations, management attitudes toward AMT, and methods used during the appropriate decision making processes. We will demonstrate that these issues could easily influence the relevant projects and their outcomes.

## 2 Previous Work

It is clear that advanced manufacturing technology deployment itself does not automatically guarantee a lower cost of production, higher productivity, better quality of products etc. That is why there are various studies concerning the practical impact of AMT utilization in manufacturing companies. Small [1] presented the results of the survey from United States that was targeted on level of importance of objectives and level of satisfaction with achievement of benefits that managers expected from utilization of AMT in companies. He realized that managers attached high levels of importance to product quality improvement, reduction of production lead-times and reduction of production costs. He reported that responding firms had achieved positive levels of satisfaction for each of the fifteen objectives that were taken into consideration there.

We have been inspired by interesting series of surveys focused on anticipated differences between management expectations and real experience associated with AMT adoption that were carried out in the United Kingdom, New Zealand, and in Australia [2–4]. Sohal [2] prepared a pair of questions designed to examine the extent to which respondents' views of the benefits of investing in AMT has changed as the result of the project implementation. The respondents scored the importance of a list of benefits as perceived at the time of the appraisal investment and then the extent to which these benefits were seen to have been achieved after the new technology has been deployed. Sohal claimed there that reduced cost, improved quality, increased throughput, increased flexibility, and acquirement of competitive advantage were the top five expected benefits and that the same benefits were placed within top six positions amongst benefits experienced after the relevant advanced technology project implementation too. While he could see more similarities between the expectations and experience rankings, he realized that there are many benefits whose ranking varies considerably. First of all, "enhanced company image" that was ranked sixteenth on the expectations list has moved to the very first position on the experience list. Similar perception change was registered at several other items as "improved workforce attitudes", "widening product range" or "improved working environment" that were originally rather underestimated. On the contrary, a number of expected benefits as, for example, "reduced work in progress", "better management control", or "improved response to variations in product mix or in product volume" ranked noticeably lower after the AMT project implementation.

We have realized that the same problems that were ascertained by Sohal [2–4] in the above mentioned countries occur in the Czech Republic too [5]. We have described there that there are appreciably high differences between AMT benefits expected before the particular AMT project has been implemented and the benefits attained after the project actual implementation. This fact constitutes a big problem and obstacle for AMT projects. While the total cost of AMT implementation is usually well defined and known, it is very difficult to calculate the total value of AMT contribution to the company as many benefits are unidentified, ignored at all, or wrongly assessed. Adding on the top of it the above mentioned differences between expectations and reality we can straightforwardly come to the conclusion that it is rather easy to jeopardize the overall feasibility of the project. Underestimation of some benefits leads to the situation when the project proposal fails in initial phases of the relevant decision making processes or the project is carried on only at the price of various restrictions. On the other hand, overestimation of potential benefits is dangerous too as there will be a clear disappointment in the later phases of project when the implemented technology will be unable to fulfill the originally promised and expected benefits [6]. Therefore, it is necessary to pay adequate attention to these issues and to make sure that there is a higher degree of harmony between the benefits expected and benefits actually derived there.

Thomas, Barton, and John [6] investigated attitudes toward benefits of AMT in 300 manufacturing SME in the United Kingdom. They found that many SMEs were unaware of potential benefits that a new technology can offer and none of them utilized any formal model that would ensure that the implemented technology effectively contributed to the overall performance of the company. As there were no clear benchmarks, many companies were unable to evaluate correctly the success of the new technology implementation.

## 3 Methodology

Our team carried out three major surveys focused on advanced manufacturing technology utilization and exploitation in the Czech Republic within last two decades. Our first postal survey was realized in 1998 and the goal of this survey was to find out the level of implementation of AMT that had been achieved in the Czech manufacturing companies to date; to determine which techniques and criteria were used in capital project appraisal and what methods, if any, were used to measure and take into account project risk; to determine which measures were used to assess the performance of senior executives as it appears that management in general is reluctant to make long-term risky investments (such as those in AMT) and prefers to invest in short-term projects that show early profits and low risk; and to explore opinions about the need for AMT investment, the efficacy of the investment criteria used and the extent to which other factors and considerations had a bearing on capital investment decisions. The second postal survey that was focused on the same issues was conducted in 2005 and we decided to include also the middle sized Czech manufacturing firms this time. The results of the both surveys (1998 as well as 2005) concerning AMT utilization in the Czech Republic were described in Lefley et al. [7].

Our last survey in the Czech Republic was conducted at the end of 2008 and the beginning of 2009. This time a completely new questionnaire was designed and used. Of course, we have partially built upon our previous experience acquired during the former surveys, but as we already indicated above we wanted to enlarge the scope of our research focus too. The first part of the questionnaire was designed in order to find out which kind of AMT is regularly used and/or planned and comparing to our earlier surveys we have broaden our view with the aim to include not only "hard" technology but the relevant pieces of "soft" technology too. The second part was devoted to the advanced technology benefits evaluation issues and the following one was focused on measurement of these benefits and the pertinent problems. The fourth section comprised of questions related to the measures used to assess the performance of senior executives and the opinions of top management concerning utilization of advanced technology. Final part of the questionnaire was devoted to the whole company performance measurement and the utilization of EVA concept.

The survey was aimed at those companies who, it was believed, would have had some experience in the utilization of AMT and that the person who was asked to complete the questionnaire should have had a significant contribution to make decisions in the field of AMT. A number of relevant databases and business registers were reviewed in order to identify the manufacturing companies in the Czech Republic. Due to the economic problems caused by the global financial crisis we have decided to address the relatively large set of 1,360 manufacturing companies. Unfortunately, many questionnaires returned back as undeliverable, some companies were closed down and several companies reported termination of their manufacturing activities, which restricted the original pool into 1,127 virtual respondents.

The questionnaires were send out in two rounds within a time span of 6 weeks and then we started a wide campaign based on individual attempts to get the results by means of individual e-mails and telephone calls. Altogether we have managed to collect 132 usable questionnaires out of 1127 respondents. The response rate 11.7 % is not very high but taking into account the economic circumstances it should be considered favorably. In addition to the postal survey we have also visited 12 selected companies and we held structured interviews with the top managers of these companies in order to learn more about some specific issues and problems related to the AMT utilization in general and AMT benefits evaluation in particular the Czech Republic.

## 4 Characteristics of Respondents

Majority of companies-respondents belonged to the category of small and medium enterprises with less than 100 employees (76 companies), there were 37 middle sized companies (100 up to 499 employees), and only 10 large companies (over 500 employees) there (see Table 1 for details).

Another important characteristic of respondents is the kind of advanced manufacturing technology that is regularly used and/or planned in surveyed companies. We have included 28 different types of AMT in our questionnaire and the respondents were asked to indicate those of them that have been implemented in

**Table 1** Profile of respondents

| Number of employees | Number of companies | Ratio of companies (%) |
|---|---|---|
| 50–99 | 76 | 57.6 |
| 100–499 | 37 | 28.0 |
| 500+ | 10 | 7.6 |
| Unknown | 9 | 6.8 |
| Total | 132 | 100.0 |

**Table 2** Technology implemented and planned

| Technology | Implemented | | Planned | |
|---|---|---|---|---|
| | Companies | [%] | Companies | [%] |
| Computer-aided design (CAD) | 62 | 47.0 | 4 | 3.0 |
| Computer numerical control (CNC) | 51 | 38.6 | 3 | 2.3 |
| Computer-aided engineering (CAE) | 33 | 25.0 | 2 | 1.5 |
| Computer-aided/integrated manufacturing (CAM/CIM) | 27 | 20.5 | 7 | 5.3 |
| Computer-aided process planning (CAPP) | 24 | 18.2 | 2 | 1.5 |
| Radio frequency identification (RFID) | 24 | 18.2 | 10 | 7.6 |
| Computer-aided quality (CAQ) | 23 | 17.4 | 7 | 5.3 |
| Automated material handling system (AMHS) | 17 | 12.9 | 2 | 1.2 |
| Automatic inspection (AI) | 14 | 10.6 | 4 | 3.0 |
| Robotics | 14 | 10.6 | 5 | 3.8 |
| Flexible manufacturing systems (FMS) | 5 | 3.8 | 4 | 3.0 |
| Automated guided vehicles (AVG) | 2 | 1.5 | 2 | 1.5 |

their companies and separately those that are planned to be adopted in near future. There were two types of technology involved there—"hard" AMT (like, for example, CAD, robots, CIM, etc.) and "soft" AMT which includes technologies like material requirements planning (MRP), enterprise resource planning (ERP), business intelligence (BI) etc.—for further details concerning the classification of "hard" and "soft" technologies please refer to Swamidass [8]. Our paper focuses on "hard" technology only and so we do not dwell on specific issues related "soft" technology here. That is why Table 2 summarizes the types of "hard" technology utilized or planned to be implemented by our respondents in their companies.

We can see from Table 2 that the most often used technologies in surveyed companies are clearly CAD, CNC, and CAE. On the other hand, RFID, CAM/CIM, and CAQ seem to be the most often planned manufacturing technologies. Considering the differences between number of companies that have already implemented particular technology and the number of companies that are planning to invest into the same technology, we can see that we cannot expect any dramatic changes in coming years. There are 296 AMT installations and 52 intentions to invest into AMT in Table 2 which represents 17.6 % increase only (providing that all the plans will be carried out successfully). Concerning the various types of AMT it is obvious that the highest ratio between planned and already implemented technology is adherent to flexible manufacturing systems (FMS—potential increase of 80.0 %), to RFID (potential increase of 41.7 %), and then to robotics (35.7 %). From this point of view we can say that especially the plan to increase the number of FMS installations is very ambitious as these systems belong to the most advanced and complex level of AMT. However, we must be very careful here as the high percentage of potential increase is caused by a very limited number of already implemented systems until now.

**Table 3** Problems of advanced manufacturing technology benefits evaluation

| Problems of advanced manufacturing technology benefits evaluation are associated with: | Agree [%] |
|---|---|
| Quantification of relevant benefits | 70.7 |
| Identification of relevant benefits | 70.4 |
| Lack of interest in using project appraisal and evaluation techniques | 65.4 |
| Unfamiliarity with project appraisal and evaluation techniques | 59.5 |
| Quantification of relevant implicit costs | 58.8 |
| Identification of relevant costs | 53.8 |
| Difficulty with interpreting results | 51.9 |
| Identification of relevant implicit costs | 50.7 |

## 5 Issues Affecting AMT Projects

We believe and we have also discussed in [9] that the main motivation to invest in AMT is based on specific benefits that are associated with the particular AMT implementation. Unfortunately, managers admit serious problems related to advanced technology benefits identification and quantification [7]. We have already pointed out at the beginning of this paper that AMT we are interested in are predominantly computer-based technologies and that is why we can expect that issues affecting AMT projects will be rather common for much wider class of information technology in general. We have found an interesting study written by Remenyi [10], who concluded that the four important factors that substantially influence the problems related to information technology benefits assessment are identification of the relevant benefits, identification and quantification of intangible benefits, complex impact of implemented system on individual parts of organization as well as the organization as a whole, and evolution and versatility of benefits and their importance in time. Similar but more detailed analysis of the problems associated with information and communication technologies can be found in [11]. They identified eleven problems that could be viewed as relevant for AMT assessment too. That is why we have built on their research and we wanted to confirm this assumption. We presented these issues to our respondents and we asked them whether they regard each of them relevant in the process of AMT projects assessment. The problems that were acknowledged by more than half of our respondents are listed in Table 3.

It is apparent that the most difficult problems are related to benefits identification (70.4 % of respondents) and their subsequent quantification (70.7 %). This ascertainment is fully conformable with the results that were mentioned above [10, 11]. Let us stress and remind once again that we suppose that companies invest in AMT because they wish to derive some benefits from the implementation of the particular technology. Regardless of the nature of these benefits—and we know that these benefits range from cutting cost, improving quality and so on up to enhanced image of the company or better employees attitudes—it is an unpleasant piece of information that seven out of ten managers in surveyed companies confirmed problems associated with identification and quantification of relevant benefits. The unknown and/or unquantifiable benefits could be perceived even as pleasant surprises when an unexpected benefit is realized after AMT project implementation or when the magnitude of such a benefit is much bigger than it was originally expected but it is not the common case and we do not recommend anyone to rely on fortune.

Conversely, manufacturing companies operate within a very competitive environment, AMT investments compete for limited resources with other investment needs, technology is expensive and the failure to implement is successfully could jeopardize the company as whole and therefore we cannot rely on promised benefits that could appear if we are fortunate. Moreover, our inability to identify and to quantify the benefits of AMT quite often does serious harm to the project. Underestimation of benefits leads to the situation when the project is unable to repay initial outlay within an expected time period and the project has to be cancelled or carried out only at the cost of further restrictions. These restrictions usually decrease the list of potential benefits as well as their magnitudes and in the case of significant restrictions it is even necessary to scale down the level of implemented technology. The formerly planned fully integrated system is modified to semi-integrated or stand-alone pieces of AMT only and it brings along further reduction of benefits that could be realized only at the required level of integration. Implementation of restricted AMT project could then be very disappointing for the management of the company (as much more has been promised and expected) as well as for the technology specialist who proposed completely different solution and the restricted system is viewed as fragmentary and completely insufficient.

Secondly, it is a very anxious fact to realize that two out of three managers (65.4 %) admitted lack of interest in using project appraisal and evaluation techniques. It is a very disturbing ascertainment especially remembering the above established issues. The combination of awkward facts that too many managers admit problems related to the identification and quantification of AMT benefits amplified by their unfamiliarity with the relevant project appraisal techniques is further enhanced by the lack of interest in these appraisal and evaluation techniques. Moreover, our earlier studies [7] demonstrate that concerning financial appraisal methods it is evident that AMT project are knowingly or unknowingly disadvantaged by the utilization of simplest methods (like undiscounted payback period) that prioritize short-term projects. Altogether, it seems to be a lethal concentration of unfavorable circumstances for AMT projects.

Finally, we can see that the sixth problem identified in the Table 3 is identification of project relevant cost as 53.8 % of respondents supported this statement. This issue is further underlined by problems related to identification of relevant implicit cost that was acknowledged by every second respondent too (50.7 %). Summarizing the problems identified here, we can see that there are not only serious problems related to identification and quantification of benefits of AMT but there are many difficulties that companies have to face when calculating the total cost of AMT project. The project is regularly considered as financially feasible when aggregate benefits are higher than or equal to total cost. When some benefits are left unidentified and some benefits are hard to quantify and at the same time we are not sure what the total cost of the project is, it is almost impossible to make economically properly justified decision.

On the top of the above discussed issues, there are indications that some managers show reserved attitudes toward AMT projects. They tend to underestimate strategic importance of AMT. Moreover, they have a tendency to follow their own career development paths and then it is clear that the strategic decisions and goals do not match with the length of their contracts. We have described these issues in [12] and so we will not dwell on them here. Nevertheless, there is no doubt that these attitudes influence negatively the relevant decision making processes and make it even more difficult for AMT to get from the project up to the stage of routine operation.

## 6 Summary

Utilization of AMT seems to be a convenient way to address the challenges the manufacturing companies in economically developed countries have to face nowadays. It is not easy to select the most appropriate technology, purchase it, implement it successfully, and to reach the stage of its routine operation. Moreover, AMT is usually quite expensive and long-term nature, which means that the company needs some time to accommodate it, to integrate it within existing environment, to get used to it in order to derive its full potential, and even more time is needed to repay the money invested into that piece of technology. And of course, especially small and middle-sized companies do not possesses relevant experience and an unsuccessful attempt to adopt AMT can easily lead to serious problems that could easily destabilize and even put in jeopardy the whole company. Therefore it is necessary to avoid typical mistakes and pitfalls and we have described here the problems that seem to be the most important ones from the point of view of manufacturing company managers as we collected their views within our surveys. The majority of our respondents were managers of small and medium manufacturing enterprises and we believe that their experience as well as concerns could be quite instructive and worthwhile for broader professional community.

## References

1. Small MH (1998) Objectives for adopting advanced manufacturing systems: promise and performance. Ind Manage Data Syst 98(3):129–137
2. Sohal AS (1994) Investing in advanced manufacturing technology. Comparing Australia and the United Kingdom. Benchmarking Qual Manage Technol 1(1):24–41
3. Sohal AS, Burcher PG, Millen R, Lee G (1999) Comparing American and British practices in AMT adoption. Benchmarking: Int J 6(4):310–324

4. Sohal AS (1996) AMT investments in New Zealand: purpose, pattern and outcomes. Integr Manuf Syst 7(2):27–36
5. Hynek J, Janeček V (2010) Advanced technology benefits evaluation: expectations and attained experience. In: Proceedings of IEEE 14th international conference on intelligent engineering systems, Las Palmas of Gran Canaria, Spain, pp. 293–298, 2010
6. Thomas AJ, Barton R, John EG (2008) Advanced manufacturing technology implementation. Int J Prod Perform Manage 57(2):156–176
7. Lefley F, Wharton F, Hájek L, Hynek J, Janeček V (2004) Manufacturing investments in the Czech Republic: an international comparison. Int J Prod Econ 88(1):1–14
8. Swamidass PM (1996) Benchmarking manufacturing technology use in the United States. In: Gaynor GH (ed) Handbook of technology management, 1st edn. McGraw-Hill, New York
9. Hynek J, Janeček V (2012) The post-implementation assessment of advanced technology utilization. J Competitiveness 4(3):3–13
10. Remenyi D, Money A, Sherwod-Smith M (2003) The effective measurement and management of IT costs and benefits, 2nd edn. Butterworth Heinemann, Oxford
11. Ballantine JA, Stray S (1999) Information systems and other capital investments: evaluation practices compared. Logistics Inf Manage 12(1/2):78–93
12. Hynek J, Janeček V, Svobodová L (2009) Investment in advanced manufacturing technology difficulties from the management point of view. In: Proceedings of 9th WSEAS international conference on robotics, control and manufacturing technology (ROCOM'09), Hangzhou, China, pp 79–84, 2009

# Part III
# Manufacturing Operations Management and Optimisation

# A Reference Model for a Synchronized and Dynamic Alignment of the Order Fulfillment Process

**Thomas Wochinger, Frank Zwißler and Engelbert Westkämper**

**Abstract** The market and technology environment of manufacturing companies in Europe is rapidly changing. Past crises have shown that variability in demand is far greater in magnitude in a highly networked global economy. With growing customer requirements, companies expand their variety of products, a trend that is intensified by the order-specific product customization typical for build-to-order and small batch production. Companies will only be able to address these challenges if a high level of technological and process flexibility and adaptability on the shop floor is provided for and made use of. Within a socio-technical production system (where men and technology interact), organizational and process-related response mechanisms are also necessary to dynamically align the complex order fulfilment process to be found in build-to-order and diversified mass production. The presented approach describes a reference model with a takt-based production system enabling the dynamic alignment of the entire order fulfillment process, spanning all stages from sales via material planning to manufacturing and assembly. The takt times are modularized and designed in a way to enable integration across functional boundaries for a dynamic alignment.

## 1 Introduction

The market and technology environment for manufacturing companies in Germany is changing in very short cycles. The closer worldwide economic relations result in greater demand peaks which has been able to observe during the crises.

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Due to the growing individual customer requirements the amount of variants in the companies are increasing. Furthermore the typical customer order specific adjustments of products in small batch and one-piece production foster these effects [1].

Nowadays, productions are challenged to satisfy customer demands and being competitive without the scale effects of mass production. In terms of costs the competition with low-wage countries cannot be won. Therefore, the European industry has to adapt itself to highly dynamic requirements of markets through correlating adaptable production systems.

Companies can face these challenges only by provision and use of high technological flexibility and changeability of the production. Furthermore, organizational and process related reaction mechanism within the socio-technical production system (meaning the interaction of human and technology) are needed to be changeable in the one-piece and mass production for variants. Such production systems and especially order fulfillment processes, that can be changeable in short time and very flexible for highly complex products, represent the future competitive advantage of European industry.

The lack of transparency for the customer as well as for the company at all stages of the order fulfillment process complicates the fast adaptation. For example, the inconsistency of data and information flow from material and production planning to the production and final assembly. Therefore a takt-orientated approach need to be implemented that helps the companies to achieve transparency and especially a method to become changeable along the complete order fulfillment process. The takt assures that at all stages of the complete process the interfaces between different units are feasible in terms of changeability.

## 2 State of the Art

In order to understand the takt-orientated model, several aspects have to be specified. First the widely used term of changeability must be clarified. In further steps it is necessary to particularize the changeability enabler and to specify the takt-orientated approach.

### *2.1 Changeability*

In literature the term changeability has been widely used. Wirth et al. [2] understand the term changeability as a result of flexibility, mobility, and a very fast conversion in connection with highly integration. They divide the flexibility into the basic flexibility that is the result of the adaptability under a constant factory structure and the expandable flexibility that compresses all structural changes. The

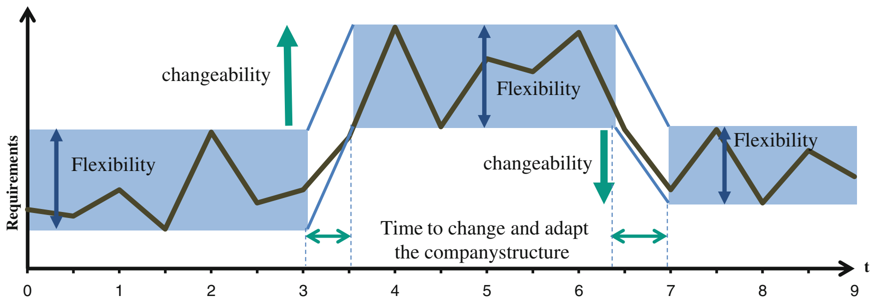



**Fig. 1** Difference between changeability and flexibility [5, 6]

foundation of the basic flexibility represents the existing machinery, in contrast to the expandable flexibility that compress the changes in process and machinery [2].

Wiendahl et al. [3] consider the changeability in a technocratic manner. The changeability is the ability of a factory to react effective and efficient on planed and unplanned changes. The authors divide into spatial, structural, and technical changeability [3]. Spatial changeability includes the expandability and reducibility of the production in terms of space. Vice versa the structural changeability includes organizational changes and the adaption of organizational principles and operational sequences. Speaking of technical changeability reconfigurable technical systems like equipment, processes and building services engineering are considered. These three different types have to be considered for planning the changeability under restrictions of the time of use. Hence, changeability is as well divided into short, mid-term, and long-term changeability [3].

According to Westkämper et al. [4], changeable companies are defined if they adopted besides the production system also the structure of organization and the resources on a steady base on changing conditions. It has to be differentiated between short term adjustments, e.g., machinery, systems and processes and middle to long-term adjustments, e.g., arrangements of factories and networks to achieve changeability [1]. Therefore changeability means more than flexibility. Flexibility means only the adaptability within certain corridors, but changeability means the possibility to react flexible in a complete new corridor (see Fig. 1).

Changeability is possible in Fig. 1 because the company is able to switch from one corridor to another corridor in a very short period of time. As long as the company moves within the corridor, this paper understands this as flexibility. Only the leaving of the flexibility corridor and the switching to another flexibility corridor is deemed as changeability. If this is instantly possible for a company, the company is very changeable in terms of time factor. And as higher or lower the requirements of changeability are and the company can fulfill these, it is more changeable in terms of content.

Changeability shall be defined for this paper as follows:

> Changeability is composed of flexibility and reconfigurability within a defined reaction time. Flexibility is the possibility to change in defined dimensions and scenarios.

Reconfigurability is the potential to change the dimensions and corridors according to changing internal and external requirements. The reaction time is the measure of the ability to adapt the company structure fast and actively to changing requirements.

## *2.2 Changeability Enabler*

Changeability enabler, in the following called enabler, are characteristics that foster and allow the change in a system.

Wiendahl et al. [7, 8] divide the enabler into five categories: catholicity, modularity, compatibility, mobility, and scalability.

Catholicity comprises the usage of factory elements for different functions, requirements in terms of organization, product, and technology. It can be widened for human resources, e.g., through training and qualification in terms of higher flexible assignment.

Scalability comprises the organizational, personal, spatial, and technical expandability and reducibility of factory elements. From an organizational point of view for example a flexible working time model that adapts to the available resources.

Compatibility describes the ability to build up networks within factory elements in terms of energy, material, and IT. This ability to build up networks is used for interaction of the elements within the networks to support the exchange of information.

Mobility describes the spatial flexibility of physical factory elements. For example the spatial change of equipment. A continuous adaption of the factory layout on basic conditions.

Wiendahl regards the modularity as the most important enabler. It describes the inner structure of a factory element. It is called modular if it consists of standardized, functional and provable units that can be substituted. Furthermore these modules are characterized by high compatibility to other factory elements [5]. For example a robot in an assembly line that can be adjusted to different requirements for different tasks.

In order to align a company with changeability, the described changeability enabler have to be applied to the domains of a production system, the domains of design in matters of changeability. A domain of design can be considered as boundary for, with regard to contents, similar or the same improvement measures.

The literature provides various approaches to structure the domains of design in matters of changeability. Nyhuis defines the three sectors technology, organization, and human [9].

Westkämper et al. [1] regard less the technology, adjacent to the human rather the structure, the resources and the strategy as significant domains of design in matters of changeability. Thereby the organization and the structure resemble strongly each other, so that in the following the organizational structure, the process organization as well as the factory structure of a company are meant by the term structure. The term resource is defined comprehensive by Westkämper [1] and contains material and information resources. Moreover technological resources can be taken into consideration, so that also the contents of Nyhuis [9] definition regarding technology can be subsumed by the term resource. The holistic adjustment is achieved by the domain of design strategy which brings the strategic alignment pertaining to changeability into focus (strategy development, orientation of market service and market performance, adaptable production structure …) [1].

To succeed in gaining a high changeability and an appropriate degree of changeability respectively (compare also Bauernhansl et al. [6]) it is necessary to design changeable the individual domains of design as well as their interaction. It is merely possible to reach the target state by an appropriate interaction of all domains of design. Yet, not adequate design of one domain of design impedes the flexible and fast adaptation: if a human for instance is not at all or badly prepared concerning changeability process, the potential of the actual possible changeability cannot be exhausted even though the technology and resource equipment is supremely changeable.

## 2.3 Takt-Orientated Approach

Especially organizational aspects of changeability demand the flexible and quick adjustment of organizational structures, the process organization, production and logistics concepts, and the work organization in order to respond to the changes with as little effort as possible. The significance in which way the organizational change affects the overall system is severely restricted due to the dynamic and complex behavior characteristics of the system and the in transparent structures. Furthermore, fixed hierarchy concepts and strongly centralized decision-making authorities extend often companies‘ reaction times [10].

In order to foster changeability of an organization, to improve the prediction of future changes' impacts, and to accelerate the reaction times of a system, it is unavoidable to reduce the system complexity and to extend the scope of action for the employees and workers. In this context, a comprehensive decentralization containing all system levels as well as a process-oriented task structure are fundamental attributes of changeable organization structures [4].

The term decentralization denotes thereby mainly the allocation of decision-making authorities to the location of value performance. The extension of the scope of action and the leeway in decision-making in combination with a modularization (respectively decoupling of system elements) as well as, where applicable, a decrease of hierarchy levels to reduce the system complexity lead to a better quality with regard to reaction time and decision making. The use of modularization to reach autonomous system elements ensures that a system is able to reorganize more easily and to arrange to the new requirements in times of change. However, it is thus necessary to synchronize the autonomous system agents across interfaces.

A well-proven approach to guarantee this synchronization, to consider the domains of design strategy, structure, resources and human, and to achieve an appropriate interaction in a holistical way is represented by the takt-orientation. The principle of the customer takt that originates from the lean production philosophy and that is already widespread in final assemblies and standardized production lines is used thereby as the basic concept. The cycle time/takt time is withal the time between the completion of the last and the successive product [11]. Other definitions rather refer to the customer orientation: the takt time in this case represents the time frame that is predetermined by the successive process (customer). This time frame is available for the production of one unit [12]. The average customer requirement in units per time unit (for example per year) and the available working period per time unit (also for example per year) are used to determine the customer takt. The customer takt is calculated by the following formula:

$$CT = FD \, * \, DH \, / \, Pcs \tag{1}$$

where, CT customer takt [hours/piece], FD factory working days [d/a], DH daily operational hours [hours/d], Pcs number of produced pieces per year [pieces/a].

The customer takt is interpreted as the average, market-given ratio with which the divisions and resources of a company work in the optimum. If every division and resource works exactly in time with the customer takt, then the company will work exactly according to the market requirements. The use of a takt time, in this case in the form of a customer takt in synchronous production systems entails following benefits:

- The frequency of sale is synchronized with the production rate in a very easy way: the production gains a direct perception concerning the market requirement.
- Workers and employees have a straight objective: they recognize if the takt is kept/can be kept and obtain by this mean a feedback to what extent the performance is in line with the market.
- Capacity of the resources can be adapted in an improved manner to the market need: the market information that is comprised in the takt enables the company to supply the necessary resources on the basis of average values at an early stage and to apply flexibilities in a projected way.

The principle of the customer takt is currently diffused in division and resources in which particular conditions are existent: standardized products and a number of not to many variants, homogeneous process times that do not show a high mean variation, a low material flow complexity, little or non-existing set-up times as well as a high degree of standardization.

The application of the customer takt in other divisions or resources is without complexity not possible. Whereas non-reducible set-up times in production areas cause for instance manufacturing in lots and thereby a turning away from the one piece flow and the customer takt, process times with a high mean variation and a high number of different variants make the working in upstream divisions or resources like the construction or the process planning in time with the customer takt, which is based on average values, impossible.

In order to implement an integrated takt-oriented approach along the whole order fulfillment process it is required to broaden the customer takt with further takt types in a takt-oriented model.

## 3 Takt-Oriented Model

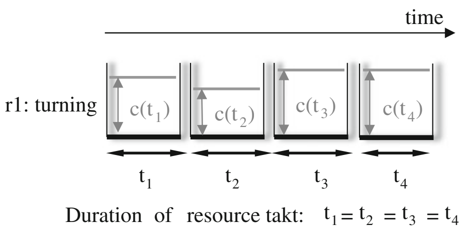
The takt-oriented model comprises three different types of takts: the customer takt, the resource takt, and the process takt. The customer takt is defined according to Chap. 2.

First of all, it is crucial to design further issues according to the customer takt: the assembly and logistics system, the technology, and the human resources are directly geared to the customer takt. The variation of the customer takt, maybe caused by a fluctuation of the market need, entails the realignment of the sectors that are a directly dependent subject to the customer takt. Proactive qualification measure for workers and employees, information dashboards, or mobile technologies and machines support the flexible and quick realignment according to the customer takt.

In addition to the customer takt a resource takt is defined. If the in time alignment with the customer takt is not possible, it is under these circumstances reasonable to assign a time frame ($t_x$) as well as an available capacity $c(t_x)$ to a resource r, see also Fig. 2: concerning the resource r1 "turning" the time frames $t_1$ to $t_4$ are defined as one shift. For each shift a certain capacity $c(t_1)$, $c(t_2)$, $c(t_3)$, and $c(t_4)$ is available due to the availability of workers or machine maintenance.

This assignment can be conducted for every resource involved in the order fulfillment process. The time frame per resource, the so-called resource takt, can be different for each resource (shift, day, two days, week, …), but has to be considered as static (in Fig. 2: $t_1 = t_2 = t_3 = t_4$). If the resource takts are defined, the upcoming orders are planned into the resource takts including the necessary dependencies and taking into account the available capacity till the resource's

**Fig. 2** Definition of resource takts



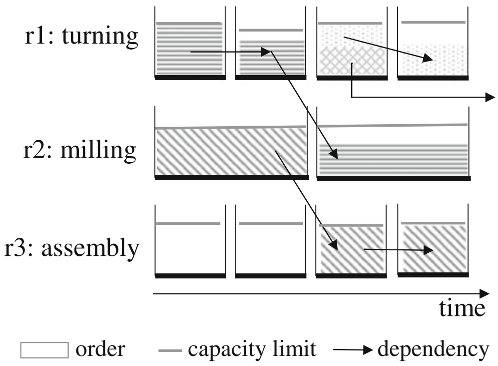



**Fig. 3** Example of planning model with resource takts

capacity limit is reached. Figure 3 shows three resources with resource takts. The resource takts for turning and assembly are the same (one shift), the resource takt for milling to twice as much. Corresponding to Fig. 2 capacity limits are determined for the time frames. Different orders are planned into the resource takts considering their working plans and dependencies. In some cases the capacity limit is reached so the order has to be postponed to the next time frame (Fig. 3).

The orders that are planned in the resource takts have to be executed subsequently by the teams on their own responsibility with the aim to finish all of the orders until the end of the resource takt. For example that the sequence of the available orders can be determined locally by teams, maybe to optimize the set-up times. The superior takt-oriented planning must be adapted not until one of the due dates that are specified by the resource takts cannot be held.

The process takt is the third takt type that is defined in the model. Basis is the classification of the existing processes in process steps and process types. This modularization of the processes permits the definition of a planned duration and the probably needed resource for every process step or process type. In contrast to the resource takt, which refers to the resource units along the order fulfillment process, the focus of the process takt is merely on the process steps and process types. In Fig. 4 the process step "construction of actuator" is separated in three different process types that vary in their duration: a short-time verification of the construction, an adaptation of the construction (redesign) and a new construction which has to be executed by another resource:

If a disturbance or a change occurs, the already prestructured and predefined process entities enable the quick reaction by appropriate combination of the

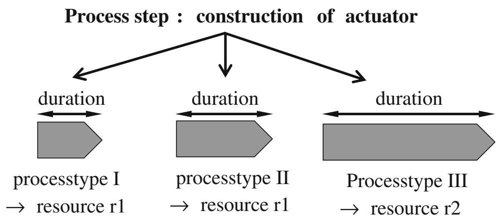



**Fig. 4** Definition of different process types to a process step

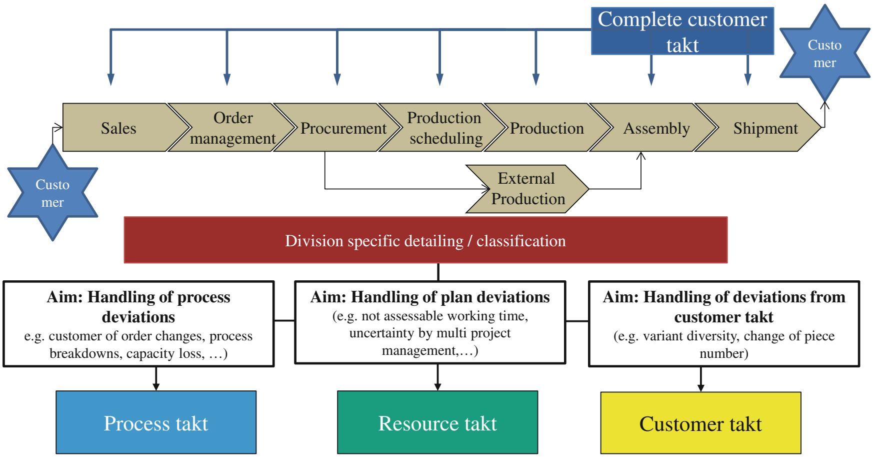



**Fig. 5** Interaction and application of customer takt, resource takt and process takt

process entities. By means of the selection of the appropriate process entities and their predefined duration a termination of the process steps is also possible. The usage of the process takt manages to gain a high level of transparency of the processes and their progress (temporal and with regard to contents).

To summarize the takt types in the takt-oriented model:

- The customer takt considers the rough "must" that the market pretends and it synchronizes the frequency of sale with the production rate.
- The resource takt focuses the performance that a company is able to effect (with regard to planning and capacities) and synchronizes the production due dates with the lead time requirements and the due date requirements of the customers.
- The process takt reflects the point of view of the orders and synchronizes the contents and the duration of the processes with the data and due dates that are given by the customers.

The takt-oriented model describes in addition the interaction of the three defined takt types as Fig. 5 describes. The customer takt is thereby the superior, joining element. It can be determined in every division and for every resource of the company on any hierarchical level if the relevant and occasional very complex customer demand data is available.

Depending on the objective (see also the domain of design strategy) and the existing framework requirements the process takt and the resource takt can be derived from the existing customer takt on any hierarchy level. Process takts are for example proper for the handling of process deviations and disturbances. If the handling of planning deviations which is furthermore checked with regard to aimed capacity availability, the usage of resource takts is reasonable.

The applicability of the takt types is determined by several surrounding conditions that have to be identified in a company-specific way and have to be attuned to the objective:

- Number of different tasks and variants as well as the degree of standardization.
- Occurring uncertainties in execution and degree of planning ability.
- Necessities of set-up times and effort for familiarization.
- Planning effort during execution.
- Desired level of transparency with regard to status and progress.
- Circumstances concerning the organizational structure and the process organization (for example segmentation).

The objectives and the existing framework requirements decide as well on the effort-benefit-ratio of the used takt type. One main advantage of the takt-oriented model which creates more transparency with less effort cannot be utilized under disadvantageous circumstances and with the choice of an inappropriate takt type. If, for example the appearing uncertainties in execution and the favored level of detail in planning are high, a big effort will arise in case of adaptation to the production or project planning. The consideration of resource takts on a higher level in order to reduce the planning and steering effort is one possible solution. Another solution is represented by the consideration of process takts so as to achieve when indicated a worse planning result, but a lower planning and steering effort. Figure 6 shows an order management process with several detail levels. The assembly has in this example the possibility to work with the customer takt on every level—stage, substage, department, and maybe even the workplaces can work exactly with the customer takt. In contract the production scheduling has indeed a customer takt, but because of the high diversity in the work steps, the usage of customer takts on lower levels of the hierarchy isn't suitable. On the substage level, the department level process takts and resource takts are used to plan and organize the work steps and tasks.

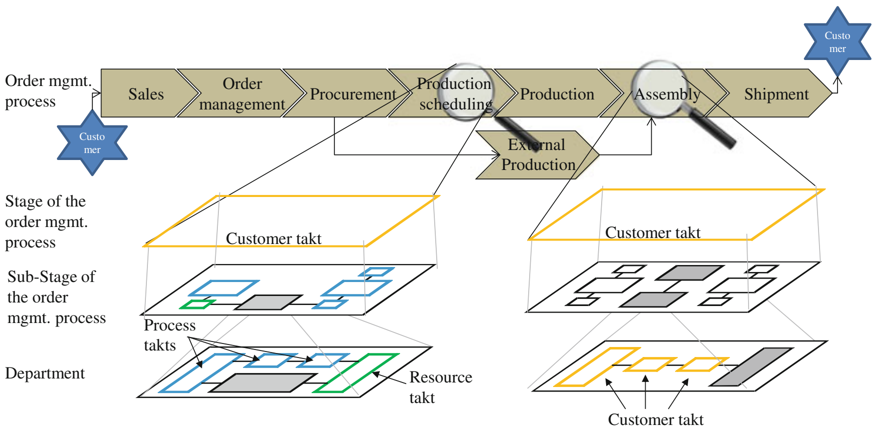



**Fig. 6** Different levels in the takt model

The elaborated takt model contains furthermore other guidelines to determine the takt type, the planning object, and the level of detail in planning and steering in order to keep the operative effort at a low level, also in case of increasing complexity.

The defined start and end dates of the takts that are specified by the takt types describe at once the explicit transfer point. The interface between the takts and for this reason also between the takt types are determined by due dates, orders, and/or information which has to be finalized or provided.

By the appropriate combination of the takt types a suitable coordination of the departments and resources is gained. The transfer of the takt principle that is up to now widely spread in assembly areas leads to a decoupling of the material and information flow as well as to an improved synchronization and a reduction of unfavorable influences across interfaces.

In this way, the takt model guarantees a strong customer orientation along the whole customer order process because the customer takt is not only present in the assembly but also in the upstream departments and resources by the use of the process and resource takts. The suitable combination of the takt types generates furthermore transparency along the whole customer order process. If disturbances and/or the need for changeability occur the generated transparency supports and eases to identify need for action concerning the divisions, departments, or resources and also with respect to the necessary hierarchy level. On this basis it is possible to find the right adjustment and improvement measures that can be initiated at a very early stage. Relevant changes concerning the market and technology environment are followed by a modification in the customer takts, resource takts, and/or the process takts so that the change is answered quickly and appropriately.

## 4 Conclusion

Companies have to address the increasing challenges with a high level of technological and process flexibility as well as adaptability at all stages of the complex order fulfillment process. The described approach presents a takt-based production system enabling the dynamic alignment of the entire order fulfillment process. Therefore, the definition and combination of three different takt types are necessary: customer takt, resource takt, and process takt. Thereby the takt model takes supports and refers to four out of five changeability enablers. Scalability is represented in the design of the scalable takts—the more stages of the order fulfillment process are useful, the reasonable takts for the stages can be defined. The different takts and also takt types can be easily combined so that the changeability enabler modularity and compatibility are represented: the different requirements of the stages of the order fulfilment process on different hierarchy levels can be combined in one model and adjusted in case of changes. The takt-oriented model includes furthermore a high level of catholicity by the applicability in different industry branches, different types of manufacturer and sizes of the company.

In case of dynamic changes in the company's environment the takt model guarantees the consideration of the need for change at all stages from sales via material planning to manufacturing and assembly at a very early stage. This represents in most cases the first important step to enable changeability: the transparent comparison of the market needs with the skills and possibilities of the company at all stages of the order fulfillment process, allowed in an easy way by the takt model, the identification of the necessary adjustments, the definition of appropriate measures and the early use of changeability enablers.

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## References

1. Westkämper E, Zahn E (2009) Wandlungsfähige Produktionsunternehmen: Das Stuttgarter Unternehmensmodell, Springer
2. Wirth S, Enderlein H, Hildebrand T (2000) Visionen zur wandlungsfähigen Fabrik, ZWF 95 (2000) 10, pp 456–462, 2000
3. Wiendahl H-P, Hernandez Morales R, Grienitz V (1997) Planung wandlungsfähiger Fabriken. ZWF 97 (2002) 1–2, pp 12–17, 1997
4. Westkämper E, Zahn E, Balve P, Tilebein M (2000) Ansätze zur Wandlungsfähigkeit von Produktionsunternehmen. wt Werkstatttechnik 90 (2000) 1/2, pp 22–26, 2000
5. Zäh M, Möller N, Vogl W (2005) Symbiosis of changeable and virtual production—the emperor's new clothes or key factor for future success? In: Zäh M (ed) 1st international conference on changeable, agile, reconfigurable and virtual production, Utz
6. Bauernhansl T, Mandel J, Diermann S (2012) Evaluating changeability corridors for sustainable business resilience. In: Proceedings of 45th CIRP CMS conference on manufacturing systems, athens, pp 414–419, 2012
7. Wiendahl H-P, Nofen D, Klußman JH, Heinrich J, Breitenbach F (eds) (2005) Planung modularer Fabriken: Vorgehen und Beispiele aus der Praxis. Hanser, München, Wien
8. ElMaraghy H, Wiendahl H-P (2009) Changeability—an introduction. In: ElMaraghy H (ed) Changeability and reconfigurable manufacturing systems, Springer, pp 3–24, 2009
9. Nyhuis P, Reinhart G, Abele E (2008) Wandlungsfähige Produktionssysteme. Heute die Industrie von morgen gestalten. PZH Produktionstechnisches Zentrum GmbH, Garbsen, 2008
10. Bullinger H-J, Warnecke H-J, Westkämper E, Spath D (2009) Handbuch Unternehmensorganisation: Strategien, Planung. Umsetzung. 3. Auflage, Springer, 2009
11. Suzaki K (1987) The new manufacturing challenge: techniques for continuous improvement. Free Press, New York
12. Takeda H (2006) The synchronized production system: going beyond just-in-time through Kaizen. Kogan Page, London

# Closed-Loop Sustainable Supply Chain Design Under Uncertainties

**Li-Chih Wang, Tzu-Li Chen, Yin-Yann Chen, Yi-Wen Chen and Allen Wang**

**Abstract** This paper studies an integrated forward and reverse (closed-loop) supply chain network design problem with sustainable concerns under the uncertain environment. We are interested in the logistics flow, capacity expansion, and technology investments of existing and potential facilities in the multi-stage closed-loop supply chain. First, a deterministic multi-objective mixed integer programming model capturing the tradeoffs between the total cost and the carbon dioxide ($CO_2$) emission is developed to tackle the multi-stage closed-loop supply chain design problem from both economic and environmental perspectives. Then, due to the uncertainty in supply side, customer demand and return quantities, the robust counterpart of the proposed multi-objective supply chain design model is presented using the robust optimization theory. Both deterministic and robust multi-objective supply chain design models are transformed into single-objective models to obtain non-dominated compromise solutions using LP-metrics-based compromise programming method. In the numerical evaluation and results, we analyzed the relationship between the total cost and carbon emission in integrated supply chain network and verified robustness of the proposed robust multi-objective supply chain design model by the generated non-dominated compromise supply chain design solutions.

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**Keywords** Closed-loop · Supply chain design · Multi-objective programming · Robust optimization

## 1 Introduction

A sustainable enterprise is an organization that eliminates or decreases the environmental harm caused by the production and consumption of their goods while maintaining a profit. Global warming and ecocide force worldwide countries to establish environmental friendly laws, regulations, and agreements to limit natural resource consumptions and environmental calamities. Hence, many enterprises need to increase the production efficient, maintain the profit, and raise the competitiveness with the low carbon emission. A sustainable supply chain with low carbon, 3E (Effective, Efficient, Environmental; 3E) ,and robust concepts has been a guarantee for the competitive products. Moreover, the carbon assessment management became a critical issue in supply chain management. Enterprises should provide a better and effective solution to reduce the carbon dioxide emission. Recent years, carbon asset became a critical subject to global enterprises. Global enterprises need to provide effective energy-saving and carbon-reduction means to meet the policies of Carbon Right and Carbon Trade [1]. In this scenario, forward and reverse logistics have to be considered simultaneously in the network design of entire supply chain. Moreover, the environmental and economic impacts also need to be adopted and optimized in supply chain design [2]. Chaabane et al. [3] introduce a mixed-integer linear programming based framework for sustainable supply chain design that considers life cycle assessment (LCA) principles in addition to the traditional material balance constraints at each node in the supply chain. The framework is used to evaluate the tradeoffs between economic and environmental objectives under various cost and operating strategies in the aluminum industry. Wang et al. [4] also studied a supply chain network design problem with environmental concerns. They are interested in the environmental investments decisions in the design phase and propose a multi-objective optimization model that captures the trade-off between the total cost and the environment influence. Through a comprehensive set of numerical experiments, the results show that their model can be applied as an effective tool in the strategic planning for green supply chain. In addition, many studies have discussed the sustainable supply chain design and management [5, 6].

In the other aspect, enterprises have recycled, disassembled, repaired, and refurbished the End-of-Life (EOL) products and inputted EOL products to remanufacture, therefore, formed into a closed-loop supply chain structure. This operation model not only provides enterprises to another material supplier and lower the operation cost of material purchase, but also reduces finite resource consumption [7]. Sheu et al. [8] formulate a linear multi-objective programming model that systematically optimizes the operations of both integrated logistics and corresponding used-product reverse logistics. Factors such as the used-product return ratio and corresponding subsidies from governmental organizations for reverse logistics are considered. Results of numerical studies indicate that using the proposed model, the chain-based aggregate net profits can be improved by 21.1 %, compared to the existing operational performance. Özceylan and Paksoy [9] propose a new mixed integer mathematical model for a closed-loop supply chain network that includes both forward and reverse flows with multi-periods and multi-parts. The proposed model guarantees the optimal values of transportation amounts of manufactured and disassembled products in a closed-loop supply chain while determining the location of plants and retailers. Finally, the computational results are presented to show and validate the applicability of the model. Pishvaee et al. [10] concerns about significant changes in the business environment, such as customer demands and transportation costs. They propose a robust optimization model for handling the inherent uncertainty of input data in a closed-loop supply chain network design problem. First, a deterministic mixed-integer linear programming (MILP) model is developed for designing a closed-loop supply chain network. Then, the robust counterpart of the proposed MILP model is presented by using the recent extensions in robust optimization theory. Finally, the robustness of the solutions obtained by the novel robust optimization model is assessed; they are compared to those generated by the deterministic MILP model in a number of realizations under different test problems. Moreover, other scholars also offered a supply chain design which was based on Robust Optimization Methodology [11, 12].

In summary, this study will discuss an integrated forward and reverse (closed-loop) supply chain network design problem with sustainable concerns under the uncertain environment. We are interested in the logistic flows, capacity expansion and technology investments of existing and potential facilities in the multi-stage closed loop supply chain. First, a deterministic multi-objective mixed integer programming model capturing the tradeoffs between the total cost and the carbon dioxide ($CO_2$) emission is developed. Then, due to the uncertainty in supply, customer demand and return quantities, the robust counterpart of the proposed multi-objective supply chain design model is presented, using the robust optimization theory.

## 2 Multi-Objective Closed-Loop Supply Chain Design

In this section, the indices, input parameters, decision variables, economic objective, and environmental objective for the multi-objective closed-loop supply chain design model with mixed integer programming are defined as follows:

***Indices***

$S$ Index for material suppliers ($s = 1, \ldots, S$)

$i$ Index for production stages of forward supply chain ($i = 1, \ldots, I$)

$\Phi(i)$ Set of existing production units in each stage $i$ of forward supply chain ($\Phi(i) = \{1, \ldots, Num(i)\}$)

$(i, k)$ Existing production unit $k$ in stage $i$ of forward supply chain, where $k \in \Phi(i)$

$c$ Index for end customers ($c = 1, \ldots, C$)

$j$ Index for recycling stages of reverse supply chain ($j = 1, \ldots, J$)

$\Psi(j)$ Set of potential recycling units in each stage $j$ of reverse supply chain ($\Psi(j) = \{1, \ldots, Num(j)\}$)

$(j, p)$ Potential recycling unit $p$ in stage $j$ of reverse supply chain, where $p \in \Phi(j)$

$l$ Index for capacity expansion levels ($l = 1, \ldots, L$)

$t$ Index for technology types ($t = 1, \ldots, T$)

***Parameters***

- Cost-related parameters

$pc_s^{rm}, pc_j^{sm}$ Purchasing cost from material supplier and secondary market in reverse supply chain

$dc_{(j,p)}$ Disposal cost in potential recycling unit of stage

$sc_{sk}, sc_{(i,k)(i',k')}, sc_{kc}$ Transportation cost in forward supply chain

$sc_{cp}, sc_{(j,p)(j',p')}, sc_{(j,p)(i,k)}$ Transportation cost in reverse supply chain

$nc_c$ Shortage cost of customer $c$

$bc_{(j,p)}$ Fixed installation cost of potential recycling unit $p$ in stage $j$

$cc_{(i,k)tl}, cc_{(j,p)tl}$ Capacity expansion cost of each capacity level using each technology type at existing production unit and potential recycling unit

- Capacity related parameters

$ca_{(i,k)}$ Existing capacity of existing production unit $k$ in stage $i$

$cl_{(i,k)tl}, cl_{(j,p)tl}$ Expanded capacity amount of each capacity level using each technology type at existing production unit and potential recycling unit

- Supply and Demand-related parameters

$s_s^{rm}, s_j^{sm}$ Supply quantity of material supplier and secondary market

$d_c, r_c$ Demand and Recycling quantity of customers $c$

- Environment-related parameters

$pce_{(i,k)t}, pce_{(j,p)t}$ Carbon emissions quantity of each technology type at existing production unit and potential recycling unit

$tce_{sk}, tce_{(i,k)(i',k')}, tce_{kc}$ Carbon emissions quantity for transportation in forward supply chain

$tce_{cp}, tce_{(j,p)(j',p')}, tce_{(j,p)(i,k)}$ Carbon emissions quantity for transportation in reverse supply chain

- Logistic-related parameters

| | |
|---|---|
| $ta_{sk}, ta_{(i,k)(i',k')}, ta_{kc}, ta_{ji}$ | Transportation capability in forward supply chain |
| $t_{sk}, t_{(i,k)(i',k')}, t_{kc}$ | Minimum transportation quantity in forward supply chain |
| $t_{cp}, t_{(j,p)(j',p')}, t_{(j,p)(i,k)}$ | Minimum transportation quantity in reverse supply chain |

- Ratio-related parameters

| | |
|---|---|
| $\lambda^{dis}_{(j,p)}$ | Disposal percentage of potential recycling unit $p$ in stage $j$ |
| $\gamma^{ret}_{ji}$ | Recovery percentage from stage $j$ of reverse supply chain to stage $i$ of forward supply chain |

***Decision Variables***

- *Continuous Variables*

| | |
|---|---|
| $TQ_{sk}, TQ_{(i,k)(i',k')}, TQ_{kc}$ | Transportation quantity in forward supply chain |
| $TQ_{cp}, TQ_{(j,p)(j',p')}, TQ_{(j,p)(i,k)}$ | Transportation quantity in reverse supply chain |
| $P_{(j,p)}$ | Purchasing quantity of potential recycling unit $p$ in stage $j$ from secondary market |
| $D_{(j,p)}$ | Disposal quantity of potential recycling unit $p$ in stage $j$ |
| $N_c$ | Shortage quantity of customer $c$ |

- *Binary Variables*

$X_{(j,p)} = 1$, if potential recycling unit $p$ in stage $j$ is open; $X_{(j,p)} = 0$, otherwise.
$AC_{(i,k)tl} = 1$, if existing production unit $k$ in stage $i$ expands capacity level $l$ using technology $t$; $AC_{(i,k)tl} = 0$, otherwise.
$AC_{(j,p)tl} = 1$, if potential recycling unit $p$ in stage $j$ expands capacity level $l$ using technology $t$; $AC_{(j,p)tl} = 0$, otherwise.
$TA_{sk} = 1$, if supplier $s$ ships to existing production unit $k$ in first stage of forward supply chain; $TA_{sk} = 0$, otherwise.
$TA_{(i,k)(i',k')} = 1$, if existing production unit $k$ in stage $i$ ships to existing production unit $k'$ in stage $i'$; $A_{(i,k)(i',k')} = 0$, otherwise.
$TA_{kc} = 1$, if existing production unit $k$ in last stage of forward supply chain ships to customer $c$; $TA_{kc} = 0$, otherwise.
$TA_{cp} = 1$, if customer $c$ ships to potential recycling unit $p$ in first stage of reverse supply chain; $TA_{cp} = 0$, otherwise.
$TA_{(j,p)(j',p')} = 1$, if potential recycling unit $p$ in stage $j$ ships to potential recycling unit $p'$ in stage $j'$; $TA_{(j,p)(j',p')} = 0$, otherwise.
$TA_{(j,p)(i,k)} = 1$, if potential recycling unit $p$ in stage $j$ ships to existing production unit $k$ in stage $i$; $TA_{(j,p)(i,k)} = 0$, otherwise.

**Multi-Objective Closed-Loop Supply Chain Design Problem (MOCLSCD)**:

The purpose of the closed-loop supply chain design model aims to identify the trade-off solutions between the economic and environmental performances under several logistic constraints. The economic objective, $F1 = PC + BC + CEC + TC + DC + NC$, is measured by the total closed-loop supply chain cost. The environmental objective, $F2 = PCOE + TCOE$, is measured by the total carbon (CO2) emission in all the closed-loop supply chain.

***Economic objective (F1):***

- Total material purchasing cost (PC)

$$\sum_{s\in S}\sum_{k\in\phi(1)} pc^{rm}_s \times TQ_{sk} \tag{1}$$

$$\sum_{j\in J}\sum_{p\in\Psi(j)} pc^{sm}_j \times P_{(j,p)} \tag{2}$$

- Total installation cost (BC)

$$\sum_{j \in J} \sum_{p \in \Psi(j)} bc_{(j,p)} \times X_{(j,p)} \tag{3}$$

- Total capacity expansion cost (CEC)

$$\sum_{i \in I} \sum_{k \in \Phi(j)} \sum_{t \in T} \sum_{l \in L} cc_{(i,k)tl} \times cl_{(i,k)tl} \times AC_{(i,k)tl} \tag{4}$$

$$\sum_{j \in J} \sum_{p \in \Psi(j)} \sum_{t \in T} \sum_{l \in L} cc_{(j,p)tl} \times cl_{(j,p)tl} \times AC_{(j,p)tl} \tag{5}$$

- Total transportation cost (TC)

$$\sum_{s \in S} \sum_{k \in \Phi(1)} sc_{sk} \times TQ_{sk} \tag{6}$$

$$\sum_{i=2}^{l} \sum_{k \in \Phi(i-1)} \sum_{k' \in \Phi(i)} sc_{(i-1,k)(i,k')} \times TQ_{(i-1,k)(i,k')} \tag{7}$$

$$\sum_{k \in \Phi(i-1)} sc_{sk} \times TQ_{kc} \tag{8}$$

$$\sum_{c \in C} \sum_{p \in \Psi(1)} sc_{cp} \times TQ_{cp} \tag{9}$$

$$\sum_{j=2}^{J} \sum_{p \in \Psi(j-1)} \sum_{p' \Psi(j-1,p)(j,p')} sc_{(j-1,p)(j,p')} \times TQ_{(j-1,p)(j,p')} \tag{10}$$

$$\sum_{j \in J} \sum_{p \in \Psi(j)} \sum_{i \in I} \sum_{k \in \Phi(i)} sc_{(j,p)(i,k)} \times TQ_{(j,p)(i,k)} \tag{11}$$

- Total disposal cost (DC)

$$\sum_{j \in J} \sum_{p \in \Psi(j)} dc_{(j,k)} \times D_{(j,k)} \tag{12}$$

- Total shortage cost (NC)

$$\sum_{c \in C} nc_c \times N_c \tag{13}$$

***Environmental objective (F2):***

- Total production carbon emission (PCOE)

$$\sum_{i \in I} \sum_{k \in \Phi(i)} \sum_{t \in T} \sum_{l \in L} pce_{(i,k)t} \times cl_{(i,ktl)} \times AC_{(i,k)tl} \tag{14}$$

$$\sum_{j \in J} \sum_{p \in \Psi(j)} \sum_{l \in L} pce_{(j,p)t} \times cl_{(j,p)tl} \times AC_{(j,p)tl} \tag{15}$$

- Total transportation carbon emission (TCOE)

$$\sum_{s \in S} \sum_{k \in \Phi(1)} tce_{sk} \times TQ_{sk} \tag{16}$$

$$\sum_{i=2}^{I} \sum_{k \in \Phi(i-1)} \sum_{k' \in \Phi(i)} tce_{(i-1,k)(i,k')} \times TQ_{(i-1,k)(i,k')} \tag{17}$$

$$\sum_{k \in \Phi(I)} \sum_{c \in C} tce_{kc} \times TQ_{kc} \tag{18}$$

$$\sum_{c \in C} \sum_{p \in \Psi(1)} tce_{cp} \times TQ_{cp} \tag{19}$$

$$\sum_{j=2}^{J} \sum_{p \in \Psi(j-1)} \sum_{p' \in \Psi(j)} tce_{(j-1,p)(j,p')} \times TQ_{(j-1,p)(j,p')} \tag{20}$$

$$\sum_{j \in J} \sum_{p \in \Psi(j)} \sum_{i \in I} \sum_{k \in \Phi(i)} tce_{(j,p)(i,k)} \times TQ_{(j,p)(i,k)} \tag{21}$$

***Constraints***

- *Material supply constraints*

$$\sum_{k \in \Phi(1)} TQ_{sk} \leq s_s^{rm}, \ \forall s \in S \tag{22}$$

$$P_{(j,p)} \leq s_j^{sm}, \ \forall j \in J, \ \forall p \in \Psi(j) \tag{23}$$

- *Flow conservation constraints*

$$\sum_{s \in S} TQ_{sk} + \sum_{j \in J} \sum_{p \in \Psi(j)} TQ_{(j,p)(i,k)} = \sum_{k' \in \Phi(i+1)} TQ_{(i,k)(i+1,k')} \quad \forall i = \{1\}, \forall k \in \Phi(1) \tag{24}$$

$$\sum_{k' \in \Phi(i-1)} TQ_{(i-1,k')(i,k)} + \sum_{j \in J} \sum_{p \in \Psi(j)} TQ_{(j,p)(i,k)} = \sum_{k'' \in \Phi(i+1)} TQ_{(i,k)(i+1,k'')} \quad \forall i = \{2, \ldots, I-1\}, \forall k \in \Phi(i) \tag{25}$$

$$\sum_{k' \in \Phi(I)} TQ_{(i-1,k')(i,k)} + \sum_{j \in J} \sum_{p \in \Psi(j)} TQ_{(j,p)(i,k)} = \sum_{c \in C} TQ_{kc} \quad \forall i = I, \ \forall k \in \Phi(I) \tag{26}$$

$$\sum_{k \in \Phi(I)} TQ_{kc} + N_c = d_c \quad \forall c \in C \tag{27}$$

$$\sum_{p \in \Psi(j)} TQ_{cp} = r_c \quad \forall c \in C \tag{28}$$

$$\sum_{c \in C} TQ_{cp} + P_{(j,p)} = \sum_{p' \in \Psi(j+1)} TQ_{(j,p)(j+1,p')} + D_{(j,p)} + \sum_{i \in I} \sum_{k \in \Phi(i)} TQ_{(j,p)(i,k)} \quad \forall j = \{1\}, \forall p \in \Psi(1) \tag{29}$$

$$\begin{aligned}&\sum\nolimits_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)} + P_{(j,p)}\\&\quad= \sum\nolimits_{p'\in\Psi(j+1)} TQ_{(j,p)(j+1,p')} + D_{(j,p)} + \sum\nolimits_{i\in I}\sum\nolimits_{k\in\Phi(i)} TQ_{(j,p)(i,k)}\\&\forall j=\{2,\ldots,J-1\},\ \forall p\in\Psi(j)\end{aligned} \tag{30}$$

$$\begin{aligned}&\sum\nolimits_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)} + P_{(j,p)} = D_{(j,p)} + \sum\nolimits_{i\in I}\sum\nolimits_{k\in\Phi(i)} TQ_{(j,p)(i,k)}\\&\quad\forall j=J,\ \forall p\in\Psi(J)\end{aligned} \tag{31}$$

$$D_{(j,p)} = \lambda^{dis}_{(j,p)} \times \left(\sum\nolimits_{c\in C} TQ_{cp} + P_{(j,p)}\right) \quad \forall j=\{1\}, \forall p\in\Psi(1) \tag{32}$$

$$D_{(j,p)} = \lambda^{dis}_{(j,p)} \times \left(\sum\nolimits_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)} + P_{(j,p)}\right) \quad \forall j=\{2,\ldots,J\}, \forall p\in\Psi(j) \tag{33}$$

$$\begin{aligned}&\sum\nolimits_{k\in\Phi(i)} TQ_{(j,p)(i,k)} \le \gamma^{ret}_{ji} \times \left(\sum\nolimits_{c\in C} TQ_{cp} + P_{(j,p)} - D_{(j,p)}\right)\\&\quad\forall i\in I,\ \forall j=\{1\},\ \forall p\in\Psi(1)\end{aligned} \tag{34}$$

$$\begin{aligned}&\sum\nolimits_{k\in\Phi(i)} TQ_{(j,p)(i,k)} \le \gamma^{ret}_{ji} \times \left(\sum\nolimits_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)} + P_{(j,p)} - D_{(j,p)}\right)\\&\quad\forall i\in I,\ \forall j=\{2,\ldots,J\},\ \forall p\in\Psi(j)\end{aligned} \tag{35}$$

- *Capacity expansion and limitation constraints*

$$\begin{aligned}&\sum\nolimits_{s\in S} TQ_{sk} + \sum\nolimits_{j\in J}\sum\nolimits_{p\in\Psi(j)} TQ_{(j,p)(i,k)} \le ca_{(i,k)}\\&\quad+\sum\nolimits_{t\in T}\sum\nolimits_{l\in L}\left(cl_{(i,k)tl}\times AC_{(i,k)tl}\right)\\&\quad\forall i=\{1\},\ \forall k\in\Phi(1)\end{aligned} \tag{36}$$

$$\begin{aligned}&\sum\nolimits_{k'\in\Phi(i-1)} TQ_{\left(i-1,k'\right)(i,k)} + \sum\nolimits_{j\in J}\sum\nolimits_{p\in\Psi(j)} TQ_{(j,p)(i,k)} \le ca_{(i,k)}\\&\quad+\sum\nolimits_{t\in T}\sum\nolimits_{l\in L}\left(cl_{(i,k)tl}\times AC_{(i,k)tl}\right)\\&\quad\forall i=\{2,\ldots,I=\},\ \forall k\in\Phi(i)\end{aligned} \tag{37}$$

$$\sum\nolimits_{t\in T}\sum\nolimits_{l\in L} AC_{(i,k)tl} \le 1 \quad \forall i\in I,\ \forall k\in\Phi(i) \tag{38}$$

$$\begin{aligned}&\sum\nolimits_{c\in C} TQ_{cp} + P_{(j,p)} \le \sum\sum\nolimits_{t\in T}\sum\nolimits_{l\in L}\left(cl_{(j,p)tl}\times AC_{(j,p)tl}\right)\\&\quad\forall j=\{1\},\ \forall p\in\Psi(1)\end{aligned} \tag{39}$$

$$\begin{aligned}&\sum\nolimits_{p'\in\Psi(j-1)} TQ_{\left(j-1,p'\right)(j,p)} + P_{(j,p)} \le \sum\nolimits_{t\in T}\sum\nolimits_{l\in L}\left(cl_{(j,p)tl}\times AC_{(j,p)tl}\right)\\&\quad\forall j=\{2,\ldots,J\},\ \forall p\in\Psi(j)\end{aligned} \tag{40}$$

$$\sum\nolimits_{t\in T}\sum\nolimits_{l\in L} AC_{(j,p)tl} = X_{(j,p)}, \quad \forall j\in J,\ \forall p\in\Psi(j) \tag{41}$$

- *Transportation constraints*

$$t_{sk} \times TA_{sk} \leq TQ_{sk} \leq TA_{sk} \times M \quad \forall s \in S,\ \forall k \in \Phi(1) \tag{42}$$

$$\begin{aligned} & t_{(i-1,k)(i,k')} \times TA_{(i-1,k)(i,k')} \leq TQ_{(i-1,k)(i,k')} \leq TA_{(i-1,k)(i,k')} \times M \\ & \forall i = \{2,\ldots,I\},\ \forall k \in \Phi(i-1),\ \forall k' \in \Phi(i) \end{aligned} \tag{43}$$

$$t_{kc} \times TA_{kc} \leq TQ_{kc} \leq TA_{kc} \times M, \quad \forall k \in \Phi(I),\ \forall c \in C \tag{44}$$

$$t_{cp} \times TA_{cp} \leq TQ_{cp} \leq TA_{cp} \times M, \quad \forall c \in C, \forall p \in \Psi(1) \tag{45}$$

$$\begin{aligned} & t_{(j-1,p)(j,p')} \times TA_{(j-1,p)(j,p')} \leq TQ_{(j-1,p)(j,p')} \leq TA_{(j-1,p)(j,p')} \times M \\ & \forall j = \{2,\ldots,J\},\ \forall p \in \Psi(j-1),\ \forall p' \in \Psi(j) \end{aligned} \tag{46}$$

$$\begin{aligned} & t_{(j,p)(i,k)} \times TA_{(j,p)(i,k)} \leq TQ_{(j,p)(i,k)} \leq TA_{(j,p)(i,k)} \times M \\ & \forall j \in J,\ \forall p \in \Psi(j),\ \forall i \in I,\ \forall k \in \Phi(i) \end{aligned} \tag{47}$$

$$TA_{sk} \leq ta_{sk},\ \forall s \in S,\ \forall s \in S,\ \forall k \in \Phi(1) \tag{48}$$

$$TA_{(i-1,k)(i,k')} \leq ta_{(i-1,k)(i,k')}, \quad \forall i = \{2,\ldots,I\},\ \forall k \in \Phi(i-1),\ \forall k' \in \Phi(i) \tag{49}$$

$$TA_{kc} \leq ta_{kc},\ \forall k \in \Phi(I),\ \forall c \in C \tag{50}$$

$$TA_{(j,p)(i,k)} \leq ta_{ji},\ \forall j \in J,\ \forall p \in \Psi(j),\ \forall i \in I,\ \forall k \in \Phi(i) \tag{51}$$

- *Domain constraints*

$$\begin{aligned} & TQ_{s(i,k)},\ TQ_{(i,k)(i',k')},\ TQ_{(i,k)c},\ TQ_{c(j,p)},\ TQ_{(j,p)(j',p')},\ TQ_{(j,p)(i,k)},\ P_{(j,p)},\ D_{(j,p)},\ N_c \geq 0 \\ & \forall s \in S,\ \forall i \in I,\ \forall k \in \Phi(i),\ \forall c \in C,\ \forall j \in J,\ \forall P \in \Psi(j) \end{aligned} \tag{52}$$

$$\begin{aligned} & X_{(j,p)},\ AC_{(i,k)tl},\ AC_{(j,p)tl},\ TA_{s(i,k)},\ TA_{(i,k)(i',k')},\ TA_{(i,k)c},\ TA_{c(j,p)},\ TA_{(j,p)(j'p')}, \\ & TA_{(j,p)(i,k)} \in \{0,1\} \forall s \in S,\ \forall i \in I,\ \forall k \in \Phi(i),\ \forall c \in C,\ \forall j \in J,\ \forall P \in \Psi(j) \end{aligned} \tag{53}$$

## 3 Robust Multi-Objective Closed-Loop Supply Chain Design

Since several exogenous parameters such as supply, demand and recycling quantities are uncertain in the closed-loop supply chain and hard to estimate by the exact statistical distributions, the symmetric multi-dimension box is employed to represent these uncertain parameters. We assume that the supply quantities from raw material suppliers, supply quantities from secondary markets, demand quantities, and recycling quantities in each period are uncertain and vary in a specific closed bounded interval around a known nominal value. Therefore, the box/interval form of four uncertain parameters can be defined as follows:

- Supply uncertainty from raw material suppliers: $U_{Box}^{s^{rm}} = \left\{ s^{rm} \in R^S : \left| s_s^{rm} - \overline{s_s^{rm}} \right| \le \rho_s^{s^{rm}} \times G_s^{s^{rm}},\ s = 1, \ldots, S \right\}$ where $s_s^{rm}$ is the uncertain supply quantities from supplier $s$ and $\overline{s_s^{rm}}$ is its nominal value. The positive parameters $G_s^{s^{rm}}$ and $\rho_s^{s^{rm}}$ represent the "supply uncertainty scale" and "supply uncertainty level," respectively. The particular case of interest is $G_s^{s^{rm}} = \overline{s_s^{rm}}$ which means a simple case where the relative deviation from the nominal is at most $\rho_s^{s^{rm}}$ $(0 \le \rho_s^{s^{rm}} \le 1)$. Therefore, the range of uncertain supply quantities are $\overline{s_s^{rm}} - \rho_s^{s^{rm}} \times G_s^{s^{rm}} \le s_s^{rm} \le \overline{s_s^{rm}} + \rho_s^{s^{rm}} \times G_s^{s^{rm}}$.
- Supply uncertainty from secondary markets: $U_{Box}^{s^{sm}} = \left\{ s^{sm} \in R^J : \left| s_j^{sm} - \overline{s_j^{sm}} \right| \le \rho_j^{s^{sm}} \times G_j^{s^{sm}},\ j = 1, \ldots, J \right\}$ where $s_j^{sm}$ is the uncertain supply quantities from the secondary market in each stage $j$ of reverse supply chain and $\overline{s_j^{sm}}$ is its nominal value. The positive parameters $G_j^{s^{sm}}$ and $\rho_j^{s^{sm}}$ represent the "supply uncertainty scale" and "supply uncertainty level," respectively. The particular case of interest is $G_j^{s^{sm}} = \overline{s_j^{sm}}$ which means a simple case where the relative deviation from the nominal is at most $\rho_j^{s^{sm}}$ $(0 \le \rho_j^{s^{sm}} \le 1)$. Therefore, the range of uncertain supply quantities from the secondary market are $\overline{s_j^{sm}} - \rho_j^{s^{sm}} \times G_j^{s^{sm}} \le s_j^{sm} \le \overline{s_j^{sm}} + \rho_j^{s^{sm}} \times G_j^{s^{sm}}$.
- Demand uncertainty: $U_{Box}^{d} = \left\{ d \in R^C : \left| d_c - \overline{d_c} \right| \le \rho_c^d \times G_c^d,\ c = 1, \ldots, C \right\}$ where $d_c$ is the uncertain demand of customer $c$ and $\overline{d_c}$ is its nominal value. The positive parameters $G_c^d$ and $\rho_c^d$ represent the "demand uncertainty scale" and "demand uncertainty level," respectively. The particular case of interest is $G_c^d = \overline{d_c}$ which means a simple case where the relative deviation from the nominal is at most $\rho_c^d$ $(0 \le \rho_c^d \le 1)$. Therefore, the range of uncertain demand quantities is $\overline{d_c} - \rho_c^d \times G_c^d \le d_c \le \overline{d_c} + \rho_c^d \times G_c^d$.
- Recycling uncertainty: $U_{Box}^{r} = \left\{ r \in R^C : |r_c - \overline{r_c}| \le \rho_c^r \times G_c^r,\ c = 1, \ldots, C \right\}$ where $r_c$ is the uncertain recycling quantities of customer $c$ and $\overline{r_c}$ is its nominal value. The positive parameters $G_c^r$ and $\rho_c^r$ represent the "recycling uncertainty scale" and "recycling uncertainty level," respectively. The particular case of interest is $G_c^r = \overline{r_c}$ which means a simple case where the relative deviation from the nominal is at most $\rho_c^r (0 \le \rho_c^r \le 1)$. Therefore, the range of uncertain recycling quantities is $\overline{r_c} - \rho_c^r \times G_c^r \le r_c \le \overline{r_c} + \rho_c^r \times G_c^r$.

Based on the model transformation, the robust counterpart of the closed-loop supply chain design model with supply, demand, and recycling uncertainties is equivalent to the multi-objective MILP problem with the same objectives $F_1$, $F_2$ under the constraints (24)–(26), (29)–(53) and the constraints (a)–(d) in the following.

$$(a)\ \sum_{k\in\Phi(I)} TQ_{sk} \leq \overline{s_s^{rm}} - \rho_s^{s^{rm}} \times G_s^{s^{rm}},\ \forall s \in S.$$
$$(b)\ P_{(j,p)} \leq \overline{s_j^{sm}} - \rho_j^{s^{sm}} \times G_j^{s^{sm}},\ \forall j \in J,\ p \in \Psi(j).$$
$$(c)\ \overline{d_c} - \rho_c^d \times G_c^d \leq \sum_{k\in\Phi(I)} TQ_{kc} + N_c \leq \overline{d_c} + \rho_c^d \times G_c^d,\ \forall c \in C.$$
$$(d)\ \overline{r_c} - \rho_c^r \times G_c^r \leq \sum_{p\in\Psi(j)} TQ_{cp} \leq \overline{r_c} + \rho_c^r \times G_c^r,\ \forall c \in C.$$

## 4 Computational Results

This section discusses the impacts and result comparison of the supply chain design, total cost, and carbon emission based on various uncertainty levels. In order to understand the various uncertainty level (UL) impacts of the supply chain design, total cost, and carbon emission based on two recycling strategies $RR_1 = 0.5$ and $RR_2 = 1.0$, 6 ULs of 0, 0.2, 0.4, 0.6, 0.8, 1 are set in this robust multi-objective model. Among all these ULs, UL of 0 represents no variation in material supply, customer demand, and recycling quantity; and UL of 1 indicates high variation without any predictability. The below discussions are assumed that the ULs of each variable are the same in two recycling strategies, which is $\rho_s^{s^{rm}} = \rho_j^{s^{rm}} = \rho_c^d = \rho_c^r$.

### 4.1 *Cost and Carbon Emission Performances Under Different Uncertainties*

Table 1 shows the total cost and carbon emission performances under different uncertainties. The raising total costs are observed since the uncertainty level increases. However, the raising total costs of second recycling strategy ($RR_2 = 1.0$) increases gentler than the first recycling strategy ($RR_1 = 0.5$) which

**Table 1** Total cost and carbon emission of two recycling strategies under different uncertainty levels

| Recycling strategy (RR) | Objective performance | Uncertainty level (UL) | | | | | |
|---|---|---|---|---|---|---|---|
| | | UL = 0 | UL = 0.2 | UL = 0.4 | UL = 0.6 | UL = 0.8 | UL = 1 |
| $RR_1 = 0.5$ | Total cost ($) | 392,115 | 679,598 | 1,291,534 | 2,530,307 | 3,786,682 | 5,195,522 |
| | Total carbon emission (ton) | 23,305 | 34,088 | 48,989 | 42,327 | 38,167 | 36,522 |
| $RR_2 = 1$ | Total cost ($) | 526,430 | 877,147 | 1,066,927 | 1,271,563 | 1,599,079 | 2,761,043 |
| | Total carbon emission (ton) | 37,810 | 51,031 | 65,826 | 76,834 | 84,520 | 88,044 |

can be observed in Table 1. At the scenario of higher UL, the material supply shows major shortage and the potential demand grows significantly. $RR_2$ compares to $RR_1$ will recycle more EOL products for forward logistic production which is expected to fill material shortage and avoid the shortage penalties.

In addition, the carbon emission of second recycling strategy ($RR_2 = 1.0$) significantly higher than the first recycling strategy ($RR_1 = 0.5$). In Table 1, both recycling strategies demonstrate increasing trend of carbon emission while UL at or lower than 0.4. However, the unstable material supply is assumed and the material shortage may occur while UL at or higher than 0.4. Based on the $RR_1$ strategy at high UL, the reduced carbon emission occurs because of the fewer EOL products obtained from reverse logistic are insufficient for forward logistics production and capacity expansion since the material shortage and uncertain customer demand. On the contrary, the $RR_2$ strategy at high UL demonstrates the drastically increased carbon emission since the more EOL products can be recycled. Those recyling EOL products will be disassembled, remanufacturred, and provided for the forward logistics. Furthermore, the capacity expansion is encouraged and production quantity is raised, which results in the increase of carbon emission.

Based on the results that we observed from Table 1, we conclude that both strategies show significant variation at high UL which is different from both strategies at low UL. We find that $RR_1$ strategy results in the high cost performance and $RR_2$ strategy results in the high carbon emission performance when the UL is high.

## *4.2 Closed-Loop Supply Chain Design Under Different Uncertainties*

This study lists a comparison table of number of opened recycling units, number of active edges, mean flow quantities, mean capacity, shortage quantities, total cost, and total carbon emission under two recycling strategies and various ULs in Table 2. From this table, we can conclude that the first strategy of $RR_2$ results in the low total cost and total carbon emission at low UL of 0.2. Both strategies have divergent trends in cost and carbon emission at high UL of 0.8. The number of opened recycling units, number of active edges in reverse supply chain, mean flow quantities, and total carbon emission of $RR_1$ is significantly higher than $RR_2$. Meanwhile, the shortage quantities and total cost of $RR_1$ is significantly lower than $RR_2$.

The supply chian design of $RR_2$ represents more aggressive decision than $RR_1$ since $RR_2$ can collect more EOL products through reverse logistics and expand the forward production capacity. However, when using the $RR_2$, the carbon emission also stably increases because of the high capacity consumption and complicated logistic network. The huge shortage penalties and risks are caused from the high market uncertainty and low return rate of EOL products. From the environmental perspective, the carbon emission will be reduced because of the lack of materials for production. In practice, the key materials and components are usually

**Table 2** Comparing the supply chain topology of two recycling strategies under different uncertainty levels

| Recycling strategy (RR) | Uncertainty level (UL) | Number of opened recycling units | Number of active edges in forward supply chain | Number of active edges in reverse supply chain | Mean flow quantities in forward supply chain | Mean flow quantities in reverse supply chain | Mean capacity in forward supply chain | Mean capacity in reverse supply chain | Shortage quantities | Total Cost | Total carbon emission |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RR = 0.5 | UL = 0.2 | 4 | 11 | 20 | 88.91 | 35.95 | 225 | 112.50 | 0 | 679,598 | 34,088 |
| | UL = 0.4 | 5 | 9 | 25 | 126.78 | 36.20 | 250 | 130.00 | 36 | 1,291,534 | 48,989 |
| | UL = 0.8 | 5 | 8 | 25 | 88.13 | 38.92 | 200 | 140.00 | 325 | 3,786,682 | 38,167 |
| RR = 1 | UL = 0.2 | 7 | 9 | 33 | 91.67 | 40.00 | 225 | 121.43 | 0 | 877,147 | 51,031 |
| | UL = 0.4 | 7 | 8 | 32 | 112.50 | 51.72 | 250 | 150.00 | 0 | 1,066,927 | 65,826 |
| | UL = 0.8 | 9 | 10 | 40 | 114.30 | 50.13 | 275 | 144.44 | 27 | 1,599,079 | 84,520 |

controlled and dominated by upstream suppliers. If the enterprises increase the recovery rate in order to obtain more EOL products, the shortage risks and penalties will be decreased. However, for processing EOL products, the supply chain network of the reverse logistic system will be more complicated and the carbon emission will be relatively enhanced. The enterprise should adjust the proper capacity investment and choose the optimal recycling strategy based on the actual market uncertainty level.

## 5 Conclusion

This study provides a sustainable integrated forward-reverse supply chain design model considering the uncertain market demand and supply. The open-loop supply chain was changed to the closed-loop with lowest cost and carbon emission while considering environmental friendly production. The results demonstrate the quantity of recycling EOL products will impact to the facility quantity and location of reverse logistic, furthermore, directly affect the total cost and carbon emission. In addition, the economic profit of reverse logistic establishment is low due to high handling cost of EOL products, and low price of raw materials and stable supply. To the contrary, the increasing economic profit of reverse logistic establishment is significant since the high price of raw materials and the uncertain supply. However, the increasing carbon emission is induced since the more reverse logistic units operated.

## References

1. Subramanian R, Talbot B, Gupta S (2010) An approach to integrating environmental considerations within managerial decision-marking. J Ind Ecol 14(3):378–398
2. Srivastava SK (2007) Green supply chain management: a state-of-the-art literature review. Int J Manage Rev 9(1):53–80
3. Chaabane A, Ramudhin A, Paquet M (2012) Design of sustainable supply chains under the emission trading scheme. Int J Prod Econ 135(1):37–49
4. Wang F, Lai X, Shi N (2011) A multi-objective optimization for green supply chain network design. Decis Support Syst 51(2):262–269
5. Frota Neto JQ, Bloemhof-Ruwaard JM, van Nunen JAEE, van Heck E (2008) Designing and evaluating sustainable logistics networks. Int J Prod Econ 111(2):195–208
6. Zhu Q, Sarkis J, Lai K-H (2008) Green supply chain management implications for "closing the loop". Transp Res Part E: Logistics Transp Rev 44(1):1–18
7. Lu Z, Bostel N (2007) A facility location model for logistics systems including reverse flows: the case of remanufacturing activities. Comput Oper Res 34(2):299–323
8. Sheu J-B, Chou Y-H, Hu C-C (2005) An integrated logistics operational model for green-supply chain management. Transp Res Part E: Logistics Transp Rev 41(4):287–313
9. Pishvaee MS, Rabbani M, Torabi SA (2011) A robust optimization approach to closed-loop supply chain network design under uncertainty. Appl Math Model 35(2):637–649
10. Piplani R, Saraswat A (2012) Robust optimisation approach to the design of service networks for reverse logistics. Int J Prod Res 50(5):1424–1437

# An Integrated Production and Distribution Scheduling Approach for Exceptions Handling

**Esther Álvarez, Eneko Osaba, Luis Villalón and Fernando Díaz**

**Abstract** In an international competitive environment, where companies can sell their products all over the world, coordination with other companies is of utmost importance, as a means to obtain an optimal utilization of their own resources and a competitive advantage over other supply chains. Nevertheless, in real world, most businesses are reluctant to share demand information or future plans with others, even if they belong to the same supply chain, the reason being that most of them see any other company as a potential competitor. This paper describes the architecture of an integrated approach for dynamic production and distribution scheduling in a supply chain with three levels; i.e., a company, its suppliers, and customers. This architecture tries to provide solutions to improve the performance of the supply chain by identifying the information that must be exchanged between nodes and developing methodologies for dynamic production and distribution scheduling in a coordinated manner. Moreover, a number of exceptions have been considered, both in production and distribution, to make the model as realistic as possible. Finally, the paper focuses on the distribution stage, where the problem is presented as a Dynamic Vehicle Routing Problem with Time Windows and Backhauls. This research is part of the PRODIS project (Grant PI2011-58, funded by the Basque Government in Spain).

## 1 Introduction

Traditionally, companies have focused their interest on their own assets but over the past years they have started to broaden their scope to include other companies, since competition no longer applies to individual companies but to supply chains.

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A supply chain is a network of companies which performs the functions of procurement of raw materials, transformation of these raw materials into intermediate and finished products, and distribution of these products to customers. Until recently, each company focused on its own business without considering the benefits that could arise from the collaboration with other companies of the same supply chain. But in global markets, where competition is fierce, it is more necessary than ever to promote the collaboration of the different echelons of a supply chain in order to optimize the global utilization of resources or obtain a competitive advantage over other companies. However, in practice, the companies do not collaborate with each other for fear of revealing or sharing their private information, among other things.

## 2 Problem Scope

This article describes the architecture of an integrated system for dynamic production and distribution scheduling in a supply chain consisting of three levels, i.e., the company, its suppliers, and customers. This architecture tries to provide solutions that benefit the supply chain as a whole by identifying the information that should be exchanged between the different nodes and developing methodologies for dynamic production and distribution scheduling in a coordinated manner. In this respect, this article contributes to manage not only the value chain of each individual company, but also the value chain of the extended company, because it studies in depth the implications of a change in the supply chain for other related entities. Thus, the aim of this research is to connect the production and distribution scheduling of the different entities of the supply chain in order to obtain a better global solution.

As far as production scheduling is concerned, each company has traditionally generated its own production schedules statically and independently. But supply chains are subject to the so-called bullwhip effect, where unplanned demand variations tend to increase the further they are from the ultimate customer. Equally, as regards the distribution of orders to customers, the so-called vehicle routing problem (VRP) has extensively been analyzed. But both dynamic production and distribution problems are gradually attracting more interest, due to its closeness to real-life situations and potential benefits for companies. The integration of production–distribution problems has scarcely been studied in the literature [1–3]. In general terms, these models use some simple assumptions and work only statically, which means they are neither realistic nor useful for companies.

This research proposes an approach for dynamic production and distribution scheduling with the following objectives:

- Identification of the information to be exchanged between different echelons in the chain.
- Coordination with suppliers and customers to ensure availability of raw materials and adjust unexpected production needs and untoward distribution needs.
- Exception handling in real time.

# 3 General Framework of the System

Demand variations and possible supply problems are inevitable, so it is necessary to ensure that the supply chain is responsive and flexible. Furthermore, a fluent information exchange between different members of the supply chain is highly desirable. The company that has been selected for this project has multiple plants that operate autonomously and independently, but are also able to share information and work together if unexpected events occur that requires it. In addition, the enterprise has multiple independent and autonomous local depots, which also share information with each other and can work together if it is necessary.

The general communication framework of this system is shown below (see Fig. 1).

The communication subsystems that have been identified in this framework are the following:

– The intraplant communication subsystem, in which unexpected events that may cause partial or complete production schedule reprogramming are handled. In the same manner, the intradepot communication subsystem, in which unexpected events that may cause partial or complete distribution schedule replanning are managed.
– The multi-agent interplant communication subsystem, where unexpected events occurred at a plant that may affect other plants are handled. In the same manner,

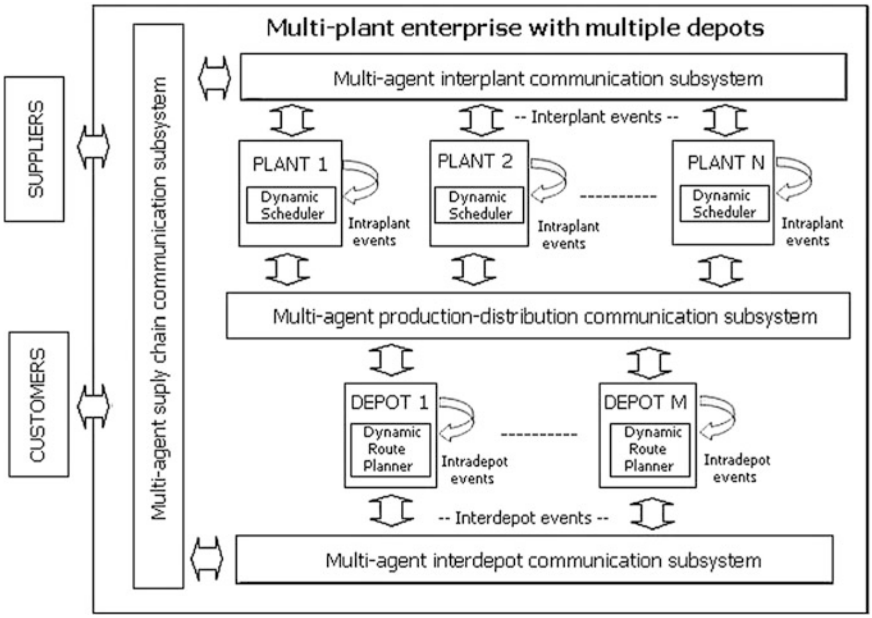


**Fig. 1** Multi-plant enterprise with multiple local depots

the multi-agent interdepot communication subsystem, in which unexpected events happened at a depot can affect other depots are managed.
– The multi-agent production–distribution communication subsystem, in which unexpected events occurred in plants that may affect depots, or unexpected events arisen in depots that may affect plants are handled.
– The multi-agent supply chain communication subsystem, where unexpected events arisen at a plant and/or warehouse that may affect suppliers and/or customers are handled.

# 4 Exceptions

One of the main contributions of the proposed framework is that it provides exception handling in real time, giving an almost immediate response to unexpected events. Exceptions have been divided into two groups, namely internal and external. Internal exceptions are company-related and may have their origin in production or distribution. Otherwise, external exceptions have their roots in suppliers or customers (Table 1).

## *4.1 Exception Handling*

At this point, a brief explanation about how an unexpected event is handled by the system is provided.

### 4.1.1 Damaged Order

This event occurs when part of one or more orders are partially or completely harmed on the way from the warehouse to the customer. This may happen when the customer or the truck driver realizes that the order has been damaged during transportation.

**Table 1** Types of exceptions

| Internal exceptions | | External exceptions | |
|---|---|---|---|
| Production-related | Distribution-related | Supplier-related | Customer-related |
| Machine breakdown | Vehicle breakdown | Returned material | Increase of order quantity |
| Missing operator | Missing driver | Partial delivery | New rush order |
| Unavailable auxiliary resource | Unavailable customer | Delayed delivery | Decrease of order quantity |
| Suspended order | Traffic delays | Faulty delivery | Changed due date |
| Repetition of faulty items | Damaged order | Canceled delivery | |

Depending on the percentage of items with quality problems and the possibility of reaching an agreement with the customer, the system considers several cases:

(a) Only the undamaged part of the order is delivered and the rest of the order is either redelivered as a new rush order or canceled, depending on the customer decision.
(b) The entire order is delivered as a new rush order.
(c) The customer decides to cancel the entire order.

If there is not enough stock in the depot to cover the damaged units, this will be communicated to production through the multi-agent production–distribution communication subsystem so as to plan the production order and calculate the new delivery date to be proposed to the customer.

This involves the generation of a new customer-related exception that is called “new rush order”. This exception involves the creation of a new production order that will be included in the current production schedule. In either of the above-mentioned cases, the distribution plan will be modified in order to include the need to pick-up the damaged order and the affected customers will be informed about the foreseen changes.

## 5 Distribution

As was previously explained, in this project there are two stages, the first one is referred to production, and the second one is about distribution. The former has already been explained in previous publications by the authors of this paper [4]. The latter is responsible for delivering products to customers and is the one that has been selected to be explained more in-depth in this paper.

### *5.1 The Distribution Problem*

In this problem, a distribution network composed of multiple warehouses or depots has been defined. These depots serve previously assigned clients, based on several factors such as proximity. This means that a customer will only be served by vehicles belonging to a single depot.

### *5.2 Specification of the Problem and Literature Review*

The problem to be tackled is the so-called Dynamic Vehicle Routing Problem with Backhauls and Time Windows (D-VRP-BTW), which is a hybrid of three different problems of routing vehicles. Although these issues have been studied separately many times, they have never been addressed at the same time. Below are described several features of the problem, i.e., backhauls, time windows, and dynamism.

### 5.2.1 Backhauls

Backhauls is a feature that allows customers to request either delivery or pick-up of materials [5], so that truck capacity becomes an extremely important factor. In recent years it has been shown that much money can be saved if we combine the two services, i.e., visiting both suppliers and consumers within the same route. The Interstate Commerce Commission estimated that, with the introduction of backhauling, savings in the US grocery industry had reached 160 million dollars [6].

In this case, customers can order either pick-up or delivery, but not both things simultaneously. In addition, deliveries are done first, and then pick-up. This is so because, otherwise, a rearrangement of materials within the truck could be necessary. This may happen for example if we put materials at the front of the truck when there are some other goods that still have to be delivered at the back. In our problem, reverse logistics could be necessary when a customer is not satisfied with the order received, either because it is defective or because a delivery error has arisen.

### 5.2.2 Time Windows

This feature allows each customer to have a time window associated $[e_i, l_j]$. This time range has a lower limit and an upper limit that trucks must respect. This means that vehicles have to meet customer demand within that time window. Therefore a route will not be feasible if a vehicle arrives at any customer after the upper limit or before the lower limit.

This problem has been studied extensively throughout history [7, 8]. One reason why it is so interesting is its dual nature. It might be considered as a problem of two phases, the first concerning the vehicle routing and the second concerning the planning phase or customer scheduling. Another reason is its easy adaptation to real world, because in the great majority of distribution chains, customers have hard temporal constraints that have to be fulfilled.

### 5.2.3 Dynamism

Dynamism in vehicle routing problems is a relatively new field which many researchers have been studying in recent years [9, 10]. Dynamism can force to update previously planned routes. This fact can be caused either by possible disruptions or the arrival of some information that was not available in the beginning. In our case dynamism is due to unexpected events, several of which have already been explained in the previous section.

Once such an event occurs, distribution must decide whether to reschedule some of the routes, or accept some delays in customer deliveries. In order to take this decision, the potential cost of each option is calculated, so that the least expensive option is chosen.

### 5.3 Objective Function and Formulation of the Problem

According to the previous concepts, we have defined a problem where customers can request either delivery or pick-up of materials, within certain time windows. Apart from this, it covers the dynamism coming from untoward events which may affect the feasibility of the distribution plan.

The objective function is to minimize the total cost incurred. This cost has several components that are evaluated as follows:

| | |
|---|---|
| $\sum_{k \in M} F_k \sum_{j \in V\prime} x_{0j}^k$ | **Cost of vehicle utilization**. For each vehicle that is used, its fixed cost is added to the function. The variable $F_k$ is the fixed cost of each vehicle, all of which are grouped in $M$. $x_{ij}^k$ is a binary variable which indicates whether the vehicle $k$ has traveled between customer $i$ and customer $j$. All the nodes are grouped in $V$ |
| $\sum_{k \in M} c_k \sum_{i,j \in V} d_{ij}^k x_{ij}^k$ | **Cost of distance traveled**. This cost is equal to the total distance traveled by each route, multiplied by the variable cost of the vehicle used for each path. The variable $Ck$ indicates the variable cost of a vehicle while $d_{ij}^k$ is the distance between customers $i$ and $j$ |
| $\sum_{k \in M} PC_k$ | **Penalty for underuse of vehicles**. For every vehicle, the load it carries is examined, and a penalty is imposed if it is underused. This penalty applies to vehicles that are loaded below 75 % of its capacity |
| $\sum_{i,j \in V} PCNSx_{ij}$ | **Penalty for unfulfilled due date**. In the case that, for any reason, a vehicle cannot supply a client, a penalty on the objective function is imposed. In this case, the penalty will vary depending on the importance of the customer and the amount of goods that have not been served |
| $\sum_{k \in M} HE_k$ | **Overtime cost**. This cost arises whenever the route exceeds the capacity of the driver in regular time and it is decided to apply overtime. To do this, the excess of hours is multiplied by the cost of each extra hour |

The objective function that has been proposed for this D-VRPBTW (Dynamic Vehicle Routing Problem with Backhauls and Time Windows) is the sum of all the aforementioned costs and is given by:

$$\sum_{k \in M} F_k \sum_{j \in V\prime} x_{0j}^k + \sum_{k \in M} c_k \sum_{i,j \in V} d_{ij}^k x_{ij}^k + \sum_{k \in M} PC_k + \sum_{i,j \in V} PCNSx_{ij} + \sum_{k \in M} HE_k$$

This objective function is subject to the following restrictions:

$$\sum_{k\in M} F_k \sum_{j\in V\prime} x_{0j}^k + \sum_{k\in M} c_k \sum_{i,j\in V} d_{ij}^k x_{ij}^k + \sum_{k\in M} PC_k + \sum_{i,j\in V} PCNSx_{ij} + \sum_{k\in M} HE_k$$

This objective function is subject to the following restrictions:

$$\sum_{j=0,\ldots,n+m} \sum_{k=1,\ldots,M} x_{ij}^k = 1, \qquad i = 1,\ldots,n+m; \quad i \neq j \tag{1}$$

$$\sum_{i=0,\ldots,n+m} \sum_{k=1,\ldots,M} x_{ij}^k = 1, \qquad j = 1,\ldots,n+m; \quad j \neq i \tag{2}$$

$$\sum_{j\,=\,0,\ldots,n+m} \sum_{k\,=\,1,\ldots,M} x_{0j}^k = M \tag{3}$$

$$\sum_{i\,=\,0,\ldots,n+m} \sum_{k\,=\,1,\ldots,M} x_{i0}^k = M \tag{4}$$

$$\sum_{i\,=\,0,\ldots,n} \sum_{j\,=\,0,\ldots,n+m} q_i x_{ij}^k \leq Q, \qquad k = 1,\ldots,M; \quad j = 0,1,\ldots,n+m \tag{5}$$

$$\sum_{i=n+1,\ldots,n+m} \sum_{j=0,\ldots,n+m} q_i^{'} x_{ij}^k \leq Q, \quad k = 1,\ldots,M; = 0,1,\ldots,n+m \tag{6}$$

$$\sum_{i\,=\,0,\ldots,n+m} x_{ij}^k - \sum_{l\,=\,0,\ldots,n+m} x_{jl}^k = 0, \quad j = 0,1,\ldots,n+m; \quad k = 1,\ldots,M \tag{7}$$

$$\sum_{j\,=\,0,\ldots,n+m} x_{ij}^k - \sum_{l\,=\,0,\ldots,n+m} x_{li}^k = 0, \quad i = 0,1,\ldots,n+m; \quad k = 1,\ldots,M \tag{8}$$

$$\sum x_{ij}^k \leq |S| - 1, \qquad S \subseteq \{2,3,\ldots,\mathrm{n+m}\} \tag{9}$$

$$\sum_{i\,=\,n+1,\ldots,n+m} \sum_{j\,=\,1,\ldots,n} \sum_{k\,=\,1,\ldots M} x_{ij}^k = 0 \tag{10}$$

$$t_j^k - t_i^k \geq t_{ij}^k - M(1 - x_{ij}^k), \qquad \forall i,j \in V \backslash \{0, n+1\}, k \in K \tag{11}$$

$$e_i \leq t_i^k \leq l_i \quad \forall i \in V \backslash \{0, n+1\}, k \in K \tag{12}$$

$$x_{ij}^k \in \{0,1\}, \qquad \forall (i,j) \in E, k \in K \tag{13}$$

$$t_i^k \geq 0, \qquad \forall i \in V \backslash \{0, n+1\}, k \in K \tag{14}$$

Before going into detail, it is important to explain the meaning of some variables. Variables $n$ and $m$ represent the number of delivery and pickup nodes, respectively. In addition, each vehicle of the fleet $M$ has a limited capacity, called

$Q$, which cannot be exceeded under any circumstances. Moreover, the variable $t_i^k$ indicates the moment when the vehicle $k$ arrives at the customer $i$. If $k$ does not visit $i$, the variable will be null. Finally, to express the customer demand, two variables are used, one that specifies the number of items to deliver $(q_i)$, and one for the number to be collected $(q_i')$.

Constraints (1) and (2) ensure that all the nodes are visited exactly once. Functions (3) and (4) assure that the total number of vehicles leaving the depot is the same as the number of vehicles that return to it, which is equivalent to the amount of available vehicles. Sentences (5) and (6) indicate that the vehicle load, in terms of delivery and pickup, does not exceed its maximum capacity. The flow of the route, i.e., all vehicles that arrive at a customer leave it with the aim of going to another customer, is ensured by formulas (7) and (8). Function (9) ensures the inexistence of sub-tours in any of the routes, while (10) restriction ensures that all deliveries are made before the pickups. Constraint (11) ensures that if a vehicle travels from $i$ to $j$, it cannot arrive at $j$ before $t_i + t_{ij}$, i.e., the sum of the time it takes to reach $i$ and the time it takes to get from one node to another. Finally, clauses (12), (13), and (14) express the nature of the variables.

## *5.4 Proposed Solving Techniques*

For solving the aforementioned problem the use of three different meta-heuristics has been proposed. Two of them are some of the most used techniques for combinatorial optimization problems throughout history. The third, in contrast, is a novel meta-heuristic proposed as an alternative to the previous two.

The first two techniques are the Tabu search [11] and the genetic algorithm [12]. The third technique, as already mentioned, is a new population based meta-heuristic for solving combinatorial optimization problems. This new meta-heuristic prioritizes individual improvement of each component of the population, making crossovers between them only when it is necessary and when it is known that it is going to be beneficial for the results.

## *5.5 Case study*

The distribution case that has been defined includes three different depots which are distributed within a particular geographic area. In turn, each depot has a number of customers to be served. The number of customers varies between 15 and 20.

Each customer can decide whether to use hard or soft time windows. In addition, an order can be delivered to each customer or picked-up from him/her. Each depot has its own vehicle fleet in order to distribute goods to customers, the first one has three vehicles, the second one has four, and the last one has five

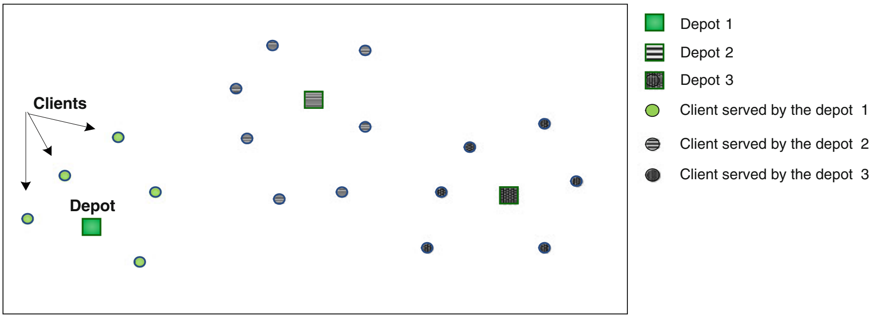


**Fig. 2** A simplified representation of the problem

vehicles. Additionally, each depot has its own driver equipment, and there is one driver for each vehicle.

A simplified representation of the problem is shown below (see Fig. 2).

## 6 Conclusions

In this paper, an approach for integrated planning and distribution has been proposed in a supply chain consisting of three levels, i.e., the company, its suppliers, and customers. The approach tries to provide solutions for exception handling that benefit the supply chain by identifying the information that should be exchanged between the different nodes and developing methodologies for production scheduling and distribution planning in a coordinated way.

Furthermore, a communication framework that links the different entities has been defined that consider several communication subsystems at the intraplant, interplant, intradepot, and interdepot levels. The possible exceptions have also been categorized into four groups depending on whether they come from production or distribution, customers or suppliers. Then, an example of an exception handling has been described that includes several possible courses of action.

Finally, regarding distribution, the problem has been defined including an objective function and its formulation. Next steps include further of the three metaheuristics proposed and software development of a prototype of the system.

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## References


1. Park Y, Hong S (2009) Integrated production and distribution planning for single-period inventory products. Int J Comput Integr Manuf 22(5):443–457
2. Safaei AS, Moattar Husseini SM, Farahani RZ, Jolai F, Ghodsypour SH (2010) Integrated multi-site production-distribution chain by hybrid modeling. Int J Prod Res 48(14):4043–4069
3. Bilgen B, Günther HO (2010) Integrated production and distribution planning in the fast moving consumer goods industry: a block planning application. OR Spectrum
4. Álvarez E, Fernando D (2011) A Web-based Approach for Exceptions Management in the Supply Chain. Robot Comput Integr Manuf 27(4): 681–686 Elsevier, The Netherlands
5. Toth P, Vigo D (2000) VRP with backhauls. Monographs on discrete mathematics and applications. In P Toth, D Vigo The vehicle routing problem. SIAM: 195–224
6. Golden BL, Baker E, Alfaro J, Schaffer J (1985) The vehicle routing problem with backhauling: two approaches. In R Hammesfahr Proceedings of the XXI annual meeting of S.F. TIMS, Myrtle Beach, SC. 90–92
7. Bräysy O, Gendreau M (2002) Tabu search heuristic for the vehicle routing problem with time windows. Official J Spanish Soc Statist Oper Res 10:211–237
8. Condeau F, Desaulniers G, Desrosiers J, Solomon M, Soumis F (1999) The VRP with time windows. Technical report Cahiers du GERAD G-99-13, École des Hautes Études Commerciales de Montréal, 1999
9. Pillac V, Gendreau M, Guéret C, Medaglia AL (2011) A review of dynamic vehicle routing problem. Ind Eng 0-28
10. Beaundry A, Laporte G, Melo T, Nickel S (2010) Dynamic transportation of patients in hospitals. OR Spectrum 32:77–107
11. Basu S, Ghosh D (2008) A review of the tabu search literature on traveling salesman problem. IIMA working papers 2008. Indian Institute of Management Ahmedabad, 1-16.2008
12. Holland JH (1975) Adaptation in natural and artificial systems: an introductory analiysis with applications to biology, control, and artificial intelligence. University of Michigan Press, Oxford, England
13. Solomon MM (2005) Vehicle routing problem with time windows benchmark problems. http://web.cba.neu.edu/~msolomon/problems.htm

# Performance Framework Geared by a Proactive Approach

**António Almeida and Américo Azevedo**

**Abstract** Currently, performance analysis on complex manufacturing systems is performed in an ad hoc way since the main objective is to verify if the strategy designed has been helping companies achieve their targets following a reactive approach. However, more and more companies are performing in competitive markets, forcing them to become more proactive than reactive. This way, a simple approach is no longer suitable for this type of companies, and a stronger and effective interaction between the strategic and operational layers is key. Therefore, this research proposes a framework composed of both qualitative and quantitative methods that allow decision-makers to better understand their production system. Moreover, using key leading indicators as reference, the idea is to provide companies with the ability to anticipate future performance behaviors based not only on the knowledge acquired, but also on a mathematical tool that will synthesize this knowledge and infer future performance behaviors. This paper explores a critical issue for contemporary industrial organizations and sustainability issues concerning energy consumption. In this scope, an important research was performed aiming at modeling and understanding the normal behavior of electricity consumption, as well as the factors affecting energy consumption in the painting line of an automotive plant.

## 1 Introduction

Currently, performance analysis in complex manufacturing systems is performed in an ad hoc way since the main objective is to verify if the strategy designed has been helping companies achieve their targets following a reactive approach. Thus,

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simply calculating lagging indicators using an excel tool is normally enough to achieve this objective. However, more and more companies are performing in competitive markets forcing them to become more proactive than reactive [1]. This way, a simple approach as described before is no longer suitable for this type of companies and, therefore, it is essential to have an effective approach that allows them to accelerate the learning process of their complex systems [2]. Companies should be able to analyze their leading indicators, and to understand their meaning and the feedback loops that affect them. Only this way can decision-makers look to the future and act even before these consequences affect the systems' efficiency and effectiveness [9].

Nevertheless, learning about complex systems is not a trivial matter since it requires an interdisciplinary approach. This is one of the reasons why the state-of-the-art around the performance management discipline is still in expansion but still much focused on the work developed by Kaplan and Norton about the balanced scorecard (BSC) [3]. Hence, this research work is proposing an innovative concept for the performance management discipline, through the development of a predictive approach to assess critical performance variables based on the system-thinking concept for complex manufacturing systems. Using these key-leading indicators as reference, the aim is to provide companies with a performance management framework that allows them to foresee future performance behaviors, and consequently anticipate decision-making processes, aiming at implementing corrective/improvement actions in a proactive way. Moreover, this approach should support companies so that they can establish their own ambitious and yet reachable targets.

Therefore, this document is divided into five main chapters. After the introduction chapter where the research context is depicted, the second chapter explores the challenges of this research. Here, not only will the current limitations be presented, but also a literature review supporting this research will be provided, as well as the connection between the different research topics. The Predictive Performance Management Framework is presented next. This chapter provides a detailed analysis of the methodology and mathematical tool that compose this framework. Finally, the proof of concept validation scenario developed within an automotive plant will be presented, as well as the results obtained. This paper ends with the conclusions and with the description of future research steps.

## 2 Research Scope

The Performance Management concept defines that in order to take the decision that will really improve the manufacturing system and support the organisation in achieving their strategic targets, it is crucial to periodically collect and assess information feedback about the real world. By using this information in a continuous way, it is possible to revise the existing understanding on the system, as well as the strategy adopted to drive the perception of the state of the system closer to the reality [4].

However, achieving this organizational maturity level depends on a number of concepts, such as: information management, operations research and industrial dynamics. While the information process management concept stresses the information link between the real system and the control level in order to make the information available, operations research focuses on the decision process itself. Doing so, operations research assumes a set of system states, creating a mental model based on the available information and arrives at a specific but isolated decision. Therefore, these two concepts for themselves are not sufficient, creating a gap related to the information that should be generated. To understand the system as a whole, these components should not be treated independently or without recognizing how they should be linked. Hence, industrial dynamics emerged with the goal of dealing with what information should be available at a decision point, as well as the consequences of defects and gaps in the information taken into account [5]. Only this way can organisations provide decision-makers with the right information that will allow them to approximate their vision of the system to reality, and thus develop a proactive management attitude.

In order to meet these challenges, this paper proposes a framework based on the combination of the System Dynamics approach and the concept of Learning Machine. From this combination, the Performance Management Thinking methodology was developed as an extension of the Systems Dynamics approach for the process-based performance management area. Furthermore, if this qualitative approach is extended by a learning machine tool capable of correlating the different feedback loops and its measurements, then this framework should be capable of anticipating how the system will behave in the future based on the leading factors that can be envisioned. Therefore, as complement of the system dynamics approach, a learning machine algorithm composed of both the Neural Network (NN) and Kalman Filter concepts is proposed to model the system's nonlinearity behaviors.

## *2.1 System Dynamics*

Aiming to provide an important contribution in the scope of the industrial dynamics, Jay Forrester at the MIT developed the system dynamics approach as a solution to help decision-makers enhance their knowledge on varying (or dynamic), nonlinear, closed boundary systems behaviors, and in converting real-life situations into enhanced simulation models. The system dynamics approach was then created as a standard for information flow representation using a complex system based on the policies that govern those systems.

The fundamental concept of this methodology is that manufacturing systems should be represented by a series of stocks and rate variables, embedded within a feedback structure. Stock variables represent accumulations within a system, or describe the state of the system. Furthermore, rate variables flow from one area of the system to another and control stock changes. In other words, rate variables model the system's policies imposed by endogenous and exogenous factors in order to represent the system dynamics as reliably as possible. While endogenous variables can be easily managed, since they are strictly connected with the decision taken by systems stakeholders, exogenous factors cannot be controlled due to the fact that they are mainly linked to the external environment that surrounds the system and, directly or indirectly, affects the normal behaviour of the system. From the knowledge generated by this learning model, it is possible to understand and represent the synergies observed in the real world, and thus understand how the manufacturing system will behave in the future, based on a series of leading factors that can be measured from the operational level, captured from the strategic level, or estimated based on an external environment analysis (such as market, economic, social analysis) [4].

Therefore, the idea of combining performance management with system dynamics is almost natural since these two concepts complement each other. For instance, while performance management intends to improve the systems performance based on feedback analysis, system dynamics support decision-makers so that they can explore and understand the existing feedback loops and their synergies.

## *2.2 Learning Machine*

Manufacturing processes are becoming more and more complex, presenting stronger nonlinearity behaviors. Moreover, due to the fact that products and the respective life cycles of the manufacturing systems are decreasing, the ability to design a mathematical formulation that is robust enough to represent the manufacturing behavior with high levels of reliability, and capable of being continuously updated, is normally limited and expensive. This way, the aim is to enhance the current performance management approach for dynamic systems, proposing the development of a so-called gray-box model [6]. From a practical point of view, the gray-box modeling is a very convenient way to model nonlinear processes since part the system behavior can be derived from the existing knowledge, converted into a mathematical model, while the nonlinear characteristics of the process can be captured by an iterative learning algorithm [7]. Therefore, as a complement to the system dynamics approach for the performance management domain, a learning machine composed of both the Neural Network (NN) and the Kalman Filter approaches should be explored.

Neural networks, whose concept is inspired in the biological nervous system, can be defined as a composition of simple elements, called neurons, distributed by a graph according to a layered architecture. A neural network should be composed of at least: one input layer, one hidden layer, and one output layer. However, depending on the level of complexity of the system in analysis, the number of hidden layers of the network can increase in order to enhance the polynomial function generated by this mathematical tool. As in nature, the network function is determined largely by the connection function between elements.

Commonly, neural networks are trained in order to assure that a particular set of inputs leads to a specific target output, emulating the real system behavior. This way, a training algorithm capable of capturing the system behavior should be explored. Usually, a network training is an iterative method based on the comparison of the network's output with the real value, measured from the real system, until the network output matches the target. The most used training algorithm is the backpropagation. This is a batch training that propagates the error observed at the output of the network, through the different layers, until its input layer, in order to correctly update the weights of each neuron, and thus approximate the curve of behavior to reality, maintaining the generalization capability. This generalization feature represents neural network's aptitude to infer information, even when the set of input values is entirely new.

In sum, the neural network approach belongs to the learning machine concept, with which complex system behavior can be easily emulated without any extensive quantitative knowledge of the system. However, within world-class industry scope, manufacturing systems should be seen as living entities that continuously change their behavior in order to meet market requirements. This way, the simple application of neural network approach, in which the learning algorithm is normally based on past measurements of the real world, may prove to be unreliable since it is not capable of envisioning the evolution of manufacturing systems. Hence, in order to predict behavioral changes, this paper proposes the implementation of a predictive Kalman algorithm, and its nonlinear extensions, in parallel with the Neural Network tool.

In classical linear estimation and control theory, a system is described by a state vector $x_t$, whose value at each discrete time t follows the dynamic rule depicted in Eqs. 1 and 2.

$$x_{t+1} = Fx_t + Bu_t + m_t \tag{1}$$

$$y_t = Hx_t + n_t \tag{2}$$

where, $m_t$ and $n_t$ represent the plant and measurement noise, respectively, while the optional vector $u_t$ is an external driving term and/or a computed control term.

The aim of an optimal filter (or, respectively, one-step-ahead predictor) is to compute a posterior state estimate $\hat{x}_t$ (or $\hat{x}_{t+1}$ respectively, a prior state estimate $\hat{x}_{t+1}$) that minimizes the generalized mean-square estimation error. In 1960, Kalman showed that under a variety of conditions the optimal estimation solution for both filter and predictor is given by Eq. 3,

$$\hat{x}_{t+1} = \hat{x}_t^- + k_t e_t \tag{3}$$

where $k_t$ represents the Kalman gain, $\hat{x}_t^-$ represents the estimation provided by the linear model, and $e_t$ represents the error between the estimated and the real values. The Kalman gain is learned iteratively, starting with an arbitrary matrix, and converging exponentially rapidly to its final value as each new measurement is obtained.

The basic Kalman filter is a linear, discrete-time, finite-dimensional system, which is endowed with a recursive structure that makes a digital computer well suited for its implementation. However, if the system presents a nonlinear behavior, an extension of the Kalman filter should be explored throughout a linearization procedure. The resulting filter is referred to as Extended Kalman Filter (EKF). The basic idea of the EKF is to linearize the state-space model at each time instant around the most recent state estimated. Due to its foundations, the EKF presents characteristics that allow it to be used as the basis of a second-order neural network training method. Therefore, it is a practical and effective alternative to the batch-oriented approach described before. The essence of the recursive EKF procedure is that, during training, in addition to evolving the weights of a network architecture in a sequential (as opposed to batch) fashion, an approximate error covariance matrix that encodes second-order information on the training problem is also maintained and evolved [8].

In sum, this research paper proposes that if a learning machine, composed of both NN and nonlinear Kalman Filter approaches, capable of continuously capturing and correlating the knowledge structured by the system dynamics approach, then it is possible to anticipate how a complex manufacturing system will behave in the future, based on the leading factors that can be envisioned. Consequently, the research question proposed for this paper is: how can the predictive performance management approach arise from the combination of the System Dynamics and Learning Machine concepts?

## 3 Performance Management Framework

The Performance Management Framework was developed with the main purpose of helping decision-makers structure their knowledge concerning their manufacturing systems behavior, based on a causal loop approach, taking as reference the respective KPIs that are directly linked to their strategic goals. Causal loop approach is mainly related with the capability to identify and understand intricate processes and root causes. This approach explores how variable X affects variable Y and, in turn, how variable Y affects variable Z through a chain of causes and effects. By looking at the all the interactions of the variables, the behavior of the complex manufacturing system can be revealed.

In other words, this methodology is expected to inspire decision-makers to think on their process performance, instead of simply using performance measurements as numerical variables, and thus achieve the objectives described in the introduction section.

As presented in Fig. 1, there are two main components within the predictive performance management Framework: a qualitative perspective (right grey box) called Performance Thinking methodology, and a more quantitative perspective (left grey box). While the first is mainly oriented to understand the process execution, find the endogenous and exogenous factors, and to model the existing

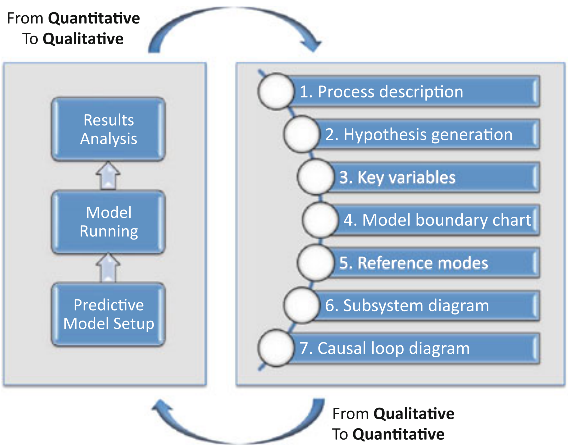


**Fig. 1** Machining features and their tool access directions

synergies between them, the quantitative perspective is responsible for dynamically correlating the different feedback loops and estimating the system behavior based on a set of input leading variables.

## *3.1 Performance Proactive Methodology*

The methodology developed, and named Performance Proactive Methodology (PPM) should be seen as an extension of the system dynamics approach to manage performance. The PPM is composed of seven main steps: describing a process, generating hypotheses, identifying key variables, model boundary chart, reference modes, subsystem diagram, causal loop diagram, predictive model setups, and running mode. Next, a detailed analysis of each step of the methodology is presented.

Initially, a detailed description of the process in analysis should be performed. Here a BPMN approach is used in order to show the real workflow of the process, people involved, and events/triggers. Next, after the process is understood, testimonies from stakeholders involved in the process should be collected and analyzed in order to create an initial knowledge base. From the different hypotheses provided in the previous stage, all key variables that can affect the system and hinder the achievement of the expected objectives should be identified, enumerated, classified, and described.

After selecting the key variables, these should be classified as endogenous (controlled from inside the system), exogenous (affecting the system from outside of the boundary; they cannot be controlled), or excluded (if the variable is very unstable and cannot be modelled). Afterwards, the reference mode step should be performed. This means that it is necessary to design and understand the behavior of each variable represented by the evolution curve. Thus, at this step of the methodology it is essential to guarantee that the data is properly extracted from the different databases in order to assure that the behavior of each variable (trends, periodicity, and fluctuations) will be deeply analyzed for a specific time horizon. Since with this step the aim is to think in terms of graphs over time, looking for long-term dynamic behaviors, a proper selection of the time horizon will affect the overall result of the framework application.

If well performed, previous steps will support the design of the subsystem diagram. The main goals of this step is to represent, in a graphical way, the overall architecture of the system's model, where the key variables are presented, as well as its influence on the system behavior. Finally, a causal loop diagram (CLD) should be designed. This is a causal diagram that helps visualize how interrelated variables affect one another. The diagram consists of a set of nodes representing the connected variables. After concluding the application of the methodology, it is important to go from a qualitative to a quantitative perspective, using the knowledge gathered from this methodology to setup the learning machine.

It is important to highlight that this is a learning process that requires an iterative approach. In fact, for more complex systems it is not expected to run this framework only once. Instead, it is expected that during the framework implementation users go to previous steps in order to tune their perception and knowledge on the reality of the system, and thus increase the model reliability.

## *3.2 Predictive Performance Engine*

The Predictive Performance Engine (PPE), which is a mathematical tool composed of Neural Network (NN) and Kalman Filter approaches, was developed to enhance the performance management discipline envisioning proactivity. The main goal of this tool is to provide decision-makers with performance estimation values, as well as to help decision-makers stipulate ambitious but achievable targets, taking into account the normal behavior of the system, captured by the PPM, previously presented.

From the combination of the NN and Kalman Filter approaches, it is possible to model a complex system, in a simple and intuitive manner for the final user and to guarantee that this model is capable of following the natural evolution of the manufacturing system [8]. Figure 2 shows the architecture of the predictive performance engine.

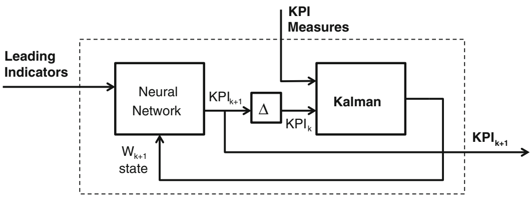


**Fig. 2** Predictive performance engine architecture

A neural network critically depends on the set of weights ($w_k$) that emulate the system behavior curve. Nevertheless, if a batch-training algorithm is used, then it is not feasible to assure that this network is capable of adjusting itself or even following the continuous evolution of the system, maintaining, or increasing the estimation reliability of future KPI values ($KPI_{k+1}$). Therefore, a combination of a batch and incremental training algorithms is proposed which is composed of both backpropagation and Kalman approaches. While the first one will provide a first approximation of the weights of the network, the Kalman filter is responsible for continuously estimating the correct weights of each node of the network, comparing the real KPI measurements with the estimations provided by the NN. Next, a detailed description is provided.

Initially, the network goes through a learning process where a backpropagation algorithm is used to adjust the weight of each neuron in order to guarantee that the behavior curve, represented by this graph, generates a good approximation of the real output for each set of inputs. Since the main objective of this step is to capture the behaviour shown by the manufacturing systems in the past, at the end of this stage the network should be capable of estimating the future performance of the system (Eq. 5) with some measurement error ($e_k$). For instance, one of the reasons why the set of weights defined by the training algorithm is not as reliable as expected, directly affecting the process error ($r_k$), is due to the fact that during the learning stage it was not possible to gather a complete and rich training data set. Therefore, the estimation results depend mainly on the generalization capability of the network.

Hence, at this stage it was not yet possible to achieve the expected level of reliability and the algorithm is still not capable of dynamically following the evolution of the manufacturing system. Thus, aiming to decrease the variable error ($e_k$) as much as possible and to guarantee that the estimation model is capable of continuously reducing the error index, even over time, the following step is coupling the Kalman filter at the output of the network. With this add-on, the algorithm is capable of continuously monitoring the error $e_k$ and adjusting the weights of each neuron (Eq. 4). This way, it is possible to achieve a dynamic learning machine that is continuously changing its parameters in order to approximate the estimation model to reality.

$$w_{k+1} = w_k + r_k \tag{4}$$

$$KPI_k = NN(x_k, w_k) + e_k \tag{5}$$

The Kalman filter used in this algorithm is the Unscented Kalman Filter (UKF). This special variant of the Kalman concept is very similar to the EKF, presenting some details that make it more efficient. Since the EKF algorithm only provides an approximation to the optimal nonlinear estimation, the Unscented Kalman Filter (UKF) can be seen as an important alternative to increase the estimation reliability in more complex systems analysis [10]. Indeed, the basic difference between the EKF and the UKF is the way in which Gaussian random variables (GRV) are propagated through dynamic systems. In the EKF, the state distribution is approximated by a GRV, which is then propagated analytically through the first-order linearization of the nonlinear system. This can introduce large errors in the true posterior mean and covariance of the transformed GRV, which may lead to suboptimal performance and sometimes divergence in the filter. On the other hand, the UKF addresses this problem by using a deterministic sampling approach. The state distribution is again approximated by a GRV, but is now represented using a minimal set of carefully chosen sample points (called sigma points). These sample points completely capture the true mean and covariance of the GRV, and, when propagated through the true nonlinear system, they capture the posterior mean and covariance accurately to second order (Taylor series expansion) for any nonlinearity.

The UKF is a straightforward extension of the unscented transformation (UT). This is a method for calculating the statistics of a random variable that undergoes a nonlinear transformation. Consider propagating a variable $w$ with dimension L using a nonlinear function, $KPI = NN(w, f_{leading})$. In this specific case, the variable $w$ is strictly connected to the set of weights of the neural network that better models the system under analysis. Assume that $w$ has mean $\bar{w}$ and covariance $\mathbf{P_w}$. To calculate the statistics of KPI, we form a matrix $\chi$ of 2L + 1 sigma vectors $\chi_i$ according to the following equation (Eq. 6):

$$\chi_{k-1} = [\bar{w}, \bar{w} + \left(\sqrt{(L+\lambda)}P_x\right)_i, \bar{w} - \left(\sqrt{(L+\lambda)}P_x\right)_{i-L}] \tag{6}$$

where $\lambda = \alpha^2(L+k) - L$ is a scaling parameter, the constant $\boldsymbol{\alpha}$ determines the spread of the sigma points around $\bar{w}$, and the constant $k$ is a secondary scaling parameter, which is used to incorporate prior knowledge on the distribution of $w$. The mean of these sigma points is calculated using a weighted sample ($W_i$) of the posterior sigma points (Eq. 7),

$$\hat{w}_k^- \approx \sum_{i=0}^{2L} W_i^{(m)} \chi_{k-1} \tag{7}$$

$$P_w \approx \sum_{i=0}^{2L} W_i^{(c)} (\chi_{i,k-1} - \hat{w}_k^-)(\chi_{i,k-1} - \hat{w}_k^-)^T \tag{8}$$

Finally, the weights set of the network should be updated as presented in Eq. 9,

$$\hat{w}_k = \hat{w}_k^- + \mathcal{K}_k\left(kpi_k - K\hat{P}I_k^-\right) \tag{9}$$

$$KPI_{k+1} = NN(\hat{w}_k, f_{leading}) \tag{10}$$

where $\mathcal{K}_k$ is the Kalman gain, $kpi_k$ is the measured KPI value and $K\hat{P}I_k^-$ represents the estimated KPI in the previous time slot. The estimated KPI value for the following time period is calculated by a nonlinear function defined by the estimated weights for each neuron of the graph and the expected leading factors (Eq. 10).

With this proposed approach, it is stated that the UKF represents an alternative to the EKF for estimating the weight parameters of the NN. However, as the state transition function is linear, the advantage of the UKF may not be as obvious. A distinct advantage of the UKF occurs when either the architecture or the error metric are so large that it is hard to differentiate the parameters as required in the EKF.

## 4 Application Case

In order to validate the importance and reliability of this proposal, a proof of concept validation scenario was established at an important Portuguese automotive plant. The environment is one of the main pillars at this organization. This means producing wealth, consuming less natural resources and energy, as well as producing less waste and emissions. Approximately 60 % of the entire energy required by the plant is consumed at the Paint Shop. Thus, the aim of this validation case was designing a predictive model capable of emulating the synergies between factors that influence the energy consumption in this organizational unit, using the KPI Energy per Unit (EPU) as reference.

Although mathematically the KPI EPU is a simple indicator (EPU = Electricity Consumed/Volume), its variables are affected by a series of endogenous and exogenous factors that significantly increase its complexity. The boundary of the system used for this validation case is the entire painting shop, from the output of the Body area to the input of the assembly area. In fact, the production mix imposed by the Body area can be seen as a factor that can possibly disturb the energy consumption. However, these areas of the production line are not the only factors to be taken into account. Hence, the painting area is also strongly influenced by the external environment (for instance, external temperature and humidity, rainfall), by the decisions made by the administrative layer (DownDays and shutdowns), as well as by the factors imposed by the tactical strategies of the painting area (such as preventive maintenance). The following figure shows the causal loop diagram designed according to the implementation of the PPM.

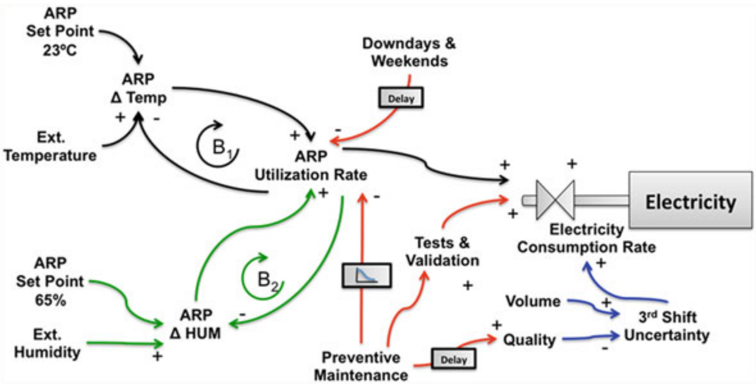


**Fig. 3** Machining features and their tool access directions

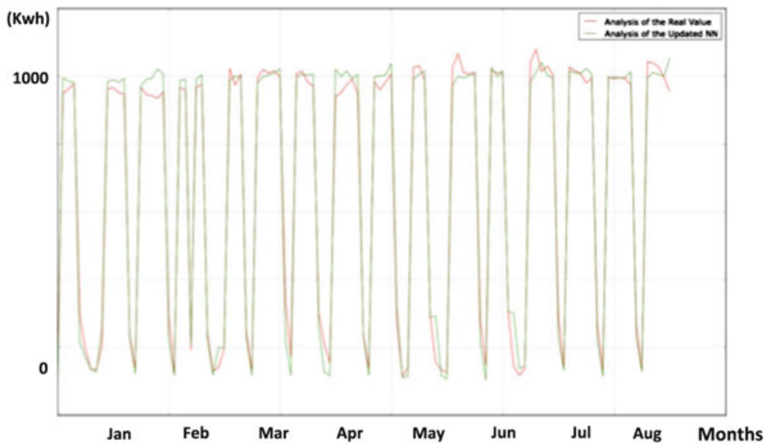


**Fig. 4** Machining features and their tool access directions

As depicted in this figure, all endogenous and exogenous variables directly or indirectly affect the electricity consumption rate (flow variable) and consequently the electricity consumed (stock variable) (Fig. 3).

The cluster of factors retrieved from the previous step and the respective data were then used as inputs of the learning machine, during the learning and generalization stages, to estimate the energy consumption. The graph in Fig. 4 shows the daily energy estimation during six months.

## 5 Conclusions and Future Work

Contrarily to a discrete event analysis, where manufacturing systems can be analyzed as a causal chain of events, in this approach the system's behavior emerges from the structure of its feedback loops. This means that route causes are not the events that start the cause and effect chains, but they are the synergies between different endogenous and exogenous factors. Moreover, in contrast to linear regression methods, the estimation of performance behavior not only depends on the knowledge extracted from past measurements, but also on the organization's ability to foresee future leading factors, increasing their reliability.

This framework provides a solution to handle nonlinear dynamic systems in a feasible and reliable way. Using this estimation model, stakeholders responsible for the painting process are capable of annually defining the expected budget necessary for the energy consumption per car. It is important to highlight the fact that the estimation was done based on the leading factors extracted from the fieldwork done, and not based on a simple regression analysis of the KPI. However, concerning the causal loop diagram developed with the PPM, there are still some improvements to be made since this should be seen as a result of an iterative approach. Nevertheless, in cases where the difference between the real and estimated EPU measurements is higher than expected (more than 5 %), there are only two possibilities: the system changed abruptly, requiring a new learning process, or there is some kind of malfunction that is affecting the performance of the system. Thus, this approach also helps decision-makers increase their capability to detect system breakdowns, normally invisible to the current quality programs.

The aim with this research is to present a new approach to performance management that breaks with the current methods as it is based on predicting the KPIs identified as core performance measurements. Indeed, from the analysis of the results presented before, it is possible to state that the output of the framework is promising, presenting a high level of reliability. For further work, both the methodology and mathematical tool will be refined once the main objective is to achieve maturity through the implementation of this approach in different and distinct test cases.

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## References

1. Almeida A, Politzei D, Azevedo A, Caldas A (2012) Linking strategic goals with operational performance: an integrated approach. In: Proceedings of the IEEE international conference on industrial engineering and engineering management (IEEM), Hong Kong, China
2. Garengo P, Biazzo S, Bititci US (2005) Performance measurement systems in SMEs: a review for a research agenda. Int J Manage Rev 7(1):25–47
3. Busi M, Bititci U (2006) Collaborative performance management: present gaps and future research. Int J Product Perform Manage 55(1):7–25
4. Sterman JD (2000) Business dynamics: system thinking and modeling for a complex world. McGraw-Hill, New York
5. Forrester JW (1968) Industrial dynamics: a response to Ansoff and Slevin. Manage Sci 14(9):601
6. Xiong Q, Jutan A (2002) Grey-box modelling and control of chemical processes. Chem Eng Sci 57:1027–1039
7. Barrios JA, Torres-Alvarado M, Cavazos A (2002) Neural, fuzzy and grey-box modelling for entry temperature prediction in a hot strip mill. Expert Syst Appl 39:3374–3384
8. Haykin S (2001) Kalman filtering and neural networks. Wiley, London
9. da Piedade Francisco R, Azevedo A, Almeida A (2012) Alignment prediction in collaborative networks. J Manuf Technol Manage 23(8):1038–1056
10. Kandepu R, Foss B, Imsland L (2008) Applying the unscented Kalman filter for nonlinear state estimation. J Process Control 18(7–8):753–768

# Application of Non-conformity Matrix to Predict System Interactions in Complex Quality Problems

**S. M. O. Tavares, Arsalan Farooq, António Araújo and Henriqueta Nóvoa**

**Abstract** Assuring the highest quality at a realistic cost is a permanent challenge for commodities manufacturing. Complex processes, demanding customer specifications and high production rates make the traceability of Non-Conformities (NCs) a defiant task, requiring a holistic approach and methods to complement the traditional quality control tools. This paper presents a new tool, that addresses the different NCs generated along a production line in a matrix way and apply the Design Structure Matrix (DSM) principles for a more comprehensive analysis. This tool was applied in an industrial setting with the purpose of improving the quality of three-piece tin plate aerosol cans. Due to the complexity of the problem, where many NCs can be generated along the production process eventually causing defective aerosol cans, the application of this Non-Conformity Matrix (NCM) tool showed promising results, by a clearer identification of interactions among NCs. Subsequently, DSM algorithms of clustering and sequencing were applied on this matrix, pointing out which are the most important clusters of NCs throughout the overall manufacturing process, thus targeting the efforts of quality control engineers at the critical activities of the production process. Linking this tool with other process improvement tools, such as design of experiments and failure mode and effects analysis will significantly improve the final product quality, thus reducing the overall costs.

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## 1 Introduction

Quality is a key competitive factor, transversal to all industrial sectors of the economy and an integral part of virtually all products and services. According to recent studies [1], quality and reliability of products and/or services are today the major competitive factors for manufacturers, even when compared to price, which, somehow surprisingly, has been considered a relatively less important factor. In mass production industries, the quality control can be challenging due to the reduced lead times and the inevitability to introduce increasingly more sophisticated statistical methods for quality control. In this type of production, it is essential to effectively use Cost of Quality (CoQ) models in order to have a thorough understanding of the impact of quality control procedures and policies in terms of the cost of the final product.

For a solid quality improvement, management should be supported by the several available quality tools for the diagnosis and control of the different manufacturing processes. A positive correlation between the quality levels of a given company and the application of the quality tools was studied by Tari and Sabater [2], showing a positive correlation between the application of quality tools and total quality management programmes, pointing out the importance of management actions related to leadership, planning and human with the technical tools and techniques which support the quality improvement process. Several technical tools are widely implemented, including the seven basic quality control tools [3, 4], usually composed by: (1) flow-chart; (2) cause effect diagram; (3) check sheet; (4) control chart; (5) histogram; (6) Pareto chart, and (7) scatter diagram. These tools are an essential complement to the quality improvement programs or to the ISO 9000 certifications [5]. These seven basic quality tools are a first set of tools that can support quality improvement decisions in most processes. They have reached their maturity and are applied from the product conceptualization to management of processes, on a day-to-day basis [6]. Nevertheless, these tools are not extensively applied as a regular tool for continuous process analysis in most SMEs. According to Bamford and Greatbanks [7], these tools allow a greater understanding of the processes by the managers and operators due to: (1) in-depth knowledge of the processes and products; (2) formal training in problem solving activities; (3) suitability of tools selected for different requests, and (4) simple models at all levels in the organizations to aid communication and learning.

Further to the seven basic tools, new quality control tools have recently emerged to complement the systematic quality control. These tools are focused on the complex products and processes, promoting new ways to innovate, communicate and plan [8]. The tools that are usually considered part of these seven new quality control tools are: (1) the affinity diagram; (2) the arrow diagram; (3) matrix data analysis; (4) matrix diagrams; (5) process decision program charts; (6) relations diagrams, and (7) tree diagrams. The seven new quality tools have been interconnected to the higher innovation in new products and processes, moving from a cost oriented attitude to an innovation-oriented attitude [9]. This trend has been visible in high-tech products and has being disseminated to more traditional products.

The application of these tools was explored in a quality improvement program of three-piece tin plate aerosol can production, which is composed by multiple manufacturing processes, with high production rates. This sort of products requires very low defect rates since a defective aerosol can will endorse several repercussions in the forward supply chain. A three-piece tin plate aerosol can is a simple product composed mainly by three major parts: the dome, the bottom and the body, with an intricate production process, composed by many stages. As all manufacturing processes are not one hundred per cent reliable, different NCs occur along the production line, which might originate defective products. Usually, a significant part of these NCs are traced by the quality control system. They can be generated at the very beginning of the manufacturing process—like as in the case of the tin plate thickness as received from the material supplier being slightly out of specification (slightly too thin or slightly too thick)—in the middle of the manufacturing process—as in the case the rectangular tin plate from which the body is made being cut out of specifications—or at the end of the manufacturing process—for instance in the case of a quality parameter of the final can not being according to specifications.

In order to have a systemic view of all the NCs and their dependencies, a new tool has been developed based on the matrix diagram and on Design Structure Matrix (DSM) in order to evidence and understand how NCs relate between each other and generate defects on products. This new tool, labeled Non-Conformity Matrix (NCM), allows to understand which NCs are the most important, which groups of NCs are related among each other, which NCs influence the final quality and which ones do not. This new tool is suitable for complex production processes, highlighting the processes and operations that are less reliable in the manufacturing processes, prioritizing the ones that should be the focus of the quality improvement teams.

In the following sections, the DSM principles are presented, including the essential operations to analyze and organize the matrix information. Then, the new tool, the non-conformity matrix is presented and a methodology for application of this tool is described. An industrial application example of this tool is also included in this article, where it was applied to analyze the NCs interactions along the manufacturing process of aerosol cans, allowing to understand their impact of the final product quality and to focus quality improvement actions on specific processes.

## 2 Design Structure Matrix

The design structure matrix was developed in 1960s as a tool to analyze tasks dependency and their sequence; however this tool became popular on 1990s applied in product and process development of complex systems [10, 11]. This tool is a $N \times N$ matrix based tool that represents the interactions between $N$ different elements, which composes the system. Representing the relations inside a system in a matrix form provide intuitive and compact representation of complex systems, being easily adjustable and scalable in order to take into account the different interactions of product or process development. With this matrix it is also possible to operate mathematically, revealing information about the interactions that can be used for system scrutiny and optimization. Several advantages of the DSM tool were pointed out by Eppinger and Browning in [12]: conciseness of the information; easy visualization of the interactions between system components, intuitive understanding of the data, perform analysis based on matrix mathematical tools, flexibility to be adapted for different situations and problems. Commonly, DSM exploration involves three major steps: (1) identification and decomposition of the elements that compose a system; (2) identification and interpretation of the interactions between the elements, and (3) analyses of potential reintegration of the elements with matrix operations.

Currently, DSMs can manage different type of data, which are commonly divided in four types [11]: component-based (mainly for products), people-based (for organizations management), activity-based (mainly for activities and process), and parameter-based (low-level process as design decisions). However, other types of DSMs are possible, as the one discussed in this paper, where this technique is applied to scrutinize quality problems through the NCs detected and measured along a manufacturing process.

An example of DSM is presented in Fig. 1. Considering, for instance, Fig. 1a, we should read the matrix column by column. Starting on column 1 the DSM shows that component 1 has an unidirectional relationship with component 2 and component 6. There is no relationship between component 1 and the other components (3, 4, and 5). If we now move to column 2, the DSM shows that component 2 has unidirectional relationships with components 1, 3, and 4, and no relationship with components 5 and 6. The matrix can also be written line by line instead of column by column. The information is exactly the same but we would have the transposed matrix of the one shown in Fig. 2a. The way you write the matrix is just a convention. In the present paper we will write the matrixes column by column, which is the most usual convention.

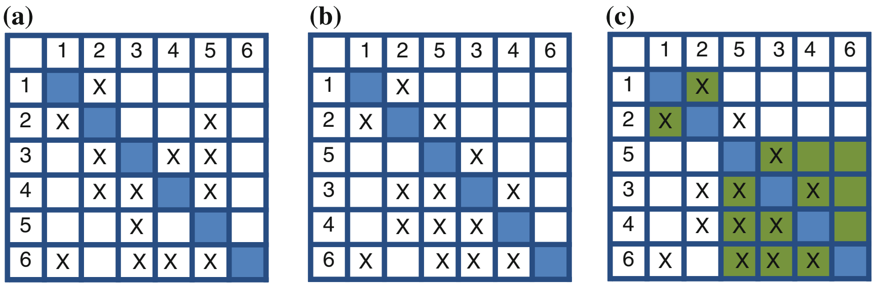


**Fig. 1** Generic DSM clustering operation. **a** Initial system. **b** Partitioned system. **c** Clustered system

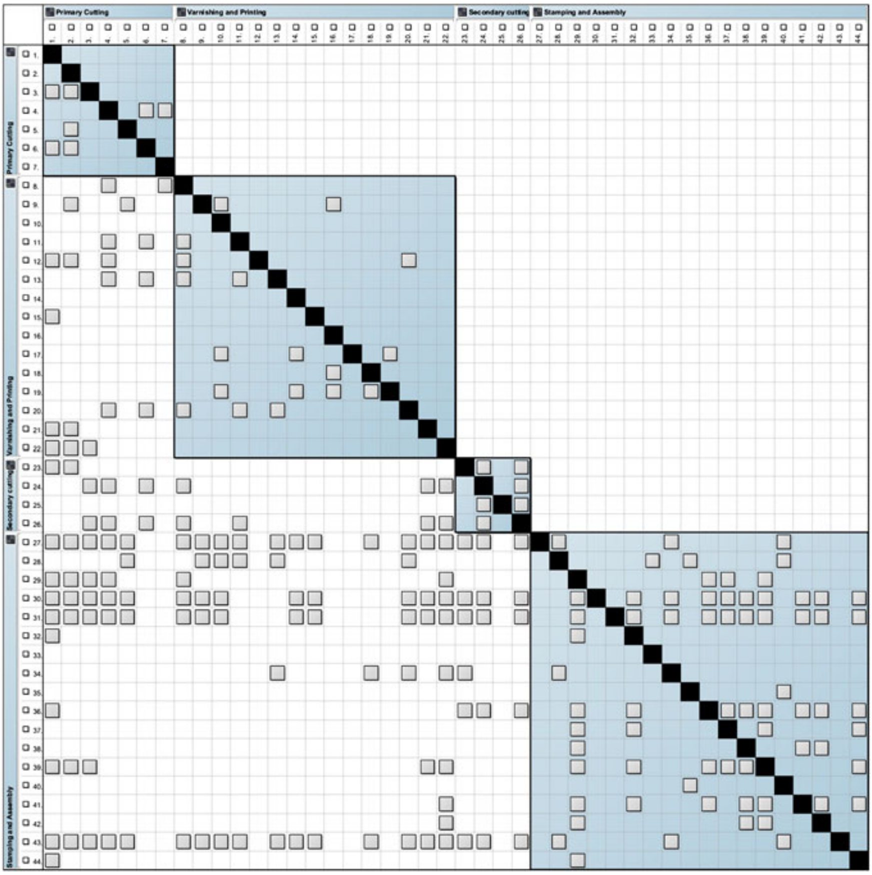


**Fig. 2** DSM NCM built after expert inputs and detail corrections

If the relationships between all the matrix components are bidirectional, then the matrix would be symmetric relative to its diagonal (which is not the case of Fig. 1a). This occurs with some components of Fig. 1a. For instance component 1 and component 2 have a bidirectional relation between them (1 provides something to 2 and 2 provides something to 1), that's why the crosses relating them are disposed symmetrically relative to the diagonal.

## 2.1 Data Gathering and Matrix Operations

Data collection for DSM construction is essential for the success of this technique. In several circumstances all the relations between elements are not obvious, requiring the involvement of many stakeholders related to the system, in order to identify and understand all possible relations. After data gathering, several matrix operations can be done to process and analyze a DSM, such as:

- Optimization of the information flow (partitioning);
- Clustering;
- Decomposition or integration;
- Tearing;
- Sequencing;
- Identification of correlation levels.

The most common operation in DSM is clustering of the matrix. This operation finds subsets of elements that are exclusive or with minimum interactions. Figure 2 shows an example of clustering using a generic matrix. This operation is composed by two steps, a partitioning operation to reorder the elements to reduce the number of interactions upwards the diagonal and identification of clusters with minimum interactions between them.

The final result of a DSM analyses through clustering, will provide a cluster of elements that are strongly interconnected between them, supporting the categorization of important sets for optimizations or improvement actions in the systems.

## 3 Non-conformity Matrix

Non-conformities and non-conforming products originated along production lines are not always easily identified and analyzed. This is due to the multiple sources of variability present in any manufacturing environment, as well as to the complex correlations that exist between non-conformities. The authors propose to use a new tool, the Non-Conformity Matrix (NCM), to support this analysis and systematization of the non-conformities, highlighting these multiple relations and giving a comprehensive scrutiny of the system. This tool organizes all NCs and defects in a matrix, highlighting relations between them. Applying DSM principles, it is possible to create clusters of NCs and defects, organizing and demonstrating clusters of the most important NCs for a given defect. After this clustering operation, it is possible to redirect quality efforts to a specific cluster, filtering variables for further analysis using techniques like Design of Experiments (DoE), thus reducing NCs and improving the final quality.

We propose a 10 step method for applying this new tool (NCM), based in:

1. Identification and definition of the defect or problem to be analyzed;
2. Identification of all NCs along the production line of a product;
3. Collection of all relations between NCs with clear explanations about each dependency (including interviews to operators, quality controllers and managers, and engineers);
4. Transfer all data to a DSM, parsed by manufacturing process;

5. Apply mathematical operations to DSM (mainly clustering and sequencing operations);
6. Perform design of experiments in the important clusters;
7. Improve the manufacturing process;
8. Evaluate again the relations of NCs, deleting the NCs that were eliminated;
9. Update the DSM;
10. Refine the model over time.

# 4 Industrial Application Example

An industrial application example, applied to three-piece tin plate aerosol cans production, is presented in the current section. The first five steps of the methodology described above were applied successfully, allowing to clearly improve the understanding, from a systemic point of view, of how the several NCs are related between themselves and how they affect the final product quality parameters.

## *4.1 Data Gathering*

The NCM application method proposed starts by the identification and definition of the defect or problem to be analyzed. In this case there are several output quality factors of the final aerosol cans that need improvement. When these output quality parameters are outside specification limits, defective cans are produced.

The second step in building the NCM started by modeling the production process in fine detail, highlighting all the quality control points and the NCs traced in each of the quality control points. This big picture of the complete production process and the points where the NCs are determined, enabled the understanding of the chronological sequence of the NCs, being certain that a NC that is created at the beginning of the production process may generate a NC later in the production process, but a NC generated at the end of the production process shouldn't generate a NC earlier in the production process. Although the details of production processes cannot be disclosed, it is important to understand the high-level production sequence of the manufacturing process under analysis. The three-piece aerosol cans pass successively by the following production areas: primary cutting, varnishing & lithography, secondary cutting, and stamping & assembly.

The second step proceeded further with clarification and selection of the NCs that are related to the final quality parameters. Brainstorming process was conducted with production and quality managers to list down all the NCs. From this process, a total of 65 NCs was identified, number that was later reduced to 44 NCs after performing an additional brainstorming with line managers. In this second brainstorming session, all NCs not related with the final quality parameters under analysis were removed from the list. These brainstorming sessions correspond at the same time to step 2 and step 3 of the methodology introduced in Sect. 3, since the same brainstorming sessions were used to list the NCs and the dependencies between them.

After all the NCs and the dependencies between them were listed down, this information was transferred into a matrix. This corresponds to step 4 of the above-mentioned methodology, and generated a 44 × 44 matrix having 1936 cells with 44 non-working cells (the diagonal elements, which have no significance in DSM). Therefore the NCM of this industrial case has an impressive number 1892 working cells, all requiring a detailed and thorough analysis.

The matrix should be read column by column, in the following way: the 44 NCs are written down in 44 columns and 44 rows exactly in the same order. When going down one column, a mark (or a 1) is generated every time the NC stated in the column being followed can originate the NC stated in the line being analyzed. Every time the column NC can't generate the line NC, then the matrix position is left empty (or zero is written). After building the first NCM a pilot survey to the industry experts was conducted to ensure that the matrix was properly built and it is understandable for every concerned person. This phase allowed the construction of what was called the "experts input NCM". With this new matrix, it is important to evaluate and validate the prior correlations one by one. This generated a second matrix, the "corrected NCM" (shown in Fig. 2), as some of the relations from the "experts input NCM" were considered not to be precise. The difference between the two matrices is very small, with only 31 different cells out of 1892 (1.6 %) between one matrix and the other. A more detailed comparison between these matrices is left for future work.

For the next steps of the methodology, the "corrected NCM" was considered the most appropriate for further analysis, by applying analytical models such as clustering and sequencing algorithms. Due to confidentiality clauses, the NCs are hidden. As example, Fig. 3 shows interactions among NCs occurred at the primary cutting process before and after the mathematical operations. The mathematical operations applied to the "corrected NCM", as well as the main conclusions taken after these operations will be explained in the next sub-section.

## *4.2 Matrix Operations*

In this sub-section the application of step 5 of the NCM proposed methodology (see Sect. 3) to the industrial case is presented.

The "corrected NCM" was initially defined in an Excel worksheet, and then transferred to the Cambridge Advanced Modeler, [14]. This modeler allows performing several mathematical operations on the DSM. Many different operations were applied to the "corrected NCM", but some of them didn't help in reducing

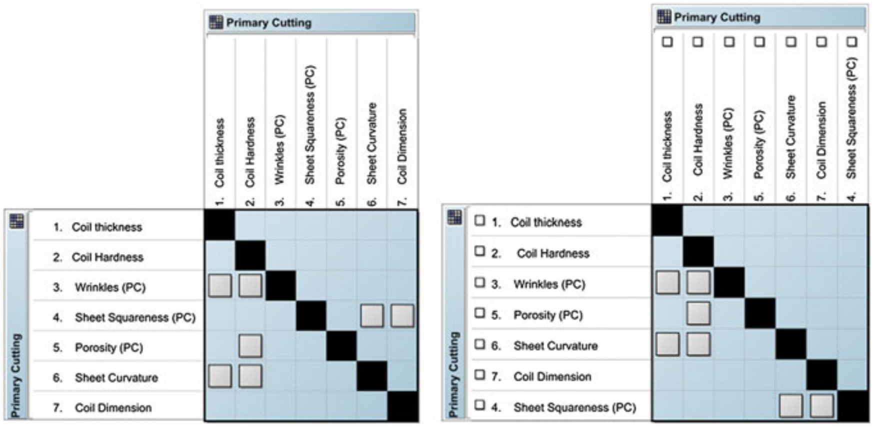


**Fig. 3** NCM showing interactions among primary cutting process NCs before and after applying mathematical operations

the matrix apparent complexity. Thus, only the operations that were most successful in reducing the matrix apparent complexity are reported.

The "corrected NCM" (see Fig. 2) is already parsed by the high level manufacturing process, i.e., primary cutting, varnishing & lithography, secondary cutting, and stamping & assembly. Nevertheless, inside each manufacturing process the order of appearance of the NCs is random. In all the successful operations done to the matrix, the high level production processes were kept as primary clusters, and then operations of sequencing inside these primary clusters were performed. Sequencing operations across the complete matrix (i.e., without any of the high level production process clusters) were carried out, but the resulting matrixes seemed even more complex than the original "corrected NCM". The sequencing operation inside each of the 4 high level manufacturing process clusters resulted in an apparently less complex matrix (Fig. 4), with most marks bellow the diagonal (lower triangular matrix). Also the marks above the diagonal appeared now much closer to the diagonal than before.

The importance of having a lower triangular matrix (a matrix with all marks bellow the diagonal) is that feedback type of relationships are eliminated: when a mark is above the diagonal it means that a NC that is written later in the NCM is generating a NC written earlier in the NC matrix. As stated before (Sect. 4.1) simple logic makes one expect that NCs generated at the beginning of the process can generate other NCs later in the process, but NCs generated late in the production process shouldn't generate other NC's that were generated earlier in the process. The fact that the NCM, despite all the operations carried on it, still has some marks above the diagonal, shows that there are some complex relationships between those few NCs, whether because they can be generated in several points along the production process, whether because they can be generated at a certain point relatively early in the production process but only much later detected by the

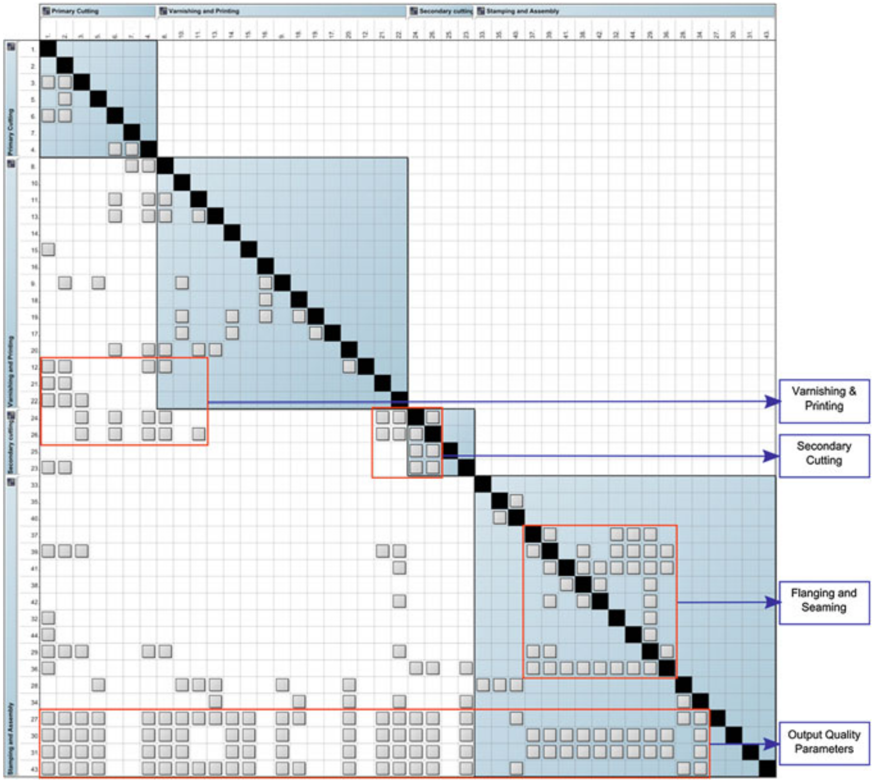


**Fig. 4** DSM build after sequencing algorithm

quality control system, or possibly because of other reasons. Although the complex relationships between the NCs who have marks above the diagonal need to be investigated (for instance using DoE), Fig. 4 already allows to concentrate on just two small blocks of NCs. This was not evident from Fig. 2.

The NCM presented in Fig. 4 also allowed to identify four important clusters of NCs. Varnishing and Printing NCs are influenced mainly by primary cutting NCs. Secondary cutting NCs are influenced mainly by varnishing and Printing NCs and also Secondary cutting NCs. Flanging and seaming NCs are mainly influenced by themselves (although with complex feedback relations), which is called modularity. Finally it can also be seen that the output quality parameters, which logically appear at the matrix end, are influenced by NCs generated all along the production process. Still it can be seen that some of the NCs don't affect the final output quality parameters, which is, by itself, already an improvement on the previous state of knowledge (initially there were 44 NCs potentially influencing the output quality parameters, now there are only 31). Figure 4 DSM also shows many empty spaces in the lower triangular matrix. This, again, is a further simplification of the problem, since many NCs have no or few interactions with the other ones.

The clusters of components highlighted in Fig. 4 are the future work starting point (step 6 of the methodology proposed in Sect. 3). Design of Experiments (DoE) would be a good tool to validate the interaction between these NCs, identifying weak and strong interactions and reducing the impact of NCs. These important clusters can further be analyzed by introducing new NCs or eliminating some NCs and expanding them into higher detail. The two different DSMs ("expert input NCM", and "corrected NCM") can be studied further comparing the system interactions that engineers actually experienced, [15]. Additional mathematical operations can be applied on Fig. 4 matrix to perceive if there are different possible conclusions. The operations could be producing clusters within clustering and then applying the sequencing algorithm to analyze the interactions within and outside the clusters. The sub clustering could be done on family basis, i.e., within each cluster those NCs, which are subjected to similar type of NC, would be grouped.

## 5 Conclusion

Quality improvement on complex production systems is a huge challenge, not only due to the multiple interactions of manufacturing operations, but also due to the high number of non-conformities (NCs) that can occur along the production. To support the management and traceability of NCs, a new tool was developed, labeled non-conformity matrix (NCM) that can highlight relations between critical NCs and defective products. This tool takes advantage of the design structure matrix (DSM) principles, allowing the identification of clusters of NCs for prioritizing quality improvement actions.

This tool was applied in an industrial setting with the purpose to improve the quality of three-piece tin plate aerosol cans. Due to the complexity of the problem, where many NCs can be generated along the production process eventually causing defective aerosol cans, the application of this NCM tool showed promising results, by a clearer identification of interactions among NCs. Subsequently, DSM algorithms of clustering and sequencing were applied on this matrix, pointing out which are the most important clusters of NCs throughout the overall manufacturing process. The results enable a reduction of the problem complexity, by highlighting the critical stages of the manufacturing process, namely the activities of flanging and seaming, which deserve special attention of quality improvement teams. Improving the reliability of these processes will lead to quality enhancements in the final aerosol cans.

The authors believe that the presented NCM can support the quality level improvement of complex production processes, highlighting the existent relationships between NCs and product defects. Exploring the usage of this tool together with more standard process improvement tools, such as design of experiments and failure mode and effects analysis, might significantly improve the final product quality, thus reducing the overall costs.

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## References

1. Karim MA, Smith AJR, Halgamuge S (2008) Empirical relationships between some manufacturing practices and performance. Int J Prod Res 46(13):3583–3613
2. Tari JJ, Sabater V (2004) Quality tools and techniques: are they necessary for quality management? Int J Product Econ 92(3):267–280
3. Montgomery DC (2009) Statistical quality control: a modern introduction, 6th edn, Wiley, London
4. Defeo JA, Juran JM (2010) Juran’s quality handbook: the complete guide to performance excellence, 6th edn, McGraw-Hill, New York
5. Tari JJ (2005) Components of successful total quality management. TQM Mag Res Concepts 17(2):182
6. Paliska G, Pavletic D, Sokovic M (2007) Quality tools–systematic use in process industry. J Achieve Mater Manuf Eng 25(1):79–82
7. Bamford DR, Greatbanks RW (2005) The use of quality management tools and techniques: a study of application in everyday situations. Int J Qual Reliab Manage 22(4):376–392
8. Duffy GL, Laman S, Mehta P, Ramu G, Scriabina N, Wagoner K (2012) Basic quality: beyond the basics-you’ve heard about the seven basic quality tools, but how much do you know about the seven new quality tools? Qual Prog 45(4):18–23
9. Levesque J, Walker HF (2007) The innovation process and quality tools. Qual Prog 40:18–22
10. Carrascosa M, Eppinger SD, Whitney DE (1998) Using the design structure matrix to estimate product development time. In: Proceedings of the ASME design engineering technical conferences (design automation conference), pp 13–16
11. Browning TR (2001) Applying the design structure matrix to system decomposition and integration problems: a review and new directions. IEEE Trans Eng Manage 48(3):292–306
12. Eppinger SD, Browning TR (2012) Design structure matrix methods and applications. MIT Press, MA
13. Reading a DSM, http://DSMweb.org/dsmweb/en/understand-dsm/technical-dsm-tutorial0/reading-a-dsm.html. Accessed Jan 2013
14. Wynn DC, Wyatt DF, Nair SMT, Clarkson PJ (2010) An introduction to the Cambridge advanced modeller. In: Proceedings of MMEP 2010, Cambridge, UK
15. Hommes QDVE, Whitney DE (2003) The predictability of system interactions at early phase of the product development process. In: ASME 2003 international design engineering technical conferences and computers and information in engineering conference (IDETC/CIE2003), Sept 2–6 2003

# Nonconformity Root Causes Analysis Through a Pattern Identification Approach

**Michael Donauer, Paulo Peças and Américo Azevedo**

**Abstract** Controlling, maintaining, and improving quality is a central topic in manufacturing. Total Quality Management (TQM) provides several tools and techniques to deal with quality related topics, which are not always applicable. With the increased use of Information Technology (IT) in manufacturing there is a higher availability of data with great potential of further improvements. At the same time this results in higher requirements for data storage and processing with demanding, time consuming sessions for interpretation. Without suitable tools and techniques knowledge remains hidden in databases. This paper presents a methodology to help analyzing root causes of nonconformities (NCs) through a pattern identification approach. Hereby a methodology of Knowledge Discovery in Databases (KDD) is adapted and used as a quality tool. As the core element of the KDD methodology, the data mining, a well-known statistical measure from the field of economics—the Herfindahl–Hirschman Index (HHI)—is integrated. After presenting the theoretical background a new methodology is proposed and validated through an application case of the automotive industry. Results are obtained and presented in the form of patterns in matrices. They suggest that concentration indices may indicate possible root causes of NCs and invite for further investigations.

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## 1 Introduction

Controlling and maintaining quality is a central topic in manufacturing. Increased use of information technology in mass production entails more data availability but also demands a great deal of data processing, interpretation, and presentation. Total Quality Management (TQM) can be understood as a philosophy consisting of values, tools, and techniques to increase customer satisfaction and continuous improvement. Techniques for controlling process parameters are a central point and deviations of those controlled measures signal need for action. Nowadays information storage and processing capabilities exist but suitable tools are not always available or must be tailored for answering specific questions of interest. If suitable tools are not available knowledge remains hidden in databases [1]. Quality tools and techniques offer a variety of methods to visualize and control process data and statistics can be applied to gain certainty about cause effect relations [2]. These tools are remedies to numerous quality problems but might not always take effect. The application case of this paper's methodology for example offers too many variables to be adequate for statistical analysis and visualizations of traditional quality tools do not serve as evaluation instruments.

Occurring nonconformities (NCs) at machines within the production steps are aimed to be identified for further investigation of root causes. Hereby the traceability of products in mass production with numerous machines at several production steps is highly depending on the level of implementation of information technology. In addition to that this becomes only transparent depending whether efforts for data analysis, interpretation, and visualization are done. Knowledge Discovery in Databases (KDD) for example offers a general framework consisting of sub-elements to generate knowledge from a dataset [3]. A core element is data mining (DM), a method with the aim to identify patterns [3]. The developer who uses this method has a high degree of freedom for using the kind of method as the DM step.

In this paper a new methodology is presented, which is validated through an application case from the automotive industry. The study presented relates to a real industrial problem. Quality related data of two consecutive manufacturing process steps is evaluated and visually represented in a color highlighted matrix. These matrices may identify the source of origin that caused the NCs to emerge. This is done by including the total number of NC occurrences, measuring their concentration among the machines, and highlighting in different shades the machines with the highest incidents. The visualization takes into account production steps, production volume, and nonconformities that occur at the machines within the production steps. However, the source of origin is not identified and must be further investigated for confirmation.

Results are of interest for academia and practitioners. Different disciplines such as IT, quality, and economics are consolidated. The integration of an economics concentration measure into a KDD methodology can be used as a quality tool for quality engineers to identify possibilities to improve processes in mass production with diverse NCs.

This paper presents an efficient method for treating and visualizing data related to process quality, namely NCs that are concentrated to single machines of two consecutive production steps. The method is applied to an automotive high volume production process of similar products varying in size, composition, and shape. A literature review of relevant topics is given, a methodology suggested, and an application case presented. The definition of the production steps under analysis is firstly presented in this paper. Secondly, the identification and collection of relevant data are done. In order to identify patterns an adapted methodology from discovering knowledge in databases is used. After treating the data the core element, data mining, is introduced and results can be obtained. An application case of the automotive industry is presented, results of identifying NC root causes discussed, and conclusions drawn.

## 2 Literature Review

The following section provides the theoretical background of relevant topics. TQM and quality tools are reviewed and a method of pattern identification through knowledge discovery in databases (KDD) is presented. The applied statistical concentration measure is explained in detail.

### 2.1 TQM and Quality Tools

The subject Total Quality Management (TQM) is extensive, diverse, and influenced on a subjective body of thoughts. There is no global definition of TQM and companies often show highly diverse interpretations and uses [4]. It is generally accepted to describe TQM as a philosophy equipped with a set of tools and techniques with the target to increase customer satisfaction and continuous improvement. Having a mindset of satisfying the needs of the internal customer is achieved through tactics for changing a company's culture and structured technical techniques [5] and [6]. TQM is also understood as a management system consisting of values, techniques, and tools, as three interdependent components [7]. Common used tools and techniques are summarized by [8] and presented in Table 1.

Tools and techniques, as portrayed in Table 1, are described to be practical methods, skills, means, or mechanisms used for a specific circumstance [2]. Their purpose when applied is to achieve positive change and improvement [2] and [9]. In case the wide spectrum of TQM tools and techniques are not applicable a new tool must be tailored to solve a specific problem. This tool generation process entails efforts for data analysis, visualization, and interpretation. Knowledge Discovery in Databases (KDD) for example offers a general framework to generate knowledge from a dataset.

**Table 1** Quality tools and techniques used in industry [8]

| The seven basic quality control tools | The seven management tools | Other tools | Techniques |
|---|---|---|---|
| Cause and effect diagram | Affinity diagram | Brainstorming | Benchmarking |
| Check sheet | Arrow diagram | Control plan | Department purpose analysis |
| Control chart | Matrix diagram | Flow chart | Design of experiments |
| Graphs | Matrix data analysis method | Force field analysis | Failure mode and effects analysis |
| Histogram | Process decision program chart | Questionnaire | Fault tree analysis |
| Pareto diagram | Relations diagram | Sampling | Poka yoke |
| Scatter diagram | Systematic diagram | | Problem solving methodology |
| | | | Quality costing |
| | | | Quality function deployment |
| | | | Quality improvement teams |
| | | | Statistical process control |

## 2.2 *Pattern Identification Through Knowledge Discovery in Databases*

Knowledge Discovery in Databases (KDD) can be described as the complete process of discovering useful knowledge from data [3]. The part of identifying patterns that is relevant for further analysis is a core element [3] and referred to as data mining, which is a specific procedure of KDD [1]. Harding et al. [10] define data mining as a concept and algorithm mix consisting of machine learning, statistics, artificial intelligence, and data management. But terminology is ambiguous and one must be aware that different communities hold different terms with same meanings. Fayyal [3] compiled across communities the following names for data mining, which is the term used in this paper: knowledge extraction, information discovery, information harvesting, data archeology, and data pattern processing.

Figure 1 portrays the process of KDD that is described by [3] and starts by selecting from a database the relevant target dataset. Preprocessing the target data is relevant to remove noise and outliers for the data to be ready for further

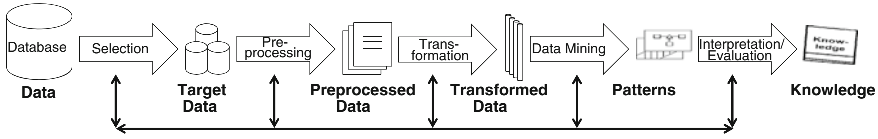


**Fig. 1** The KDD process c.f. [3]

processing. On the cleaned data the thoroughly identified or developed data mining algorithm can be performed to generate patterns. The produced patterns must be interpreted and evaluated for the knowledge to be discovered.

Fayyal et al. [3] mention that the data mining algorithm can be composed of a specific mix of the model (the function of the model and the representation form), the preference criterion (some form of goodness-of-fit function of the model to the data), and the search algorithm (the specification of an algorithm for the path of finding).

Recent reviews on KDD and data mining for manufacturing exist and indicate the popular use of KDD [1, 10, 11]. Some reviews also deal with KDD and data minding surrounding the topic of quality improvement [11] such as predictive maintenance, fault detection, quality assurance, product/process quality description, predicting quality, classification of quality, and parameter optimization.

Köksal et al. [11] reported an increasing use of data mining applications for quality related tasks. In those tasks applications for predicting quality are the most widely used ones followed by classification of quality and parameter optimization. There are plenty applications or algorithms respectively to perform data mining. Some of them are maps for classification, regression, or clustering of data. Others are summaries, dependency modeling of variables, and sequence analysis [3]. Model representation reach from decision trees over linear and non-linear models to case-based reasoning and probabilistic graphical dependencies.

## 2.3 The Herfindahl–Hirschman Index

The Herfindahl–Hirschman Index (HHI) also referred to as the Herfindahl Index is a method to measure concentration [12]. Unaware of Hirschman's published work Herfindahl developed a similar method of measuring concentration at a later date [12, 13, 14]. The equations are identical with the only difference of the square root of Hirschman's index on Herfindahl's equation [13]. Herfindahl's equation is depicted in (1).

The index is the sum of the individual market shares of the participants in a specific market. Thus one can state:

$$HHI = \sum_{i=1}^{n} a_i^2 \tag{1}$$

$$\text{with } a_i = \frac{x_i}{\sum_j^N x_j} \tag{2}$$

The index is originally used in economics to measure competition in the marked and the effects of mergers or to measure concentration of income of households [12]. It is an adopted method of the department of Justice and Federal Reserve and currently in use to analyze merger intents [12].

Transferring this sense into the realm of quality can lead to the following understanding: Each imperfect process of a production step produces output—NCs—and the concentration to single machine among the total number of producers is measured. For every production step (n-1 and n) the concentration of every single NC is measured. A high HHI is referring to a high concentration, which can be understood that the great majority of NCs is produced by (a) single machine(s). Complementing to the HHI a visualization of all machines with their NC occurrences may highlight the critical ones and might even help in identifying root causes. This has to be proven after investigating the root cause.

KDD in engineering and quality related topics is well established and known. However, data mining algorithms are plentiful and there is no strict definition for existing models. This paper integrates a well-known statistical measure from the field of economics as the data mining algorithm within the KDD methodology. When applying the suggested method on a dataset it can be used as a quality tool for fault detection in manufacturing.

## 3 Pattern Identification Methodology

In order to improve production processes and learn from data an adapted methodology for pattern identification is suggested. The methodology is alike to the KDD methodology with a concentration measuring method from the field of economics as the data mining sub-step. The resulting patterns provide the basis for interpretation and knowledge creation. Firstly, one can identify which NC occurs concentrated at individual machines. Secondly, one can identify at which individual machines specific NCs occur most. Additional knowledge serves to highlight possible origins of NCs.

To obtain results one must first gather quality related data of the manufacturing process, namely recording the NCs of the production processes of relevance. The data of relevance must include information about the machines that the product passed of all the relevant production steps and the type of NC that was identified at the inspection station. The applied methodology in Fig. 2 is an abbreviated and adapted KDD methodology as previously presented in Fig. 1.

Firstly, one must gather data over a determined period of time. In order to retrieve data in a reliable manner the format of the input data file must be defined. When having the input file the preprocessing of data can be started. This includes

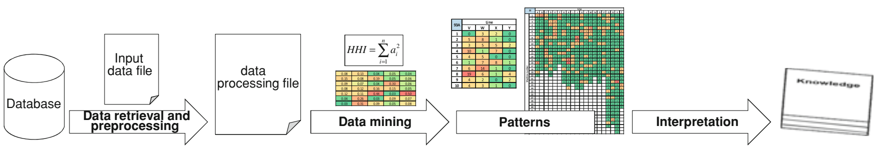


**Fig. 2** The methodology of the study

**Table 2** Retrieved data input file from database

| Step n-1 | | | | Step n | Inspection | | | |
|---|---|---|---|---|---|---|---|---|
| Barcode | Machine | Date | Time | Machine | NC type | Decision | Date | Time |
| 1***622 | V1 | 2010-12-01 | 02:32:27 | A16 | NC15 | Scrap | 2010-12-01 | 00:11 |
| 1***699 | X9 | 2010-12-01 | 00:04:53 | R12 | NC3 | Repair | 2010-12-01 | 00:32 |
| 1***244 | Y8 | 2010-12-01 | 00:03:38 | G19 | NC2 | Repair | 2010-12-01 | 00:33 |

spread sheet calculation which must be tailored or integrated to the previously obtained input data file. In this paper the Herfindahl–Hirschman index is the measure that serves as algorithm for the data mining sub-step.

The preprocessed data file provides information for every single NC: the number of incidents, the appraisal decision, and the machines the product had passed during production as presented in Table 2.

With basic calculations one can compute the occurrences of NCs according to machines on basis of the retrieved data as presented. This results in a matrix with machine number and NC type filled with the number of incidents as presented in Table 3.

Applying the statistical formula (1) and (2) to the tables one can calculate the HHI for a specific NC for one production step. After calculating for all NCs the HHI for each production step one gains information about how concentrated NCs are occurring at single machines. A specific visualization shall help in identifying the NCs with higher concentration to production machines within each production step.

The visualization in the form of patterns consists of two parts. Firstly, the concentration of a specific NC among the machines of each of the two production steps is calculated. This gives general information about whether a specific NC appears concentrated at individual machines within one production step, as one can see in Table 4. Secondly, the concentration index number of every NC for the two production steps is compared. This gives information about whether the NCs are very common and related with several machines or whether the NCs are appearing very concentrated to single machines.

## 4 The Application Case

The suggested methodology in Sect. 3 is applied to an application case of a high technology automotive parts producer. The company maintains a quality management system and is certified by quality standards such as DIN EN ISO 9000, DIN EN ISO 9004, and ISO/TS 16949.

**Table 3** Preprocessing of data to identify the number of occurrences according to machines

| Step n-1 | NC1 | NC2 | … | NCn | Step n | NC1 | NC2 | … | NCn |
|---|---|---|---|---|---|---|---|---|---|
| Machine 1 | x | y | … | z | Machine 1 | x | y | … | z |
| Machine 2 | … | … | … | … | Machine 2 | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … |
| Machine n | u | v | … | w | Machine n | u | v | … | w |

**Table 4** The HHIs of production step n-1 and n according to the NCs

| | a | b | c | d | e |
|---|---|---|---|---|---|
| 1 | 0.08 | 0.13 | 0.04 | 0.05 | 0.04 |
| 2 | 0.15 | 0.08 | 0.19 | 0.05 | 0.06 |
| 3 | 0.09 | 0.07 | 0.04 | 0.30 | 0.06 |
| 4 | 0.08 | 0.12 | 0.16 | 0.15 | 0.05 |
| 5 | 0.12 | 0.11 | 0.44 | 0.03 | 0.50 |
| 6 | 0.04 | 0.26 | 0.03 | 0.09 | 0.07 |
| 7 | 0.03 | 0.31 | 0.09 | 0.05 | 0.08 |

Step n-1

| | a | b | c | d | e |
|---|---|---|---|---|---|
| 1 | 0.03 | 0.05 | 0.01 | 0.01 | 0.03 |
| 2 | 0.05 | 0.05 | 0.02 | 0.07 | 0.02 |
| 3 | 0.04 | 0.02 | 0.01 | 0.07 | 0.03 |
| 4 | 0.01 | 0.02 | 0.04 | 0.03 | 0.01 |
| 5 | 0.06 | 0.02 | 0.09 | 0.01 | 0.13 |
| 6 | 0.00 | 0.11 | 0.01 | 0.03 | 0.08 |
| 7 | 0.00 | 0.08 | 0.03 | 0.01 | 0.04 |

Step n

## *4.1 Problem Description*

The production process is composed of several production steps that do require dominating well different scientific fields. Mixing of raw materials, assembling subassemblies, and an injection akin process characterize the production steps. Each step consists of numerous machines and every product passes exactly one machine at every step. Barcodes are attached to the product and every machine equipped with a barcode scanner saves the product machine relationship to a database. Thus the database offers information about the history of the path of the production steps and the individual machines that the products took. An inspection station is installed at the end of the manufacturing line and humans inspect manually the products upon conformance to requirements. Conforming products are forwarded to be shipped to the customer. The type of NC is added to the information system and a decision of the recoverability through rework or the product to be scrapped is made. Due to the complex nature of the product and its processes causes of nonconformities are manifold and attributable to process failures, machine stoppages, incorrect composition, quality of raw materials, or human error. In addition NCs are often only detectable at the finished product. They vary from minor cosmetic to severe imperfections that may not be recoverable. The company uses brain storming approaches and is focused on reducing scrap rates of specific NCs and form multi-departmental teams to initiate investigations. But root cause identification has proven to be difficult, which is why the tool in this paper was developed.

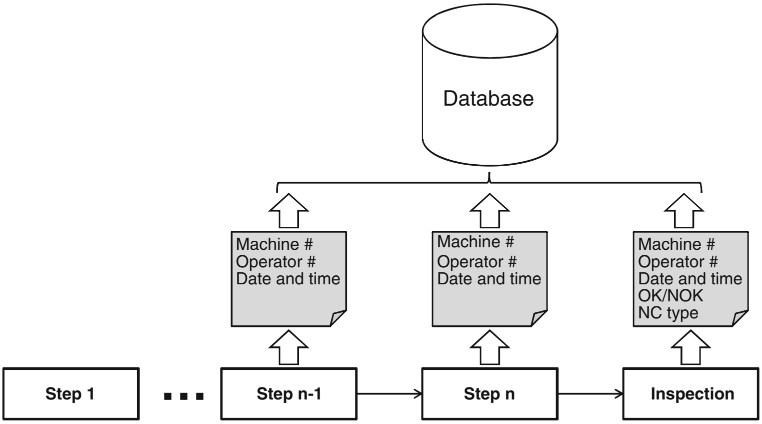


**Fig. 3** The production flow and data input to the database

Figure 3 illustrates the production steps and the input of information into the database. At the last two production steps before the inspection station corresponding data is input into the database. This data contains information about the specific production machine, the involved operator as well as time and date.

## *4.2 Overview of the NC Concentration*

After applying the tool's methodology one can build the tables illustrated below. Table 4 presents the concentration of all NCs for the two production steps. The numbers in the cells are the HHI results for each NC at the two production steps. Results for step n-1 are depicted on the left and for step n on the right side of Table 4. Each field is the concentration of NC incident of one specific NC of a production step.

Table 5 provides information about which NC corresponds to the HHI presented in the fields of Table 4 by comparing the horizontal and vertical index numbers and letters. NC18 in field '4c' for example has an HHI of 0.16 in step n-1

**Table 5** Corresponding NCs for HHI in Table 4 for step n-1 and n

| | a | b | c | d | e |
|---|---|---|---|---|---|
| 1 | NC1 | NC8 | NC15 | NC22 | NC29 |
| 2 | NC2 | NC9 | NC16 | NC23 | NC30 |
| 3 | NC3 | NC10 | NC17 | NC24 | NC31 |
| 4 | NC4 | NC11 | NC18 | NC25 | NC32 |
| 5 | NC5 | NC12 | NC19 | NC26 | NC33 |
| 6 | NC6 | NC13 | NC20 | NC27 | NC34 |
| 7 | NC7 | NC14 | NC21 | NC28 | NC35 |

and an HHI of 0.04 at step n. Both numbers are not comparable with each other because the numbers of machines are different for the two production steps. However, within one production step they do become comparable with each other. NC33 and 19 (Field 5e and 5c) show the highest HHIs for step n-1. NC33 and 13 (Field 5e and 6b) show the highest HHIs for step n.

## *4.3 Result Tables of the Production Steps*

Production step n-1 consists of fewer machines than the ones in production step n. The machines at each production step operate in parallel and exactly one machine at each production step is passed for the product to be produced. The route that the product takes from one production step to another depends on the set-up configuration of the machines. Different configurations allow producing products varying in a size, composition, and shape.

Following the suggestions of Table 4 the highest NC occurrences shows NC33 for both production steps. The NC occurrences at the machines are delineated in Fig. 4. Each field of the matrices represents one specific machine. The machines are located in lines and are numbered. Step n-1 consists of four lines (V, W, X, and

| NC 33 | Line | | | |
|---|---|---|---|---|
| | V | W | X | Y |
| 1 | 2 | 0 | 1 | 0 |
| 2 | 1 | 3 | 3 | 99 |
| 3 | 3 | 0 | 2 | 1 |
| 4 | 1 | 0 | 0 | 0 |
| 5 | 1 | 0 | 0 | 0 |
| 6 | 4 | 0 | 1 | 0 |
| 7 | 1 | 0 | 1 | 2 |
| 8 | 0 | 0 | 1 | 0 |
| 9 | 0 | 1 | 3 | 2 |
| 10 | 4 | 4 | 0 | 0 |

| NC33 | Line | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Machine number | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 15 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 47 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| 10 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 6 | 0 | 0 |
| 14 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 0 | 0 |
| 15 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 16 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 2 | 0 | | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| 19 | 0 | | | 0 | | | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | | | 0 | | | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 21 | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 7 | | 0 | 0 | 0 | 0 |
| 22 | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 18 | | 0 | 0 | 0 | 0 |
| 23 | | | | | | | | 0 | | 0 | 0 | | | | | | 0 | 0 | 0 | 1 |
| 24 | | | | | | | | 0 | | 0 | 0 | | | | | | 0 | 0 | 0 | 0 |
| 25 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 |
| 26 | | | | | | | | | | | | | | | | | 0 | 1 | 0 | 0 |
| 27 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 |
| 28 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 |
| 29 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 |
| 30 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 |
| 31 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | |
| 32 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | |
| 33 | | | | | | | | | | | | | | | | | 0 | 1 | 0 | |
| 34 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | |
| 35 | | | | | | | | | | | | | | | | | 0 | 0 | 0 | |
| 36 | | | | | | | | | | | | | | | | | 1 | | 0 | |
| 37 | | | | | | | | | | | | | | | | | | | 0 | |
| 38 | | | | | | | | | | | | | | | | | | | 0 | |

**Fig. 4** Result presentation of process step n-1 (*left*) and n (*right*)

Y) each with 10 machines. Step n consists of 20 lines (A, B, …, T) each equipped with machines varying in number between 16 and 38.

The left matrix in Fig. 4 presents the number of occurrences of NC33 for every machine of production step n-1. As one can see machine number Y2 is related with 99 NCs among a total number of 141 NCs. All other machines of this production step show numbers of occurrences between zero and four. The right matrix in Fig. 4 presents the number of occurrences for every machine of production step n. In comparison to step n-1 the NCs occur more fragmented. Machine number R8 has the highest number of NCs (47). Machine number R7, R14, and O22 show number of occurrences of 15, 18, and 13. All other machines do not produce NCs or only few.

The above obtained results highlight the high concentration of NCs to machine Y2 of production step n-1. Thus, the number of occurrences is very concentrated to one single production machine and steps for further analysis of root causes of the NC must be done. A possible tool for doing that can be the cause and effect diagram from Table 1. This lists all possible factors of contribution such as operator, machine, method, or material and one can observe and investigate with this structured help the root cause if there is one to find.

A first observation may indicate that this machine (Y2) is the main contributor of the NC and that the root cause might be found when further analyzing this machine. However, this information shall be taken as a direction and invite for further investigation and must be considered cautiously. Additional information is required to gain higher certainty of this assumption. The methodology indeed does take into account the total number of a specific NC. But it does not consider the total number of the products based on the set-up configuration of the production machines. This means the method does only take into account NC types regardless of further product features, such as size, shape, or composition.

Furthermore, when comparing the two matrices in Fig. 4 there is a mismatch in total numbers of NCs. While step n-1 has a sum of 141 occurrences of NC33, step n shows 155 occurrences. Theoretically both numbers should match since every product passes exactly one machine at each step. This inconsistency has to do with incomplete datasets, which are attributable to technical defects of scanned barcodes or neglect of data entry by operators, among others.

Similar matrices as presented in Fig. 4 are obtainable for all other NCs presented in Table 5 and ready for interpretation to discover knowledge. But presenting these figures would exceed the frame of this paper.

## 5 Conclusion

This paper proposes a methodology to help analyzing root causes of NCs. Visually represented discovered knowledge supports to identify possible root causes in mass production. An economic concentration measure (HHI) is integrated as the data-mining element of the KDD method. The proposed methodology can be used as a quality tool and is validated by an application case from the automotive industry. Data tables are generated with different cell shadings according to the concentration of specific incidents. An incident in this context is an occurrence of a specific NC. These tables may help in disguising main contributors of NCs exposing them to the user to be further investigated.

Results indicate that with the applied visualization technique it is possible to identify single machines that are highly related with specific NCs and may be the originator. Further investigation of the likelihood of being the originator of NCs is required as the next step.

The methodology integrates several disciplines namely IT, quality, and economics. A well-known and established economical concept finds in quality an additional field of application. Quality engineers of industrial companies may find interest in using the tool to identify root causes in high volume production with numerous machines and diverse NCs. According to the presented results the visual representation of the data helps to quickly understand which NCs show the highest concentrations to machines at different production steps. The highly visual results ease the interpretation and further analysis to constantly improve production quality.

While initial findings are promising, further research is necessary. As a start, the success rate of being able to identify the root cause of an NC after having highlighted a possible contributor must be identified to further validate this tool. This tool is currently developed to be used offline. With further development and integration to the installed IT system of a company it can turn into an online tool. Additional development can even automatically alert responsible persons when a critical value of concentration is exceeded and further investigations of root causes become attractive.

As this paper demonstrates combining knowledge of different disciplines can result in new emerging methods, tools, and knowledge. The authors highly encourage cross- and interdisciplinary research.

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## References

1. Choudhary AK, Harding JA, Tiwari MK (2009) Data mining in manufacturing: a review based on the kind of knowledge. J Intell Manuf 20(5):501–521
2. McQuater RE, Scurr CH, Dale BG, Hillman PG (1995) Using quality tools and techniques successfully. TQM Mag 7(6):37–42
3. Fayyad U, Piatetsky-Shapiro G, Smyth P (1996) The KDD process for extracting useful knowledge from volumes of data. Commun ACM 39(11):27–34
4. Bounds GM (1994) Beyond total quality management. Toward the emerging paradigm. McGraw-Hill, New York
5. Hradesky JL (1995) Total quality management handbook. McGraw-Hill, New York

6. Rampey J, Roberts H (1992) Perspectives on total quality. In: Proceedings of total quality forum 4, Cincinnati, Ohio
7. Hellsten U, Klefsjö B (2000) TQM as a management system consisting of values, techniques and tools. TQM Mag 12(4):238–244
8. Dale BG, McQuater R (2009) Managing business improvement and quality: implementing key tools and techniques. Wiley (Business Series), London
9. Donauer M, Azevedo A, Peças P (2012) Evaluating the effects of soft TQM tools on quality costs by means of simulation: a case study from the automotive industry. In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing (FAIM), Helsinki, pp 413–421
10. Harding JA, Shahbaz M, Srinivas, Kusiak A (2006) Data Mining in manufacturing: a review. J Manuf Sci Eng 128(4):969–976
11. Köksal G, Batmaz İ, Testik MC (2011) A review of data mining applications for quality improvement in manufacturing industry. Expert Syst Appl 38(10):13448–13467
12. Rhoades SA (1993) The Herfindahl-Hirschman index (cover story). Fed Reserve Bull 79(3):188
13. Hirschman AO (1964) The paternity of an index. Am Econ Rev 54:761–762
14. Hirschman AO (1969) National power and the structure of foreign trade. University of California Press, California

# Downtime Model Development for Evaluating Operational Performance of Workover Activities in AGOCO

**Haitham Mansour, Munir Ahmed and Ghaith Abdulrahman**

**Abstract** Improved efficiency can be achieved through the effective management of efforts to improve productivity. Effective troubleshooting requires an ability to observe changes in workover performance over time. The investigation of the cause of the downtime has been made and takes steps to prevent the problem from re-occurring in the workover procedures. The fact of the matter is that there are three types of problems mostly encountered with workover procedures: workover design errors; poor operation; poor workover practices. The objective of this work is to minimize production losses by identifying downtime factors and eliminating the causes by generating Key Performance Indicators (KPIs) to evaluate and enhance the procedures of the workover. To achieve this objective, this paper presents a downtime model framework to address this issue. Using this model, the generic factors and processes related to downtime are identified, and the impact of downtime is quantified. The work findings highlight how various factors and processes interact with each other to create downtime, and mitigate or exacerbate its impact on workover performance. It is suggested that production engineering departments at Arabian Gulf Oil Company (AGOCO) need to adopt proactive equipment management and workover programs to minimize the impact of downtime.

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# 1 Introduction

The objective of every oil industry is to make profit and not to encounter loss. It is therefore necessary to look into reducing operating costs and maintenance, instead making way for increased profit. The focus on efficient use of workover rigs has increased during the last few years; a high degree of workover utilization has a negative impact on the production process [1].

In workover business there are several key issues such as: Time, cost, health, safety and environment, technology application. Those key issues have to be well managed for a successful workover operation. Developing performance metrics is a significant stage in the process of performance evaluation as it includes related indicators that speed up the performance of the activities [1]. It is important to identify a set of KPIs to establish effective performance evaluation metrics for the activities under consideration. A Key Performance Indicators Drilling Database has been developed since 2008 [2]. The Drilling Process is observed as the generation, application, and optimization of an engineering strategy to consistently drill more productive and cost effective wells. The results are supported and integrated planning and awareness through the presentation of recommendations an implementation of operational best practices and the mitigation of drilling events and non-productive time (NPT) generators [3]. The results have validated the value chain obtained from this application. The use of this tool in conjunction with experience can revamp operational performance and safeguard expenditure. Additionally, it can maintain operational integrity and maximize an operation's potential. Its main phase applies an engineering design based on risk analysis and planning, detailed and strict execution, as well as a thorough post-job evaluation [2].

The workover activities include any interruption/non-productive activity that may have occurred, regardless of whether caused by personnel, equipment or services rendered by contractor, operator or third party. Improved efficiency can be achieved through the effective management of effort to deduce DT and improve productivity. Each year, the number of ESP failures is increasing, adversely affecting lifting costs, the workover rigs' utilization, and total oil production. The production loss of each idle well is evaluated as its average daily flow rate under regular operation, multiplied by the number of days its production is interrupted [4].

Oil production needs many procedures to keep the well running, the well needs equipment to produce, and the equipment needs tools to install or uninstall [2]. The aim of this investigation is to review the performance and establish KPIs for workover activities of rigs in order to increase production of oil wells.

## *1.1 Workover Processes*

Workover usually involves a service rig to solve the problems in oil wells with a proposed program. These procedures of the workover include the main stage of workover processes. The first step in the process is to design a workover plan; the

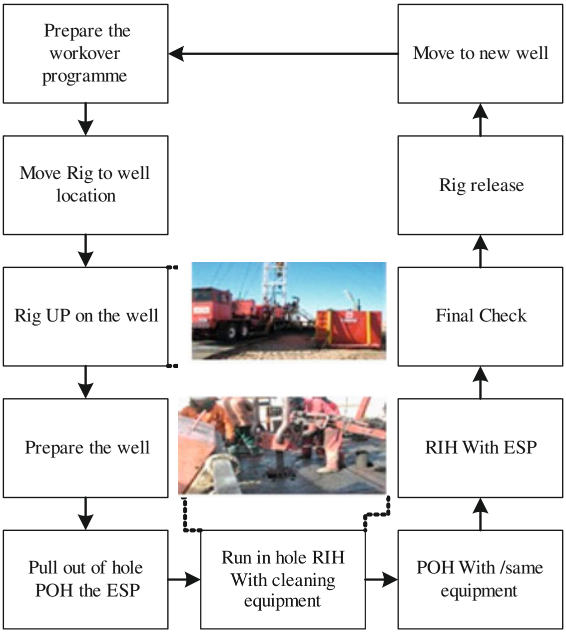



**Fig. 1** Workover processes

production engineering department at the oilfield will give the order to the rig to move to the location, then there are many procedures which must be followed to return the oil well to normal production, see Fig. 1. The procedures such as the rig up (R/U), rig down (R/D), and ESP installation, Run in Hole (RIH) and pull out of hole (POH) of the equipment such as ESP are the necessary steps to return the well to production.

## 2 Case Study

The efficiency of the workover is based on historical data that can be used to predict future performance in each rig. The area of this study focuses on workover rig processes in the oilfield and investigates the impact of workover activities on production at Arabian Gulf Oil Company AGOCO. Sarir oilfield which is owned by AGOCO in Libya has been selected as a case study to investigate workover and ESP problems. The workover rigs operated 12 h from 6 a.m. to 6 p.m. This meant the rigs had been working at a maximum operation level. The data from four workover rig activities for one year is obtained directly from the daily workover activities.

After the concept of TWT and BTWT had been developed depend on the workover processes, rig efficiency for each workover job in each well are calculated using the relationship shown in Table 1 [1]:

**Table 1** Rig efficiency for workover activities wells for various

| Rig no | | TWT | BTWT | Rig efficiency (%) | Avg efficiency (%) |
|---|---|---|---|---|---|
| Rig 1 | well 1 | 75.5 | 44.5 | 59 | 64 |
| | well 2 | 85 | 44.5 | 52 | |
| | well 3 | 70 | 44.5 | 64 | |
| | well 4 | 54 | 44.5 | 82 | |
| | well 5 | 70 | 44.5 | 64 | |
| Rig 2 | well 1 | 81.5 | 49 | 60 | 71 |
| | well 2 | 88 | 49 | 56 | |
| | well 3 | 65.5 | 49 | 75 | |
| | well 4 | 57.5 | 49 | 85 | |
| | well 5 | 61.5 | 49 | 80 | |
| Rig 3 | well 1 | 75.8 | 48.5 | 64 | 70 |
| | well 2 | 84 | 48.5 | 58 | |
| | well 3 | 69 | 48.5 | 70 | |
| | well 4 | 52 | 48.5 | 93 | |
| | well 5 | 75.8 | 48.5 | 64 | |
| Rig 4 | well 1 | 71.5 | 47.5 | 66 | 68 |
| | well 2 | 87.5 | 47.5 | 54 | |
| | well 3 | 74 | 47.5 | 64 | |
| | well 4 | 54 | 47.5 | 88 | |
| | well 5 | 66.5 | 47.5 | 71 | |

$$Efficiency = \frac{BTWT}{TWT} \tag{1}$$

where:

$$\begin{aligned} \text{BTWT (hours)} = {} & \text{total best (hostorical) time achieved by workover rig} \\ & \times \text{(minimum time)} = \text{moving} + \text{Rig Up} \\ & + \text{pulling ESP} + \text{RIH with equipment} + \text{POH with equipment} \\ & + \text{RIH with ESP} + \text{Final check} + \text{Rig release} \end{aligned}$$

$$\begin{aligned} \text{TWT (hours)} = {} & \text{total workover time (actual time)} = \text{moving} \\ & + \text{Rig Up} + \text{pulling ESP} + \text{RIH with equipment} \\ & + \text{POH with equipment} + \text{RIH with ESP} + \text{Final check} \\ & + \text{Rig release} \end{aligned}$$

Table 2 shows the average efficiency of the rigs and also the efficiency of the rigs for each well, including the operational costs. The variation in efficiencies identifies the potential for improvement. For example, the highest efficiency is 93 % for rig 3 at well 4 and the lowest efficiency is 52 % at well 2 for rig 1. Therefore it is possible that in practice all the rigs could perform at 93 % efficiency

**Table 2** Evaluate efficiencies gaps

| Rig no. | Average rig efficiency (%) | Highest efficiency achieved by rig (%) | lowest efficiency achieved by rig (%) | Gap identified for improvement (%) |
|---|---|---|---|---|
| Rig 30 | 1 for well 2 | 64 | 82 | 52 |
| Rig 29 | 2 for well 2 | 71 | 85 | 56 |
| Rig 35 | 3 for well 2 | 70 | 93 | 58 |
| Rig 34 | 4 for well 2 | 68 | 88 | 54 |

given the right procedures adopted with very little variation. The variation in rig performance is also shown in Table 1.

## 3 Quantification of DT Impact in Workover Rigs

DT is defined as the period in which the equipment assigned to work is not available because of breakdown [5]. DT is also defined as the time during which equipment is not working because it is undergoing repair or adjustment [6]. In this paper, the average DT has been calculated as in Fig. 2, it impacts the performance of workover in terms of time.

In this work, the factors that affect workover performance need to be set. The results of DT in workover operation are shown in Table 3, and identify the generic factors related to DT and the consequences that may unfold during workover operation.

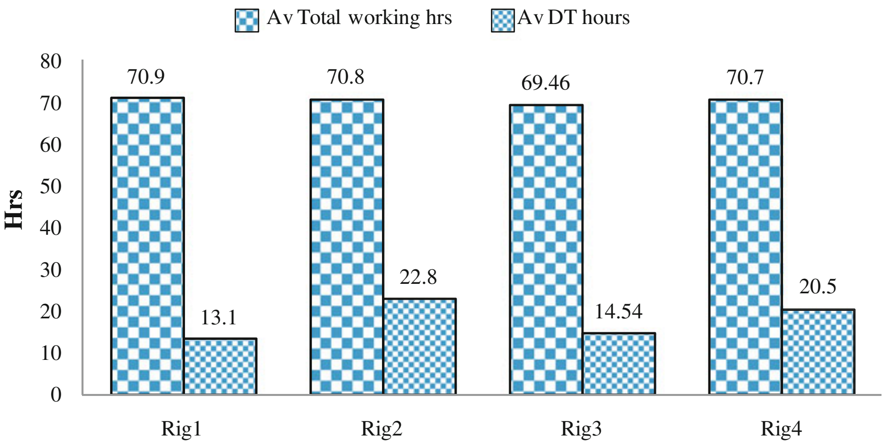



**Fig. 2** Average downtime hours for each workover rig

**Table 3** Summary statistics for rigs DT

| | Rig 1 | Rig 2 | Rig 3 | Rig 4 |
|---|---|---|---|---|
| Av. rig efficiency (%) | 64 | 71 | 70 | 69 |
| Av. TWT | 70.9 | 70.8 | 69.4 | 70.7 |
| Av. DT hours | 13.1 | 22.8 | 14.54 | 20.5 |
| Av. DT cost £ | 19926.3 | 33816.3 | 20863.9 | 33514 |
| DT cost (%) | 20 | 34 | 20 | 30 |

The variation in DT and its impact on different workover rigs reflects the condition of the rig equipment, the quality of the rig equipment, the quality of workover program and the company's operating policies, the location of the well, and the nature of the work [7].

To forecast and schedule maintenance activities in order to reduce operational and workover cost, a monitoring system to predict downtime must be adopted by looking into the in-depth analysis of downtime problems and operation process procedures [6, 8]. Figure 3 below shows the effect of DT on different rigs. The average DT in each activity has been found, the activities such as running and pulling the ESP has high DT. The difference in DT reflects the activities' characteristics, availability of services in the rig, job conditions, and the need for timely maintenance as perceived by the management. The improvement in workover procedures can greatly reduce the DT caused by incorrect operating procedures, while a good workover program reduces DT caused by poor operation and poor workover practices.

It is clear from the above problem that performance measurement is part of a system that needs to be developed to assist managers in the use of measures as part of an overall PED activities system.

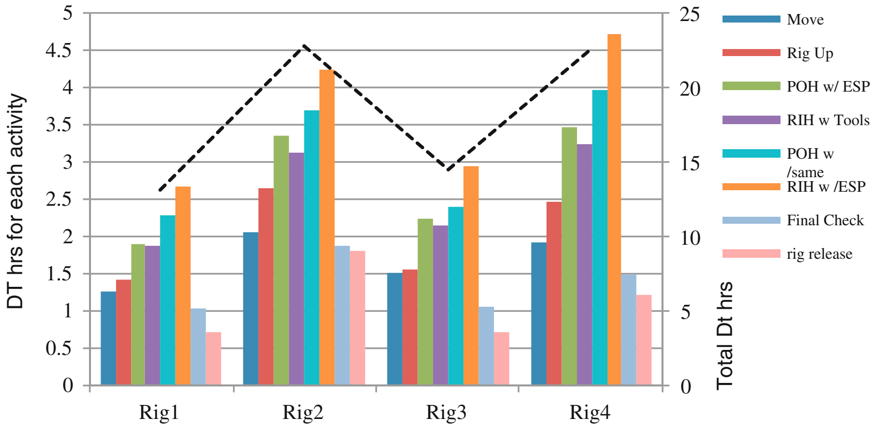



**Fig. 3** Average Downtime hours for each activities

## 4 Downtime and its Consequences

In this work, we present case studies on AGOCO's workover rigs in which we attempt to quantify the impact of DT. The details of the analysis are presented in four rigs on Sarir Oilfield. In addition to quantifying the impact of DT, the factors and processes related to DT are analyzed and discussed. The analysis of the impact of DT have been highlighted in Fig. 4, particularly from a management perspective where other industries have highlighted that factors related to plant and equipment breakdown must be considered in assessing the impact of DT.

**The factors are:**

- **Site-related factors**

As shown in Fig. 5, examples of site-related factors include poor working conditions, uncertainties during rig operation and location of oil well. The first two factors may affect the performance of equipment, for example the workover rig move has a difficult and rugged terrain, moving through soft sand which may cause rig move time delay.

- **Equipment-related factors**

Factors that are related to workover equipment are its age, type, quality, complexity of operation, and degree of usage [9].

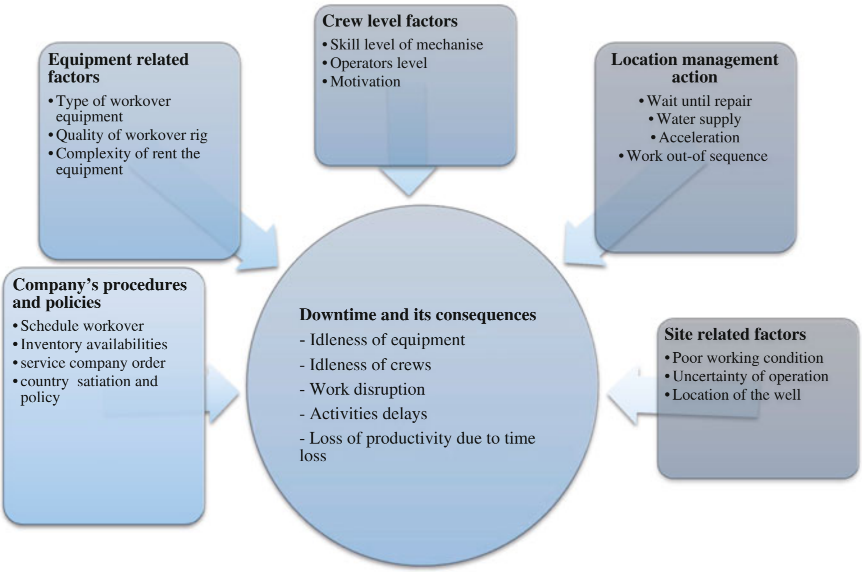
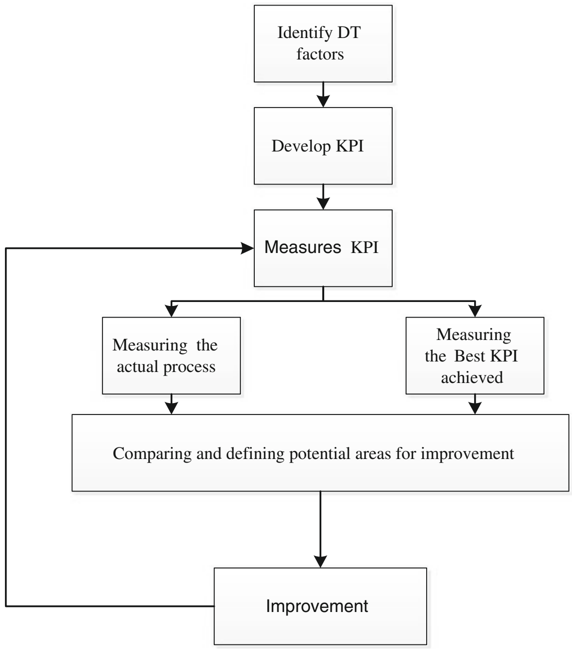



**Fig. 4** Factor analysis

**Fig. 5** Model for monitor of workover operations




- **Crew-level factors**

These factors are related with human aspects of crews who are involved in the pipe change, operation procedures, and workover process. The operator's skill is one of the most important factors and it affects the operator's performance and the direct cost of DT through workover rig efficiency [10].

- **Company's procedures and policies**

A company must, according to its standard workover procedures and policies, return the failure wells to production; this includes workover policies, replacement decisions, inventory control, standby repair and maintenance facilities, and production policy.

- **Site management arrangements**

Site management may impact DT in a number of ways, such as waiting for broken equipment to be repaired, changing resources, supplying the workover rig with water, waiting for the service companies to do some operations at the rig, transferring crews to other operations or sites, and changing the sequence of work. The DT could be reduced if they implemented these in a proper way [6].

A Downtime framework provides benefits that can help the company to improve the performance of workover activities.

## 5 Proposed Framework

In this work, the proposed framework has been developed, as shown in Fig. 5. The framework helps the PED in AGOCO in an effective way, and is expected to assist the company in controlling the DT causes in workover procedures.

The stages of the proposed framework are as follows:

- The process inputs.
- Identify DT factors that cause losses in workover processes.
- Develop KPI.
- Measuring the requirements of the KPI in the actual process.
- Identifying the best KPI achieved.
- Comparing and defining potential areas for improvement.
- Application of the improvements.

## 6 KPIs to Measure Workover Performance

In the oil industry, every well in the oilfield's product line is purely to produce the oil; it has many processes to keep the oil well producing. The oil well is as a small manufacturing plant and each plant needs different equipment as the conditions for each plant are unique. The analyses of the impact of DT have been highlighted, particularly from a management perspective from other industries which have highlighted that factors relating to workover and equipment breakdown must be considered in assessing the impact of DT.

In this research, a set of KPIs have been developed to measure workover performance. The output report will be to set specific objectives for improvement by applying the Best Practice tools to reduce waste in the workover processes. The KPIs are a tool to assist in the production departments in the oilfields, both to measure and also to translate the results into improved activity [21]. The basis of calculation of the KPIs is through the interpolation of the actual and target performance of the activities.

The KPIs have been developed to assist in the production departments in the oilfields, to measure and also to translate the results into improved activity [21]. In this research, it has developed a set of KPIs to evaluate workover performance as in the Table 4.

Key performance indicators identify gaps between current and desired performance and highlight where action must be taken to make improvements. An effective KPI measures performance and puts that performance into context using targets (such as Time of pulling of ESP per 1,000 feet.), or (Time of Run in hole (RIH) with ESP per 1,000 feet.). KPIs reflect the workover objectives, therefore they differ from one workover to the other.

**Table 4** Key downtime performance indicators

| KPI | Actual | Achieved at field | Gap |
|---|---|---|---|
| Average workover move time | 13 | 8 | 5 |
| Average rig workover hours per day | 9 h | 11 h | 2 |
| Workover rigs in operation (%) | 85 | 95 | 10 |
| Time of pulling of ESP per 1,000 feet | 1.3 h | 1 h | 0.3 |
| Time of run in hole (RIH) with ESP per 1,000 feet | 1.25 h | 0.91 h | 0.34 |
| Non-productive workover time in activities (%) | 18 | 11 | 7 |
| Workover success rate (%) | 78 | 91 | 13 |

## 7 Way for Improvements

Improved efficiency can be achieved through the effective management of effort to improve productivity [3, 5]. Effective troubleshooting requires an ability to observe changes in performance over time, and in the event of a failure, the capacity to thoroughly investigate the cause of the DT and take measures to prevent the problem from re-occurring.

The PED engineers must prioritize those factors that cause the most downtime hours and the most events. They should select the top three for each and then solve them. The fact of the matter is that there are three types of problems mostly encountered with workover [11]:

- Workover design errors.
- Poor operation.
- Poor workover practices.

The knowledge achieved through the model could also be utilized in future workover programs for other oilfields. The Reports produced by the output of the model will assist PED managers in their understanding and management of the risks associated with workover programs. The developed model tool is a possible solution for analyzing the impact of DT factors in workover operation processes.

The improvements can be achieved with a basic knowledge of how much is needed to improve workover activities to reduce the cost of the downtime and rig utilization which can be achieved from:

- Less workover rig activity for well servicing.
- Enhanced ESP equipment installation procedures.
- Enhanced in workover programs design.

## 8 Conclusion

The model presented in this paper has identified generic factors and processes related to DT, and portrayed graphically how they may interact to cause DT and its consequences. The data from four rigs at Sarir oilfield have been used to explain the framework of the model. The findings have highlighted the factors that impact the workover performance and created downtime. It is suggested that production engineering departments at AGOCO want to implement proactive equipment management and workover programs to minimize the impact of downtime. The framework developed in the study is a new methodology for managing the workover activities and could assist PED mangers in reducing the impact of DT by providing insight into equipment management. The improvement area has been highlighted; the KPIs have been developed to assist the engineers in Sarir Oilfield to evaluate the performance of the rigs. Therefore, PED managers become capable of taking possible measures in the course of reducing the impact from DT factors in workover procedures before they occur. The significant downtime events to improve asset performance through the elimination of the root cause of DT. Based on this research, the method is successful in introducing many oil companies to the subject of performance measurement. It was concluded that the developed delay analysis system can assist Oil Companies in analyzing and quantifying the impact of DT factors associated with workover programs in advance.

## References

1. Mansour H, Ahma M, Dhafr N, Ahmed H (2013) Evaluation of operational performance of workover rigs activities in oilfields. Int J Product Perform Manage 62(2):5
2. Pintelon L, Pinjala SK, Vereecke A (2011) Evaluating the effectiveness of maintenance strategies. J Qual Maintenance Eng 12(1):7–20
3. van der Leij E, Zuidema F (1999) Theoretical maximum performance, ProStar Rig 2000. Society of Petrolem Engineer, SPE 57557, Abu Dhabi, USE
4. Elazouni M, Basha M (1996) Evaluating the performance of construction equipment operators in Egypt. J Construct Eng Manage 122(2):109–114
5. Masahiro M, Yutaka Y, Osamu K (2000) ESP performance in Mubarraz field. In: International petroleum exhibition and conference, SPE 87257, UAE
6. Jardine AKS (1973) Maintenance, replacement and reliability. Pitman, UK
7. Spoerker HF, Doschek M (2005) Performance drilling onshore Iran—introducing new concepts to a mature area. Society of Petrolem Engineer, SPE 91892, Amsterdam
8. Ribeir M, Mauri R, Lorena N (2011) A simple and robust simulated annealing algorithm for scheduling workover rigs on onshore oil fields. Comput Ind Eng 60(4):519–526
9. Ikem JA (1985) Problem analysis enhances workover execution and profitabitiy. Society of Petroleum Engineers, SPE 13917, Nigerian Agip Oil Co. Ltd
10. Cochrane JE (1989) Rig performance monitoring and measurement: can it again be useful? In: SPE/IADC drilling conference, SPE 18692, New Orleans, Louisiana
11. Blikra H, Andersen R, Hoset H (2002) Cost-effective subsea drilling operation on the smallest Norwegian field development. Society of Petroleum Engineers, SPE 74508, Dallas
12. Ahmad M, Dhafr N, Elhuni R, Mansour H (2010) Managing manufacturing performance for competitiveness. In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing, Oakland, CA, USA
13. Mansour H, Ahmad M, Ahmed H (2012) A practical method for evaluating operational performance of workover activities in Sarir oilfield. In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing, Helsinki, Finland
14. Ahmad M, Benson R (1999) Benchmarking in the process industries. IChemE. UK

15. Naderinejad M, Nilipour SA (2011) Comparison of overall equipment effectiveness in continuous production line of isomax unit of Esfahan oil rrfining company (EORC) with world class manufacturing. Interdiscip J Contemp Res Bus 3(6):466–482
16. Patrik L, Magnus L (1999) Evaluation and improvement of manufacturing performance measurement systems—the role of OEE. Int J Oper Product Manage 19(1):55–78

# Potential Using of OEE in Evaluating the Operational Performance of Workover Activities

**Haitham Mansour, Munir Ahmad and Hussain Ahmed**

**Abstract** The aim of this paper is to develop OEE as a metric and a measure to monitor the actual performance of workover activities. Improved efficiency can be achieved through the effective management of effort to improve productivity. The main purpose of the OEE results is to evaluate essential data against where decisions may be made. The OEE monitors the actual performance of workover relative to its performance capabilities under optimal workover conditions. An attempt could be made to enhance the efficiencies of the workover activities rigs in the Sarir Oilfield. A case study approach was adopted for the data collection, which was undertaken over an eight-month period, and utilized a number of collection techniques including, participant observation, daily report analysis, and work experience. The concept discussed in this paper is providing the basis for developing a more uniform method of evaluating rig performance. It should result in more efficient rig operations. This method of calculating rig efficiency provides the practical measure of the workover performance which can aid in rig procedures negotiation and rig selection. The improvement opportunities in workover procedures have been identified based on OEE results for improvement and new variations of these measures can be implemented for other workover at Oilfields that use the same artificial lift method.

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## 1 Introduction

There have been many researches that use production time when evaluating production performance, and many methods have been developed for calculating manufacturing cost. When it comes to continuous improvements, there are many approaches and philosophies at hand. One of the most widely used is Lean Production [1], focusing on reducing waste by introducing standards and reducing stocks and buffers. In connection with Lean Production, companies today often implement Total Productive Maintenance (TPM) based on Overall Equipment Efficiency (OEE), originally defined by Nakajima [2]. Companies have different traditions of measuring their performance in order to reach and maintain a competitive edge in the market. Overall equipment effectiveness (OEE) is the significant measure tool for evaluation the performance [3]. The concept of OEE, introduced by Nakajima, is being used increasingly in most of the industries [2]. It measures the efficiency losses that result from rework and yield losses. OEE monitors the actual performance of equipment relative to its performance capabilities under optimal process circumstances [3]. In most industries several factors affect the productivity of equipment; however, some are easily recognizable factors earlier to process, while others are unanticipated and affect equipment productivity negatively.

In oil industries maintenance also plays a key role in their operation. Maintenance issues of offshore and onshore operation show some differences in operation. There several maintenance issues occur due to improper maintenance action on right time. The maintenance cost normally covers the major portion of the operating cost in most of the industries [4].

Thus, the workover rig scheduling problem consists of finding the best schedule for the limited number of workover rigs which minimize the production loss associated with the wells waiting for maintenance service. If a productive well is attended delayed by rig activities, a high oil production loss will arise. Therefore, it is necessary to define a scheduling of the available rigs, which minimized the production loss associated with the wells waiting for the maintenance service.

The definition and use of OEE over the years has been widely debated [2]. Many experts have found that OEE has numerous uses and definitions which have led to considerable confusion when comparing equipment-to-equipment, plant-to-plant, or organization-to-organization. Overall equipment effectiveness (OEE) is a basic, fundamental measurement method for evaluation the process. It has been suggested that OEE might be used as a “benchmark” for measuring the primary performance of process [3]. In this way, the primary OEE measure can be compared with future OEE values, thus quantifying the level of improvement made [3]. The OEE is used to measure the effectiveness of total preventive maintenance and improve it in individual equipment by reducing the concerned losses [3, 5].

The OEE measurement is an effective way of analyzing the efficiency of a single machine in the system. Nakajima suggested that ideal values for the OEE component measures are [2]:

- availability in excess of 90 %;
- performance efficiency in excess of 95 %; and
- quality in excess of 99 %.

The procedures of the oilfield operation are normally affected by some factors which lead to major production losses such as downtime of the operation process [6]. The workover process improvement opportunities continue to be identified based on OEE results and new variations of this measures can be implemented for other oilfield that using the same artificial lift method [6]. Reducing downtimes to improve the efficiency is a well-known concept, but the implementations vary considerably. Murty and Naikan [7] suggest that it is easy to over-spend when investing to reduce downtimes, and present a method used for evaluating the optimum availability.

## 1.1 Workover Processes

Workover supports oilfields to return oil wells to production by delivering operating equipment reliability and operating equipment risk reduction. Good and bad workover procedures affect both the cost and time of operations [6]. The total cost includes the rig expenses (transport, assembly, and operation), which are functions of time and distances, plus the losses of revenue in the wells waiting for the rig, which are dependent on time [8]. Therefore, the total cost depends on the ordering of the wells in the itinerary.

Workover program is an orderly step-by-step procedure to be followed in conducting the workover operation. This procedures of the workover include the main stage of workover processes, the first step in the process is to move the rig to the location of the oil well, then, there are many procedures must be followed to return the oil well to normal production see Fig. 1. The procedures such as the rig up (R/U), rig down (R/D), and ESP installation, Run in Hole (RIH) and pull out of hole (POH) of the equipment such as ESP. The program must provide operating personnel with all information necessary to achieve the required objectives safely at the minimum cost and with the minimum expenditure of resources [6, 9].

## 1.2 Purpose of OEE in Oil Industry

In the oil industry, every well in the oilfield is a product line to produce the oil, it has many processes to keep the oil well producing [6]. The oil well is as a small manufacturing plant and each plant needs different equipment as the conditions for each plant are unique [6]. The researcher offered overall throughput effectiveness (OTE) metric for factory level performance monitoring and bottleneck detection [10]. In the field of application of OEE in oil and gas industries, the researcher compare the

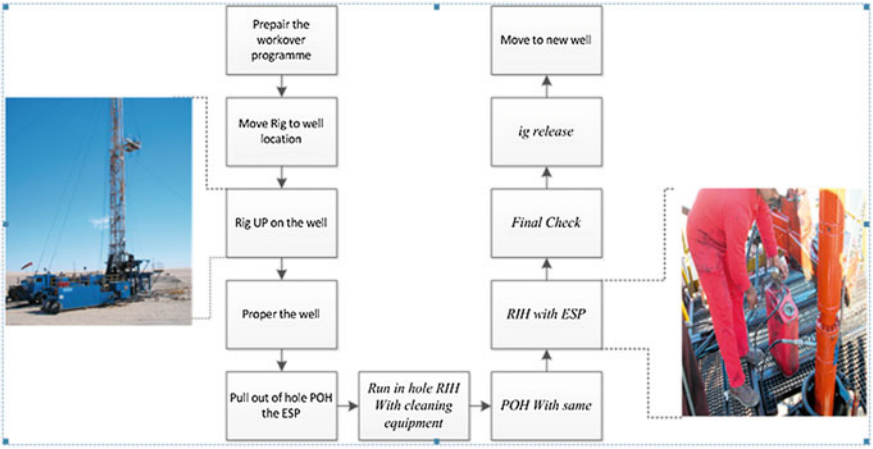


**Fig. 1** The main stages of workover processes

overall equipment effectiveness in Continuous Production Line of Isomax unit of Esfahan Oil Refining Company with World Class Manufacturing [10].

In this research the workover process improvement opportunities continue to be identified based on OEE results and new variations of these measures can be implemented for other workover at Oilfields that use the artificial lift method [6]. The OEE monitors the actual performance of workover relative to its performance capabilities under optimal workover conditions. OEE should be measured at the constraint step of the workover process. Improving the constraint will improve the overall process of the workover, and ultimately the reason for measuring OEE is to improve the process because it is a good tool for evaluation the process. It allows engineers to accurately pinpoint the area of focus that will improve the efficiency of the equipment which can be achieved through the effective management of effort to improve productivity [6, 9]. Effective troubleshooting requires an ability to observe changes in performance over time, and in the event of a failure, the capacity to thoroughly investigate the cause of the DT and take measures to prevent the problem from re-occurring. The fact is that there are three types of problems mostly encountered with workover [6]:

- workover design errors
- poor operation
- poor workover practices.

The OEE measure can be applied at numerous different levels within a workover operation environment [3, 11].

**First**, OEE can be used as a "benchmark" for measuring the initial performance of operation process in its totality. In this way the initial OEE measure can be compared with future OEE values [3].

**Second**, an OEE value can be used to compare activities performance across the process, thereby highlighting any poor activities performance [3, 12].

**Third**, if the operation procedures work individually, an OEE measure can identify which process performance is the worst [3, 13].

## 2 Overall Equipment Effectiveness for Workover

Equipment effectiveness includes equipment availability, performance efficiency and rate of quality of output. Operational performance data collection of the three OEE variables, availability, performance, and quality [2, 3, 11], was carried out during a period of four months.

$$OEE = \text{availability} \times \text{performance} \times \text{quality} \tag{1}$$

The first element of the OEE calculation is process availability: It is the ratio of the workover time to the planned workover time [6].

$$\text{Availability}\,\% = \text{workover operating time} \div \text{planned workover time}$$

where

$$\text{Planned workover time} = TWT - breaks$$

$$\text{Workover operating time} = \text{planned workover time} - \text{downtime}$$

The second element is "performance rate". This measure the ratio of the best time achieved to the actual time. That has been calculated in the method of evaluation of the workover [6].

$$Performance\,\% = \frac{BTWT}{TWT} \tag{2}$$

where:

$$\begin{aligned}\text{TWT (hours)} = \text{total workover time (actual time)} &= \text{moving} + \text{Rig Up} \\ &+ \text{POH with equipment} + \text{RIH with ESP} \\ &+ \text{Final check} + \text{Rig release}\end{aligned}$$

$$\begin{aligned}\text{BTWT (hours)} &= \text{total best (hostorical) time achieved by workover rig} \\ &+ \text{pulling ESP} + \text{RIH with equipment} \\ &+ \text{POH with equipment} + \text{RIH with ESP} \\ &+ \text{Final check} + \text{Rig release}\end{aligned}$$

The third element of the OEE calculation is the "quality rate", and is used to indicate the proportion of defective time for good workover to the total workover time [6].

$$Quality\,\% = \frac{time\,for\,good\,workover}{time\,for\,total\,workover} \quad (3)$$

## 2.1 OEE Results for Workover Rigs

OEE measurement process is the main reason for the work. Operational performance data collection of the three OEE variables, availability, performance, and quality, was carried out during a period of four months. The time distributions and target time for each rig used in the work are obtained directly from the daily workover activities in the Sarir Oilfield. The time required to perform these operation activities is defined as TWT, Table 1 presents actual and target workover hours. Based on this data Table 2 includes the main statistical data for OEE calculation.

The actual availability, performance rate, and quality measures, together with the complete OEE is shown in Table 3. The conclusion of this process resulted in an average OEE measure being calculated which was used to indicate the current performance of the workover rig as a whole.

The downtime (DT) is associated with workover procedures, resource utilization, and ESP pulling and installation [6]. The quality of workover has a major impact on the OEE result which is a base of OEE calculation Table 3. The quality is affected by the working days to complete the workover job and return the oil well to production. Monitoring the process and precise measurement of its main aspects is the key step to the workover plan and to manage improvement of the workover procedures [6, 9].

The main causes for low OEEs Fig. 2, were lack of workover procedures, ESP pulling and installation, and the location of the oil well (rig move).

The drop in OEE reflects a change in the quality and the procedures time of the workover activities in each well Fig. 1. The OEE and efficiency have different impact on the cost as in Table 3.

**Table 1** Workover hours for five wells

| Rig number | Move | Rig up | POH w/ESP | RIH w/equipment | POH w/same | RIH w/ESP | Final check | Rig release | Total working (TWT) hrs |
|---|---|---|---|---|---|---|---|---|---|
| Workover well 1 | 7 | 12 | 12 | 6.5 | 15.5 | 10.5 | 8 | 4 | 75.5 |
| Workover well 2 | 8 | 7 | 10.5 | 11.5 | 20 | 22 | 4 | 2 | 85 |
| Workover well 3 | 6 | 6 | 7.5 | 11 | 11 | 14 | 8.5 | 6 | 70 |
| Workover well 4 | 5 | 7 | 8.5 | 12 | 6.5 | 8 | 4 | 3 | 54 |
| Workover well 5 | 8 | 6 | 13 | 9.5 | 8.5 | 18 | 3 | 4 | 70 |
| BTWT | 5 | 6 | 7.5 | 6.5 | 6.5 | 8 | 3 | 2 | 50 |

**Table 2** Complete OEE for workover rig

| | TWT hours | Breaks minutes | Downtime minutes | Working days | Planned workover time minutes | Workover operating time minutes | Time for good workover hours | Time for total workover days |
|---|---|---|---|---|---|---|---|---|
| Workover well 1 | 75.5 | 120 | 510 | 7 | 4518 | 3900 | 44 | 7 |
| Workover well 2 | 85 | 120 | 660 | 8 | 4980 | 4320 | 44 | 8 |
| Workover well 3 | 70 | 120 | 840 | 7 | 4080 | 3240 | 44 | 7 |
| Workover well 4 | 54 | 120 | 1080 | 6 | 3120 | 2040 | 44 | 6 |
| Workover well 5 | 70 | 120 | 840 | 7 | 4080 | 3240 | 44 | 7 |

**Table 3** Complete OEE for five wells

| Rig | Performance (%) | Availability (%) | Quality (%) | OEE (%) |
|---|---|---|---|---|
| Workover well 1 | 12 | 15.5 | 75.5 | 28 |
| Workover well 2 | 7 | 20 | 85 | 21 |
| Workover well 3 | 6 | 11 | 70 | 27 |
| Workover well 4 | 7 | 6.5 | 54 | 33 |
| Workover well 5 | 6 | 8.5 | 70 | 27 |

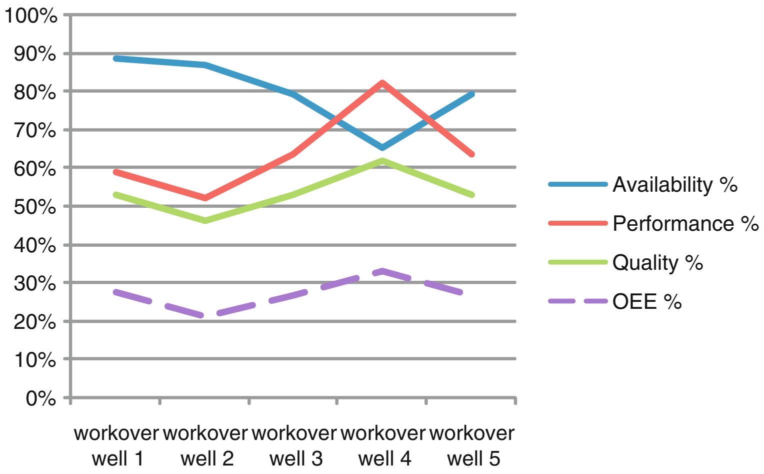


**Fig. 2** The OEE for workover activities

If a workover rig is not running at full capacity and high efficiency, it could be due to various reasons such as [9]:

- Ill defined workover procedures and lack of consistency in implementation of these procedures.
- Too much time spent on breakdown maintenance rather than implementation of total productive maintenance (TPM).
- Absenteeism and high labor turnover.

The improvement in workover procedures can greatly reduce the DT caused by incorrect operating procedures [6], while a good workover program reduces DT caused by equipment failures.

## 3 Area for Improvements

It has been found that the lack of ESP procedures was considered to be a problem that depends on the number of the technical and types of equipment used to finish the job. Table 4 shows the percentage of downtime in each activity that has a high effect on the OEE results. The improvement in workover procedures such as pulling and installing of ESP and equipment can greatly reduce the DT caused by incorrect operating procedures [14].

There are many ways to raise the OEE. Some of the actions could be the training of operators, reviewing the bottleneck machines involving technical improvements, fine tuning of production schedules, redesigning of products, and improving the operating instructions [11].

Some of these improvements may require substantial investments. With good OEE measurement it is possible to pick up the project with the quickest returns. Accurate OEE measurement makes it possible to follow up the outcomes of the development and investments [15].

It was also identified that tool such as total productive maintenance (TPM), is appropriate tool to improve the workover performance in this oilfield. In general, a sustainable performance improvement should be aligned to a firm's ability to continually achieve quality, reduce costs, and time [15].

**Table 4** The percentage of downtime in main workover activities

| | Downtime (%) | | | |
|---|---|---|---|---|
| | POH w ESP (%) | RIH w tools (%) | POH w same (%) | RIH w ESP (%) |
| Workover well 1 | 12 | 7 | 11 | 29 |
| Workover well 2 | 11 | 12 | 22 | 44 |
| Workover well 3 | 8 | 11 | 14 | 33 |
| Workover well 4 | 9 | 12 | 8 | 29 |
| Workover well 5 | 13 | 10 | 18 | 41 |

## 4 Conclusion

The evaluation of the OEE results is based on the results of method of evaluation of the workover rig and the area of improvement. Improved efficiency can be achieved through the effective management of effort to reduce DT and improve productivity. The workover process improvement opportunities continue to be identified based on OEE results and new variations of these measures can be implemented for other Oilfields that use the ESP as artificial lift method.

The concept discussed in this paper is providing the basis for developing a more uniform method of evaluating rig performance. It is should result in more efficient rig operations. This paper has identified the improvements area and processes related to OEE results. It can work as an important indicator in the continuous improvement process. The results of the example show that the proposed method of OEE is very effective for doing improvements to increase the effectiveness of the workover procedures within specific time period by identifying the problem exactly. However, the importance practical workover performance measure which can aid in rig procedures negotiation and rig selection. The improvement in the workover procedures such as pulling and installing of ESP that caused by incorrect operating procedures can be achieved [14]. Improvements tools such as TPM can be applied to enhance the performance of workover activities. Further, the metric OEE for workover activities can be used as a benchmark at various levels to achieve world-class standard.

## References


1. Womack JP, Jones DT, Roos D (1990) The machine that changed the world. Rawson Associates, New York
2. Nakajima S (1998) Introduction to TPM: total productive maintenance
3. Ahmad M, Benson R (1999) Benchmarking in the process industries. IChemE
4. Mobley RK (2002) An introduction to predictive maintenance. Butterworth-Heinemann, London
5. Pintelon L, Pinjala SK, Vereecke A (2011) Evaluating the effectiveness of maintenance strategies. J Qual Maintenance Eng 12(1):7–20
6. Mansour H, Ahmad M, Dhafr N, Ahmed H (2013) Evaluation of operational performance of workover rigs activities in oilfields. Int J Prod Perform Manag 62(2):204–218
7. Murty ASR, Naikan VNA (1993) Availability and maintenance cost optimization of a production plant. J Qual Reliab Manag 12(2):28–35
8. Ribeir M, Mauri R, Lorena N (2011) A simple and robust Simulated Annealing algorithm for scheduling workover rigs on onshore oil fields. Comput Ind Eng 60(4):519–526
9. Mansour H, Ahmad M, Ahmed H (2012) A practical method for evaluating operational performance of workover activities in Sarir oilfield. In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing. Helsinki, Finland
10. Zandieh S, Tabatabaei S, Ghandehary M (2012) Evaluation of overall equipment effectiveness in a continuous process production system of condensate stabilization plant in assalooyeh. Interdisc J Contemp Res Bus 3(10):590–598

11. Patrik J, Magnus L (1999) Evaluation and improvement of manufacturing performance measurement systems: the role of OEE. Int J Oper Prod Manag 19(1):55–78
12. Bulent D, Tugwell P, Greatbanks R (2000) Overall equipment effectiveness as a measure of operational improvement–a practical analysis. Int J Oper Prod Manag 20(12):1488–1502
13. Panagiotis T (2007) Implementation of total productive maintenance in food industry: a case study. J Qual Maintenance Eng 13(1):5–18
14. Masahiro M, Yutaka Y, Osamu K (2000) ESP performance in Mubarraz Field. International petroleum exhibition and conference, SPE 87257. UAE
15. Arévalo-Villagrán JA, Gutiérrez-Acosta T (2007) A well productivity program in PEMEX E&P increases oil production in short time and low cost. Society of Petrolem Engineer, SPE 108633-MS. Veracruz, Mexico
16. Naderinejad M, Nilipour SA (2011) Comparison of overall equipment effectiveness in continuous production line of isomax unit of Esfahan oil refining company (EORC) with world class manufacturing. Interdisc J Contemp Res Bus 3(6):466–482
17. Leij E van der, Zuidema F (1999) Theoretical maximum performance, ProStar Rig 2000. Society of petroleum engineer, SPE 57557. Abu Dhabi, USE
18. Cochrane JE (1989) Rig performance monitoring and measurement: can it again be useful?. SPE/IADC drilling conference, SPE 18692. New Orleans, Louisiana
19. Ahmad M, Dhafr N, Elhuni R, Mansour H (2010) Managing manufacturing performance for competitiveness. In: Proceedings of 20th international conference on flexible automation and intelligent manufacturing. Oakland, CA, USA

# Operating Curves of Manufacturing Systems: A Theoretical Discourse

**Gerald Weigert**

**Abstract** To assess the performance of a manufacturing system is not as easy as it seems at first. Besides common key performance indicators (KPI) mainly so called operating curves are used to this end. The advantage of the operating curves is that one can study the system behavior under varying conditions. However, the systems cannot be compared with each other so easily. To ensure the comparability of the system behavior the operating curves must therefore be normalized. In this paper a method will be developed for defining normalized operating curves, which is also suitable for complex manufacturing system structures. These methods are based on Little's law as well as a special kind of flow graphs, with which it is possible to find the limiting bottlenecks in the system under special conditions. An example will explain that the method works.

## 1 Introduction

The performance of manufacturing systems is usually assessed by using numerous key performance indicators (KPI). This includes both business-oriented and purely logistical parameters [1]. However, in the following logistical parameters are exclusively used. While a KPI assesses the system only selectively, the operating curve also gives information about the behavior of the system under various conditions (see also [2, 3]). In general, operating curves are used as displayed in Fig. 1. In this diagram, the KPIs "output rate" and "throughput time" are shown as a function of the "WIP level" (WIP = Work In Process). Such charts are usually used by practitioners, for example, to determine the optimal operating range of a system or also a single workstation (grey area).

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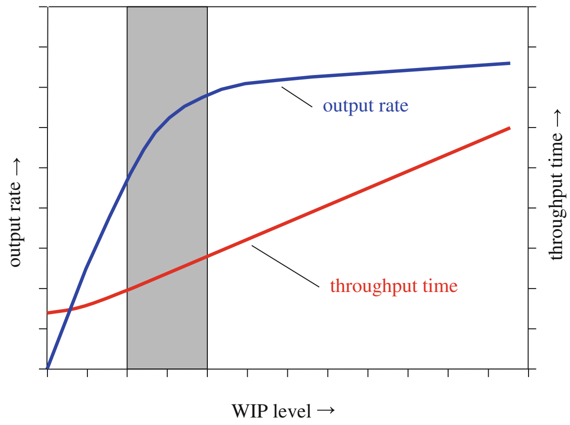
**Fig. 1** Logistic production operating curves [3]




However, for direct comparison of systems with each other, the operating curves are not suitable in the present form. Under the conditions of a more and more globalized production with complex supply chains the comparability of operating curves of different manufacturing systems is necessary. Meier [4] suggests the conversion of KPIs: "Is it the goal, to compare production lines among themselves, so the three KPIs utility factor, flow factor, and throughput rate are really only be if the comparable external conditions are identical. However, this is a highly unrealistic assumption. An alternative is to calculate the KPIs by using of the relationship from the operating curves" (translation from German).

Undoubtedly, normalized diagrams are at an advantage here. In the semiconductor manufacturing operating curves, also normalized, have long been used [5, 6]. Usually the publications in this regard describe only the application aspect but blank out the problems, which are connected with the normalization methods. At first the normalization requires reference values, which to find is not quite easy at a closer look. Because as there is no natural reference point, the WIP level is by no means a suitable choice for an independent variable. A better choice seems to be the output rate or the throughput time, because for both parameters a reference value in form of their natural limitations can be defined. The goal of the following remarks is, to define a suitable form for the normalization of the operating curve and, at the same time, to determine reference values. To avoid time consuming simulation runs, these reference values should be calculable, if possible. But, what is easily achievable in case of simple system structures can become a problem for complex systems.

The paper is divided into two parts. In the first part (Sect. 2), starting from Little's law, the theoretical basis is established for the definition of a suitable operating curve which connects the average output rate with the average throughput time. The second part (Sect. 3) shows how these operational curves can be normalized by finding the bottleneck of the system.

## 2 Little's Law and the Definition of Operating Curves

Each manufacturing system can be described by using the three parameters throughput $\lambda$, the number of product units $n$ in the system—the so called WIP level—and the throughput time $\Delta t$ (total stay time)—the average time which a product unit spends in the system (refer to Fig. 2). The throughput is the number of product units which arrive the system in a given time interval, divided by this time interval. For a stable system the input rate $\lambda_{in}$ must be the same as the output rate $\lambda_{out}$, so in the following the throughput is only referred to as output rate. The throughput time $\Delta t$ of a product unit is the difference between its arrival time and its departure time and includes both the service time (raw processing time $\Delta t_P$) and the waiting time. The raw processing time $\Delta t_P$ or shortly the processing time is the technologically necessary time which a product unit needs. All parameters are average values measured during a very long (ideally infinite) observation time. For simplicity it is assumed that our manufacturing system has only one input and one output. In addition we presuppose a plain production that means, the product units are not disassembled or assembled during the manufacturing process. Such plain production processes are typical for a lot of industrial applications, i.e., the semiconductor manufacturing, where an unprocessed wafer enters the Fab and a processed wafer leaves the Fab after the throughput time.

Already in 1961 J.D. Little proved the simple relation between WIP level, throughput and throughput time (Eq. 1) which was later named after him as Little's law (see [7]):

$$n = \lambda \cdot \Delta t \tag{1}$$

The three logistic parameters $n$, $\lambda$ and $\Delta t$ span a space where Little's law produces a saddle surface. Only the first quadrant of this space is interesting for logistic applications, because there negative values of these parameters are impossible (Fig. 3).

For practical use the 3D representation of Little's law is not very suitable. Instead one uses 2D representations, as shown in Fig. 4. Depending on which of the two variables is considered as independent, we distinguish a WIP-based (a) and flow-based (b) representation. If one of the two graphs from representation (a) overlays the other, then you get the well-known representation of the logistic production operating curves of Fig. 1. The representation of the two curves, the output rate and the throughput time over the WIP level, is common but not really necessary, because the third variable is always determined by Little's law. Both representations (a and b) are equivalent to each other. It depends only on the user

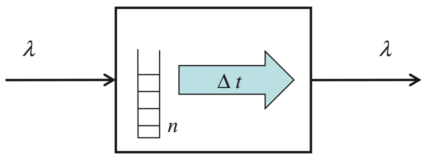
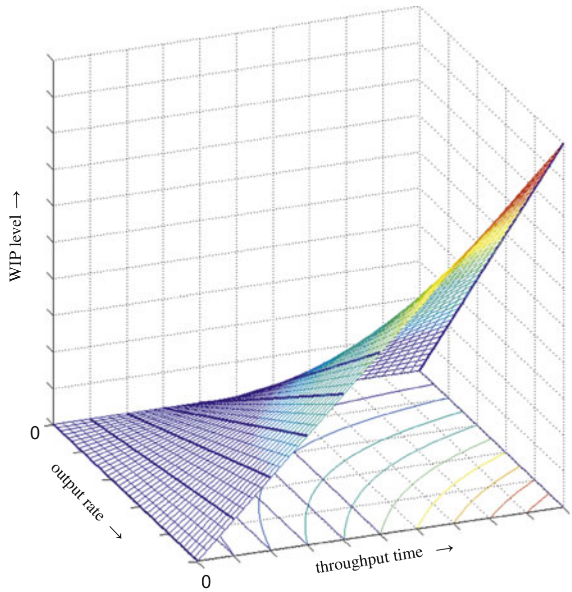



**Fig. 2** The three basic logistic parameters of a general manufacturing system

**Fig. 3** The 3D representation of Little's law




which of it he prefers. In the following, we use only the lower diagrams to describe the properties of a manufacturing system, which represents the dependence on the throughput time of the WIP level or the output rate.

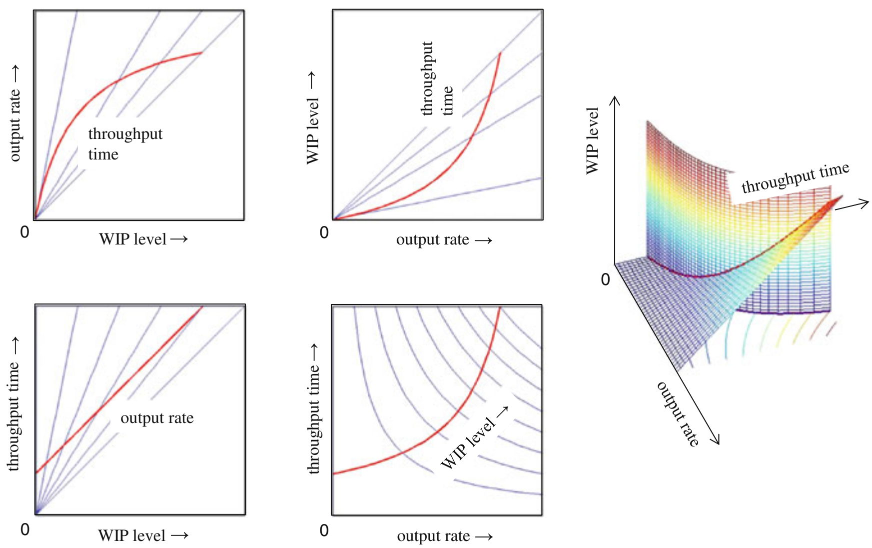



**Fig. 4** Several kinds of operating curves derived from Little's law

In the following context exclusively the relation $f$ between throughput time $\Delta t$ and output rate $\lambda$ (Eq. 2) is called an operating curve. In general the operating curve of a manufacturing system is non-linear.

$$\Delta t = f(\lambda) \tag{2}$$

# 3 Normalization of Operating Curves

The operating curve describes the long term behavior and the efficiency of a manufacturing system. The goal is to make them comparable to each other, even if their logistical parameters differ greatly in magnitude. Just think of a semiconductor factory, where the throughput time can be 2–3 months, or the production of certain foods, which usually takes only hours or days. The key for comparability is the normalization of the operating curves. First we investigate a simple queuing system, which consists of a single server and an upstream queue with infinity capacity. Thereafter these single server systems are joined together to form a production line. Finally an example of a more complex manufacturing system with alternative process steps and process loops is described by a special production graph. It is introduced a general method, how to attribute this structure to a simple serial line structure as before.

## *3.1 A Simple System with a Single Server*

Figure 5 shows a single server system with a service rate $\mu$ and an output rate (throughput) $\lambda$. To get a normalized operating curve one has to divide $\lambda$ by $\mu$ (Eq. 3). The quotient is the commonly known traffic intensity $\rho$, which is a measure of the relative system load.

$$\rho = \frac{\lambda}{\mu} \tag{3}$$

Additionally, the total throughput time $\Delta t$ is divided by the service time (raw processing time) $\Delta t_P = \mu^{-1}$. The quotient $F$ (Eq. 4) is the so called flow factor. $F$ takes values in the range of 1 (no waiting time) to $\infty$ (infinite waiting time).

$$F = \frac{\Delta t}{\Delta t_P} = \mu \cdot \Delta t \tag{4}$$

Figure 5 shows a single server system with its parameters and two examples of typical operating curves, derived from a simulation experiment. For curve1 the service rate $\mu$ is deterministic and for curve2 it is exponentially distributed. The output rate is a Poisson stream in both cases. So, the operating curve1 represents a classical M/D/1 and the curve2 represents an M/M/1 system. One can recognize

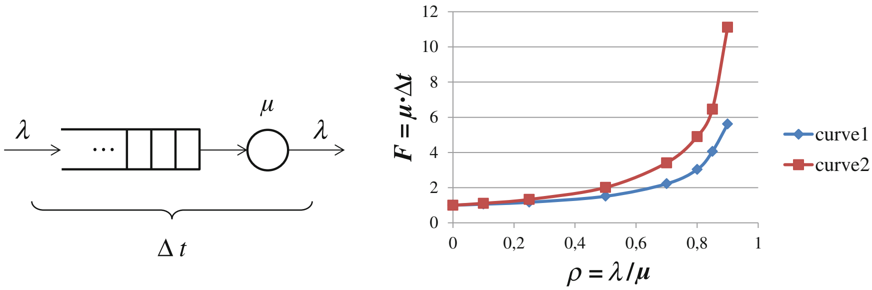



**Fig. 5** Single server system with typical operating curves

that the stochastic service time of the M/M/1 system increases the flow factor $F$ in comparison to the deterministic service times of the M/D/1 system, that is, the possible throughput of the stochastic server is lower than the throughput of the deterministic one. This behavior is commonly known as the so called hockey stock effect, because of the shape of the operating curve. The normalized operating curve in Fig. 5 is a function of the flow factor $F$ of the traffic intensity $\rho$ (Eq. 5) and it is always the same, independent on the actually absolute values of the output or service rate.

$$F = f(\rho) \tag{5}$$

Equation (5) is just another form of representation as shown in Fig. 4 (compare b, the lower diagram). The WIP level of the system, for example, can be calculated by Little's law as follows:

$$n = \rho \cdot F \tag{6}$$

The basic idea of normalized operating curves is the presence of an upper limit of the output rate, which cannot be exceeded by the manufacturing system. In case of a simple single server queuing system it is just the service rate $\mu$. Unfortunately, it is not so easy to find a upper limit of the output rate in the case of more complex manufacturing systems, which consist of more than one server. In general, it needs time consuming simulation experiments to determine such limitations exactly. But for practical purposes, there are opportunities to determine the necessary limits mathematically with sufficient accuracy, as will be shown in the following.

## *3.2 Serial System: Manufacturing Line*

The next more difficult structure is a manufacturing line, consisting of $i = 1 \ldots m$ single server systems, which are serially joined together as shown in Fig. 6. The service rates $\mu_i$ of the several stations are generally different. The total

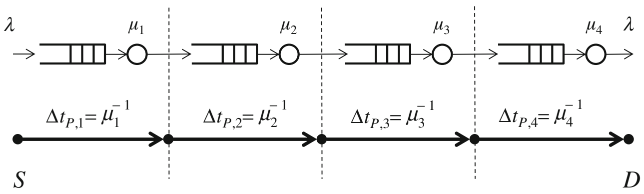



**Fig. 6** Manufacturing line, consisting of stations with different service rates $\mu_i$

raw processing time $\Delta t_{P,\ line}$ of the whole line can be calculated as the sum of all single raw processing times $\Delta t_{P,\ i}$ :

$$\Delta t_{P,\,line} = \sum_i \Delta t_{P,\,i} = \sum_i \frac{1}{\mu_i} \tag{7}$$

The output rate of a manufacturing line cannot become greater than the output rate of its bottleneck. So, the minimum of all service rates $\mu_i$ is also the upper bound (not the limit) of the output rate of the line (Eq. 8).

$$\mu_{\min} \leq \min_i\{\mu_i\} \tag{8}$$

For many practical cases a manufacturing line has a pronounced bottleneck. If this is true, the upper bound and the upper limit of the output rate are approximately equal. So we can calculate the traffic intensity $\rho_{line}$ as follows:

$$\rho_{line} = \frac{\lambda}{\mu_{\min}} \tag{9}$$

The flow factor is, like for the single server system, the quotient of the total throughput time $\Delta t_{line}$ and the total raw processing time $\Delta t_{P,line}$ (Eq. 10).

$$F_{line} = \frac{\Delta t_{line}}{\Delta t_{P,\,line}} \tag{10}$$

The normalized operating curve of a manufacturing line is again a function of the flow factor $F_{line}$ of the traffic intensity $\rho_{line}$.

## *3.3 Manufacturing System with Complex Structure*

Much more difficult than in the simple manufacturing line is the derivation of a normalized operating curve in a general complex manufacturing structure with branches and/or recirculations (e.g., repair or rework loops). Such a system structure can be modeled by a production flow graph (developed by Sauer, see also [8]), where every edge represents a workstation consisting of a server with its upstream queue (see Fig. 6, lower part). As an example Fig. 7 shows a more

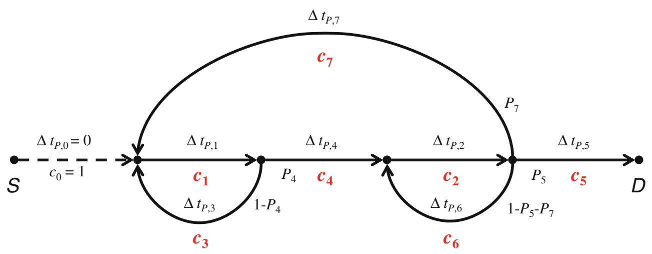



**Fig. 7** Production flow graph of complex manufacturing system (example)

complex structure. It is assumed that the raw processing times $\Delta t_{P,\ i}$ are known for all workstations. The branching into alternative process steps is random with the branch probability $P_i$. The branch probabilities are assumed as time independent and they are also independent on how often a product unit has passed the corresponding node. It is comparable with the so called First Pass Yield (FPY). It is clear that the sum of all branch probabilities of one given node must always be 1.

The difficulty with a complex structure is to determine the bottleneck and the related upper bound of the output rate, which is necessary for the calculation of the normalized operating curve of the system. Let us assume the following raw processing times as an example: $\Delta t_{P,1} = 1$, $\Delta t_{P,2} = 2$, $\Delta t_{P,3} = 9$, $\Delta t_{P,4} = 1$, $\Delta t_{P,5} = 2$, $\Delta t_{P,6} = 6$, and $\Delta t_{P,7} = 14$ (measured in time units). At first glance it seems that the workstation 7 with the longest raw processing time could be the bottleneck. Actually, this statement is not possible without the additional knowledge of the probability values, because they have an important influence on the load of the workstations. For this purpose it is necessary to calculate the intensity coefficient $c_i$ for each workstation of the manufacturing system. The value of the intensity coefficient indicates the average how often a particular product unit passes the workstation $i$. The coefficients could therefore also be measured in the real system with simple counters. The counts should finally be divided only by the total number of product units. But, in case that all branch probabilities are known, the intensity coefficients can be calculated by solution of Eq. (11). The first 4 rows of the matrix follow from the node theorem: The intensity sum of all ingoing edges of a node is equal to the intensity sum of all outgoing edges. The last 3 rows describe, in addition, the branching nodes. More information on the production flow graphs and the theory behind them can be found in [8].

$$\begin{pmatrix} 1 & 0 & -1 & 0 & 0 & 0 & -1 \\ 1 & 0 & -1 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 & -1 & -1 & -1 \\ P_4 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & P_5 & 0 & 0 & -1 & 0 & 0 \\ 0 & P_7 & 0 & 0 & 0 & 0 & -1 \end{pmatrix} \cdot \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \Rightarrow$$

$$\begin{aligned} c_1 &= (1 + P_7/P_5)(1 + (1 - P_4)/P_4) \\ c_2 &= 1 + (1 - P_5)/P_5 \\ c_3 &= (1 + P_7/P_5)(1 - P_4)/P_4 \\ c_4 &= 1 + P_7/P_5 \\ c_5 &= 1 \\ c_6 &= (1 - P_5 - P_7)/P_5 \\ c_7 &= P_7/P_5 \end{aligned} \tag{11}$$

To each workstation an effective raw processing time $\Delta t'_{P,i}$ (respectively the effective service rate $\mu_i$) can be assigned. This is the product of the single (only one pass) raw processing time $\Delta t_{P,\ i}$ and the intensity coefficient $c_i$ of this workstation (Eq. 12).

$$\Delta t'_{P,i} = c_i \cdot \Delta t_{P,i} \quad \Rightarrow \quad \mu'_i = \frac{\mu_i}{c_i} \tag{12}$$

The total raw processing time $\Delta t'_P$ of the whole system can be calculated from the sum of all effective raw processing times $\Delta t'_{P,i}$ (Eq. 13).

$$\Delta t'_P = \sum_i \Delta t'_{P,i} = \sum_i c_i \cdot \Delta t_{P,i} = \sum_i \frac{c_i}{\mu_i} \tag{13}$$

This equation is quite similar to equation to the Eq. (7), which describes a manufacturing line. This means, each complex manufacturing system, independent on its structure, can be always transformed into a simple line, in which the raw processing times are replaced by the effective raw processing times. After determining the bottleneck, the traffic intensity can be calculated in the same way as for the manufacturing line (Eq. 9). The flow factor of the system is given by Eq. (14).

$$F = \Delta t \Big/ \sum_i \frac{c_i}{\mu_i} \tag{14}$$

Assumed the branching probability values were as follows in the example of Fig. 7: $P_4 = 0.4$, $P_5 = 0.6$, and $P_7 = 0.1$., the values of intensity coefficients would be calculated using Eq. (10): $c_1 \approx 2.92$, $c_2 \approx 1.67$, $c_3 = 1.75$, $c_4 \approx 1.17$, $c_5 = 1$, $c_6 = 0.5$, and $c_7 \approx 0.17$. After this it is very easy to calculate the effective raw processing times using Eq. (11): $\Delta t'_{P,1} = 2.92$, $\Delta t'_{P,2} = 3.34$, $\Delta t'_{P,3} = 15.75$, $\Delta t'_{P,4} = 1.17$, $\Delta t'_{P,5} = 2.0$, $\Delta t'_{P,6} = 3.0$, and $\Delta t'_{P,7} = 2.38$. Now it is clear that the bottleneck of this system is not the workstation 7 but the workstation 3 which has the longest effective raw processing time of all. By the way, the total raw processing time $\Delta t'_P$ is 30.25 (Fig. 8).

Now it is possible to indicate the normalized operating curve of the system. The principle method is the same as for the manufacturing line. The upper bound of the output rate is $15.75^{-1}$ and, because of size difference to the other effective values,

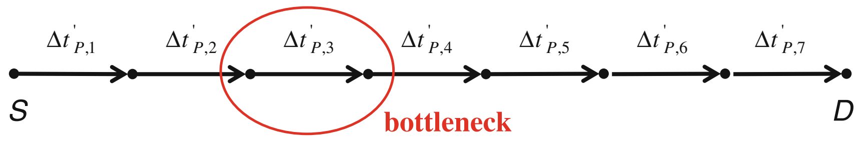



**Fig. 8** The serial structure of the production flow graph which its raw processing times

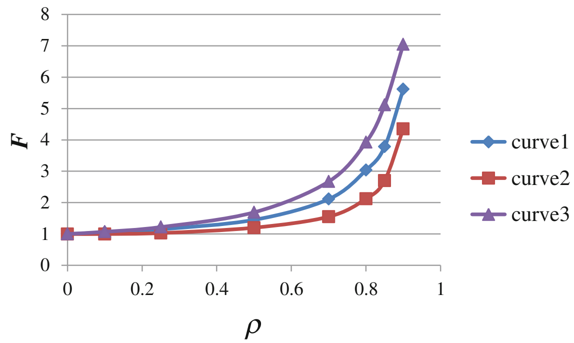



**Fig. 9** Example for several normalized operating curves of a complex system

this is approximately also the upper limit. Figure 9 shows three operating curves of the system, generated by simulation experiments with 100,000 product units. Because of the large number of product units the transient phases at the beginning and the end of the simulation runs were neglected. The operating curve2 in the diagram represents the system with deterministic service times for all workstations and deterministic inter-arrival times. It is not really an absolute deterministic system because of the random branching in it. The operating curve1 represents the same system, but in difference to curve2, the inter-arrival times are exponential distributed (Poisson stream). The operating curve3 represents the same system as curve1, but also the service times are exponential distributed. In addition the capacity of the bottleneck-queue was limited to 1, so that blocking effects occur.

## 4 Conclusion and Outlook

The operating curve is an important and commonly known instrument for the assessment of production systems of all kinds. In contrast to the usual representation of the operating curves (output rate and throughput time over the WIP level) one curve, the function $\Delta t = f(\lambda)$, covers both of them and describes the system completely. The WIP level is then determined by Little's law. On behalf of a better comparability between different systems it is advantageous to use the normalized operating curve $F = f(\rho)$. But the independent variable $\rho$ can be easily determined only for a single server system. With the help of special production flow graphs and the intensity coefficients it is possible to transform complex structures into simple production lines. If one can discover a distinctive bottleneck in this line, the calculation of a traffic intensity $\rho$, and consequently, the generation of a normalized operating curve is feasible again.

In this paper, exclusively plain production systems were investigated. For further research it will be interesting to consider other kinds of systems in addition, where the input rate and the output rate are not equal, e.g., assembly systems. Furthermore it is necessary to improve the methods for calculation of the traffic intensity in such systems by decreasing the gap between the upper bound and the upper limit of the output rate. Nevertheless, in some cases simulation methods will continue to be indispensable.

## References

1. Hopp WJ, Spearman ML (2001) Factory physics: foundations of manufacturing management. Irwin McGraw-Hill, New York
2. Nyhuis P, Wiendahl H-P (2006) Logistic production operating curves: basic model of the theory of logistic operating curves. CIRP Ann Manufact Technol 55(1):441–444
3. Nyhuis P, Wiendahl H-P (2009) Fundamentals of production logistics: theory, tools and applications. Springer, Berlin
4. Meier K-J (2011) Kennzahlen von Produktionskennlinien vergleichbar machen (Make KPIs of operating curves comparable), Institut für Produktionsmanagement & Logistik, IPL-Magazin, 15 May 2011, http://www.ipl-mag.de/scm-daten/194-scm-daten-15 (found 28.2.2013)
5. Aurand SS, Miller PJ (1997) The operating curve: a method to measure and benchmark manufacturing line productivity. In: Proceedings of the advanced semiconductor manufacturing conference and workshop, pp 391–397
6. Fayed A, Dunnigan B (2007) Characterizing the operating curve—how can semiconductor fabs grade themselves? In: Proceedings of the international symposium on semiconductor manufacturing, pp 1–4
7. Little JDC (1961) A proof for the queuing formula: $L = \lambda W$. Oper Res 9:383–387
8. Sauer W, Oppermann M, Weigert G, Werner S, Wohlrabe H, Wolter K-J, Zerna T (2006) electronics process technology: production modelling, simulation and optimisation. Springer, New York

# Elaboration of Reference Models for Improving Enterprise Performance

**Paul Eric Dossou and Philip Mitchell**

**Abstract** Due to the imposition of austerity measures, enterprises are facing increased costs and overheads due to this policy at a time when the market price is decreasing because of emerging countries and globalization. This has a knock-on effect on the quality of products and enterprises look for solutions to reduce cost such as laying off staff and relocation of production to low cost countries etc. In this paper, the bases of elaboration of new models are given. For enterprise typology, reference models are defined per sector of activity and two types of solutions will be put forward. The first solution is in accordance with existing models with the progressive improvement of the system. The second solution would imply a complete transformation and the creation of new reference models adapted to the actual constraints of enterprises. This category of reference model, complete transformation, is constructed not only for enterprises but also local authorities. Present models integrating optimization around criteria such as quality, cost, and lead time by projecting themselves toward a target to be defined will undoubtedly lead us toward new models which take into account social, societal, and environmental parameters.

## 1 Introduction

Christmas is the traditional time for pantomime and this year was no exception with the annual last-ditch attempt of the President of the United States to reach an agreement with Congress to avert the threat of the fiscal cliff. In France too, the honeymoon period for the newly-elected socialist administration seems over with criticism from both the far left about the non-respect of election promises and from

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the right regarding the high levels of taxation and general economic policy. Globally this situation is mirrored in many countries in Europe. The only prescription offered to the PIIGS and other European countries is an increase in taxation and a reduction in government expenditure. Furthermore, the countries concerned are exposed to speculation and no alternative solution to the actual situation has been offered to them. Many economists believe that this austerity policy is not the appropriate treatment to heal the economic ailments of the crisis and bring hope of recovery. Others also subscribe to the opinion that only by investing in large investment projects (infrastructure etc.) can countries find long-term solutions. In any case, it is clear that it is becoming impossible for European enterprises to be competitive in this context because of the impact and competition of emerging countries. The only solution adopted by companies is to reduce the cost by decreasing product quality, externalizing activities needing low cost workers. Enterprises continue to look for solutions to reduce cost and improve their performance. Nobody knows exactly how to solve the situation not only in terms of the global economy but also in terms of performance for enterprises. The increase in unemployment in France for December 2012 amounted to +0.9 % which means 29,300 more people in December and 29 months consecutive increase. Some economic experts advocate reducing red tape and the constraints of enterprise creation, encouraging enterprise expansion through free exchange forces, and thereby facilitating the creation of new production sites. The development of policy specially oriented towards enterprises would solve the situation. So, what about the situation across the Channel in the United Kingdom? Other experts believe that the increase of national employment is necessary and national policy should be to think about the next step forward. Then what could we think about the debt of countries like Greece, and the impact on our situation. It is clear that the best solution for enterprises has yet to be created.

Enterprise modeling is regularly used for preparing enterprises to the outcome of the crisis. Indeed, the improvement of the enterprise global performance is the main objective of this use. Enterprises need to find the best way to resist the present crisis and then to improve in order to be more efficient. GRAI Methodology is one of the three main methodologies (with PERA, CIMOSA) of enterprise modeling. To support this methodology different tools are been developed. GRAIMOD is the last one being developed by using JAVA technology, JADE, and JESS platforms, and an open architecture and structure.

In this paper, the bases of elaboration of new models adapted to enterprises are given. For enterprise typology, reference models are defined per sector of activity and two types of solutions will be put forward. The first solution is the progressive improvement of existing enterprise models in order to take into account enterprise environment together with the actual and future globalization context. The actual performance criteria will be completed with carbon footprint and integration of social, societal, and environmental dimensions. The second solution would imply a complete transformation and the creation of new reference models adapted to the actual constraints of enterprises. This category of reference model, complete transformation, is constructed not only for enterprises but also local authorities.

What type of society do we want in the future, what balance, which optimum to have. What organization should be adopted by local authorities taking into consideration the present parameters and how to define tomorrow's enterprise in accordance with the society we want to live in? Both solutions will be presented. The use of GRAIMOD as a tool for aiding enterprises during this change will also be shown.

## 2 GRAIMOD: Concepts and Architectures

GRAI Methodology is one of the three main methodologies used for analyzing and designing enterprises. The GRAI approach is composed of four phases: An initialization phase to start the study, a modeling phase where the existing system is described, an analysis phase to detect the inconsistencies of the studied system, and a design phase during which the inconsistencies detected are corrected and a new system proposed. These concepts could be used to insure the transforming of enterprises which meet the real market needs (globalization, relocation, capacity to be proactive, cost optimization, lead time, quality, flexibility, etc…) and have to be adapted. An enterprise is completely described according to GRAI Methodology by finding five models: functional (functions of the enterprise and their links), physical (the production system), informational (the net, tools and informational flows), process (suite of sequences or tasks), and decisional (structure of orders, hierarchic organization). Then these models could be improved for increasing enterprise performance. GRAIMOD (Fig. 1) is a new tool being developed by ICAM Engineer School for proposing concrete solutions to improve enterprises according to new market evolutions. In this tool three kinds of modules are present:

- GRAIKERN, GRAITRANS, and GRAIWORKER are used for facilitating the links between the other modules of GRAIMOD.
- GRAIXPERT and GRAIMANAGER are used for analyzing the enterprise existing enterprise system.
- And GRAISUC, GRAIQUAL, and GRAI-SSE are developed for supporting the design process, and improving enterprise performance by optimising Quality, Cost, and Delivery date but also the Carbon footprint, social, societal, and other environmental aspects.

GRAIKERN is a graphic editor used for representing the different models associated to GRAI methodology. It is an interface. GRAIWORKER is the work base elaborated for managing, modifying, and capitalizing knowledge about the case in question. GRAITRANS is a Transfer Interface used for putting the new case in GRAIXPERT in order to improve its Cases Base. The reference model elaborated for each enterprise domain will be improved by the acquisition of this new model in GRAIXPERT between the different modules.

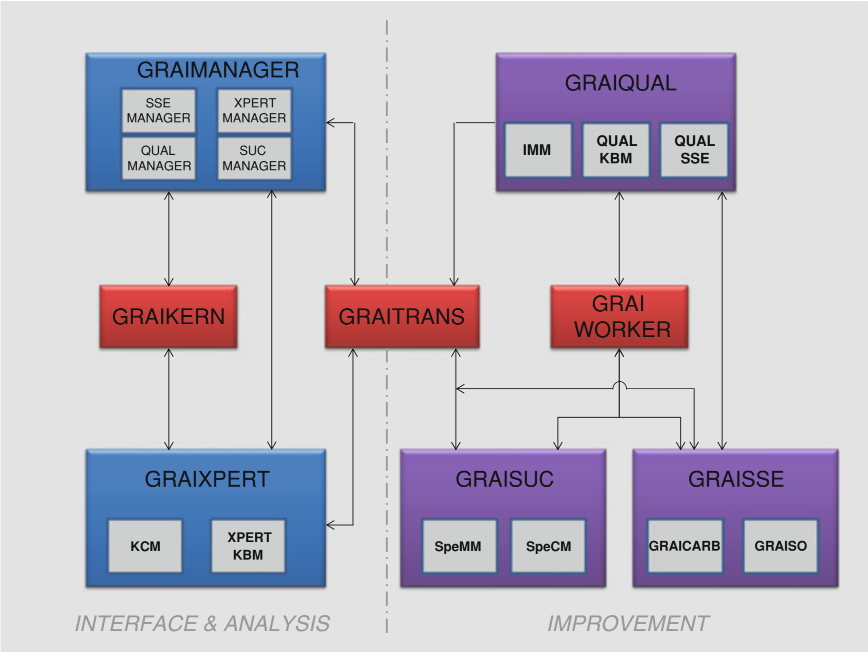


**Fig. 1** The new architecture of GRAIMOD

GRAIXPERT is a hybrid expert system [1, 3] for managing the analysis of the existing system and proposing a new system. It is composed of two sub-modules in interaction with GRAIKERN: the Knowledge Capitalization (KCM) and the Knowledge Based System (XPERTKBM) [12]. GRAIMANAGER is a management module used for organizing the different interactions between the modules of GRAIMOD [9]. It controls and manages the system's interactions with the users.

GRAISUC is a module used for managing the choice of an ERP or SCM tool for an enterprise. It is composed of two sub-modules SpeMM and SpeCM. The Specification Management Module (SpeMM) is used for choosing the appropriate ERP or SCM Tool of an enterprise. The specifications obtained are capitalized in the Specification Capitalisation Module (SpeCM). GRAIQUAL is a module used for managing quality approach implementation or quality improvement in an enterprise [2], [8]. It contains two sub-modules IMM and QUALKBM. The Improvements Management Module (IMM) is used for managing the different quality action plans of the enterprise. The Quality Knowledge Base Module (QUALKBM) is being elaborated for containing the rules related to quality certifications in order to use them for improving or elaborating quality in an enterprise.

A new module GRAI-SSE is being added to GRAIMOD in order to pinpoint the environmental, societal, and social dimensions in enterprises. This module would integrate for example changes associated to carbon management, IS0 26000, ISO

14000 implementations, social and societal evolutions impacts on enterprises [4–6, 9] but also territorial collectivities (states, associations, districts, etc.). This module is composed of two sub-modules: GRAICARB and GRAI-SO. GRAI-CARB is specially destined to manage the carbon footprint and GRAI-SO would be used for improving social, societal, and environmental dimensions in enterprises.

## 3 Enterprise Typology and Reference Models

In regards to the actual situation of enterprises and new constraints of the market, two types of design could be proposed. The first is destined to completely transform the enterprise by integrating a new economic model according to the improvement of enterprise performance; it means a new model based on a complete change. This type will be developed in the next part. The second is based on an adaptation from an existing system. Then we define knowledge as the process which transforms the whole set of known information Ci (stable state) into another Ci + 1. Knowledge Ci + 1 can be therefore defined as a sum of disjointed information or as a progressive improvement of the whole—C1 implying a restructuring of already acquired information. How does a child obtain understanding of the world around him? He integrates the new element with his already acquired knowledge and he structures his learning by employing actively what he has just experienced. Both cases correspond to a refinement of knowledge by the addition of distinct (new) knowledge or the improvement of existing knowledge. This concept is applied on GRAI Methodology and used in GRAIMOD. Then, we use this concept to define three modes of knowledge representation.

The reference models show the standard for a given sector of activity. They allow to define an ideal for each sector of activity, which can be used as a reference in the elaboration of the future model (TO BE model).

The cases studied are capitalized in order to enrich the knowledge capitalization module of GRAIXPERT with the objective being to improve the use of CBR (Case Based Reasoning).

The rules are used throughout the different phases of the operation of GRAI methodology. Not only do they serve to elaborate the modules concerning the existing situation of the enterprise (AS IS) but also to detect the malfunctions of the enterprise and establish its strengths and weaknesses and finally during the design phase of the future system(TO BE) [7, 10].

The use of a generic model corresponding to a precise activity sector appears obvious. So, two problems have to be solved: the enterprise typology and the elaboration of reference models for each domain. The use of classifying and generic reasoning allows to solve the problems and to achieve a design of enterprises. The classifying reasoning is used for elaborating enterprise classes Ci from pertinent criteria cp. The first criterion divides enterprises in subsets, the second continues this separation, and so on until obtaining a precise and specific class associated to each enterprise. The quality of the obtained tree, the new typology depends on the number of criteria used. The strength of this typology is that it could be improved progressively according to the experience acquired.

The set Sp of enterprises could be defined and characterized by the vector sp. each criterion cp could be associated to a vector $\alpha$ of which the number of column m corresponds to different attributes associated to the criterion.

$$\alpha = \left(\alpha_1 \cdot \alpha_j \cdot \alpha_m\right)^T$$

For instance, the use of the criterion “repetitiveness of production” implies the defining of three production attributes: One of a kind production, Mass production, and batch production (Fig. 2).

$X_j$ corresponds to the obtained set and $X_j$ is the associated vector, then the following linear combination could be deduced:

$$S_p = \sum_{j=1}^{m} x_j \, * \, \alpha_j$$

The union of different sets $X_j$ corresponds to the global set of enterprises.

The use of another pertinent criterion will divided each subset into small subsets. The linear combination deduced for three criteria of which the associated vectors are $\alpha$, $\beta$ and $\gamma$ is the following:

$$S_p = \sum_{j=1}^{m} \alpha_j \, * \, \left(\sum_{k=1}^{r} \beta_k \, * \, \left(\sum_{i=1}^{n} \gamma_i \, * \, c_i\right)\right)$$

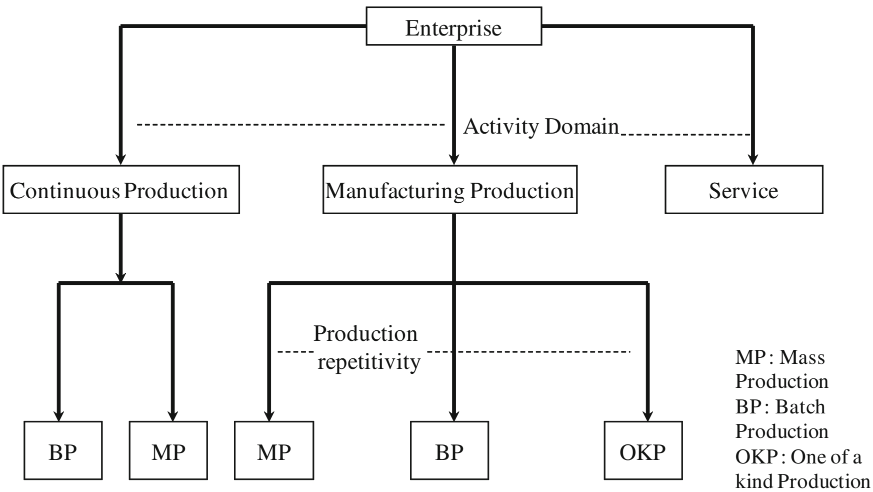


**Fig. 2** Process of typology structure

where m, r, and n correspond to the number of columns (attributes) of $\alpha$, $\beta$ $\gamma$ and $c_i$ an enterprise class.

Each class defined contains an elaborated model from expert knowledge and previous studies elaborated in the same class domain. The model obtained is called the reference model. This reference model is not sufficient for obtaining a new model for a specified enterprise.

Indeed, the generalization and classification reasoning has to be followed by a reasoning process of specifying. Experience in CAD and intelligent systems research shows that the generic approach needs to be completed by other mechanisms. The use of GRAIMOD is pertinent to capitalize reference models and the typology, the different enterprises studied and rules associated to the defined expert system (GRAIXPERT). Then the step of specifying the process could directly integrate expert knowledge and facilitate changes adapted to enterprise context and to market evolution.

In the basis of typologies existing in the literature such as Social enterprise typology, National Institute of Statistics and Economic Studies of France (INSEE) typology, economic sector typology, and size typology, some new criteria are proposed for the previous typology. A new typology is elaborated. The structure and the concepts of GRAIMOD defined typology are respected but the criteria change. The new typology combines the previous existing typologies and adapts them to GRAIMOD objectives.

The first criterion proposed in the new typology is enterprise economic sectors.

Primary sector with activities linked to the natural resources exploitation such as agriculture, forestry, fishing, and mining are included in the primary sector. It also includes all the activities producing unprocessed raw materials.

Secondary sector with activities linked to the processing of raw materials from the primary sector in production or consumption goods are included, like construction or manufacturing industry.

And the Tertiary sector with very wide range of activities like commerce, administration, transport, financial and real estate activities, services to businesses and individuals, education, health, and social action.

These sectors are used by the economists and geographers. They correspond to the three main economic sectors and are widely used.

The second criterion used is size:

– Small enterprises (less than 50 employees).
– Medium enterprises (50 to 500 employees instead of 250).
– And large enterprises (more than 500 employees).

The third criterion is activity. The idea is to use the existing INSEE classification (a French institute for …) based on branch and sector activities. A SIREN number is assigned to all French companies during their registration and this number is used for the lifetime of the company. As soon as the SIREN number is assigned, the company needs to select an APE code (Main Activity Practised) which characterizes the activity. This code is used for the Nomenclature of French activities (NAF).

The APE code is fundamental information for statistic companies because all the rankings of firms by industry are based on it. The quality of the studies about the economic and the structural situation also depends on it.

Only the first level of the NAF will be used for the primary and tertiary sectors.

The reason for using only a part this criterion is the conviction that performance models of these companies would be close to each other.

The objective is to obtain activity domains and define to each domain a reference model for facilitating enterprise improvement in this domain. Then for each enterprise of a domain, it would be possible by using GRAIMOD to define a new manufacturing model corresponding to this enterprise. GRAIMOD is being developed by using Java, JADE, and JESS platforms. The problem solving method associated to the tool uses a combination between multi-agent systems and Case Based Reasoning (CBR).Therefore, this tool is a hybrid and intelligent tool destined to improve enterprise performance.

## 4 Basis of New Economic Model

The objective of Enterprise modeling is essentially the improvement of enterprise global performance. The new economic context imposes the need to define a new economic model for enterprises. The elaboration of a typology and reference models associated to each defined class is one way for solving enterprises problems. But this way implies building the future enterprise structure by using the existing system and making changes progressively. Another way is the complete change of the enterprise in order to adapt not only to the crisis but also the post-crisis period.

The definition of reference models is used especially for a kind of ideal model according to a class. It allows to carry out benchmarking between this model and the Enterprise's existing model. Then, the improvements could be planned and applied progressively. This type of knowledge representation considers knowledge as a refinement, but the second way is complete transformation. Could we be able to propose in this case a new reference model in order to change the model definitively? This new model has not only to be developed for enterprises but also for local authorities.

The economic models associated to communism have shown their limits. Everybody thought that the best are those which are associated to capitalism [11]. Regarding the latest world events and the impact of different troubles due to non regulation in the liberal market, it is now clear for everybody that these models also have their drawbacks. However, alternative solutions presently do not exist. Therefore, it is difficult for not only countries but also for enterprises and local authorities to make sound decisions.

The objective is to develop a model with a complete break from the liberal one. This model has to take into account the reason of the actual crisis and parameters such as the environment, society, social view, and to give an optimization as a balanced model. Which type of society do we want for tomorrow? Which organization for local authorities? How to define the future enterprise in harmony with the desired future society?

What would be the place of software systems, computer aided tools in the development of this new model? What would be the place for territorial energy independence (enterprises, local collectivities, agribusiness, and people)?

How to give more efficiency to this self-sufficiency?

The objective is to build a model by integrating all the parameters. For instance, for energy independence, it would be to think about how to implement a global energy vision according to a department or town. In the French department of Vendee we could undertake an audit to analyze in detail the existing system and then detect inconsistencies, and deduce points to improve. The next step would be to define a new specific Vendee model in accordance with other best models used in the world but with the specificity and the identity of Vendee. This could give us for example a model with energy transition, integrating biomass, or solar energy, the model would be according to the most appropriate parameters possible. For validating this model, a demonstrator would be designed, elaborated, and exploited.

This approach proposed for the energy self-sufficiency problem would be generalized to all the previous questions in order to built reference models adapted to specific problems of local authority enterprises.

For logistic and supply chain problems, it would be interesting to integrate environmental, social, and societal dimensions in the improvement of the system. It would also be interesting not to focus only on B to B, flow management, packaging, cost, traceability, waste management, or B to C but also on how to take into account society, how also to reduce carbon footprint, and how to improve employee job satisfaction.

In short, the Vendee will serve as a part which will be studied completely and statistically with a scientific approach.

## 5 Application

The elaboration of reference models for each domain is undertaken. The process of elaboration is the same for both types: acquisition of context, existing system modeling, analysis, design, and finally proposition of reference model.

All the enterprises of Vendee have been chosen as a study area. Indeed, there are more than seven thousand enterprises in Vendee, corresponding well to a quota of all enterprises in France for a scientific study. The result of the study could easily be extended to enterprises nationwide in France, then throughout Europe. The quota chosen is really representative.

So, Vendee enterprises represent for the study the global mathematical population. A meeting with the Chamber of Commerce allows to define how many enterprises would give an answer to a questionnaire sent to them for acquiring context and to make an enterprise classification. Because of the crisis and the difficult situation of enterprises, enterprises are concentrating their efforts on how to find money and find it difficult to find the time to answer this kind of questionnaire, only 10 % would surely gave an answer. For the population, it means that 700 enterprises would be ready to give us data for our analysis.

The proposition of extension of GRAIMOD is for treating the data obtained and exploiting them for elaborating reference models. GRAI-SSE, this extension contains a data base with the questionnaire in which the responses will be studied. It allows to find good habits of enterprises in taking into account social, societal, and environmental dimensions. The use of GRAIMOD for improving enterprise performance is now already efficient. Indeed, for an enterprise, the modeling, the analysis, and the design phase are really well managed by the tool.

The tool is also efficient for reducing lead time, choosing and implementing new tools in the enterprise, and implementing quality approach. But it is clear that the tool is less efficient in the management of improvement integrating carbon footprint reduction, social and, societal dimensions, and respect of environmental norms. Then, GRAI-SSE would bring this efficiency, by focusing only on this criterion. The linear combination with the other performance criteria would be managed by GRAIMANAGER. The result of the questionnaire would allow to adjust the enterprise typology elaborated. It would show us the enterprises which changed their economic model by integrating other dimensions than cost, quality, and lead time. For instance, some of them are green, ecological, virtuous, showing solidarity, ethical, or socially 'responsible' enterprises. The study allows to focus on this kind of enterprises and to valorize them. The objective is to show those not having chosen to follow this way the real advantages of such an approach and for those who are already started to help them become even more efficient.

Before using the questionnaire and analyzing in detail enterprises of Vendee, the database of enterprises in collaboration with Icam Vendee is used for validating the coherence in the new typology. 802 enterprises are selected for this small statistics study. The first criterion allows to obtain subdivision of the 802 enterprises into (primary, secondary, and tertiary) sectors. The secondary sector contains 528 enterprises. The second criterion is used for subdividing enterprises of this sector is size (small, medium, and large). The number of enterprises corresponding to small enterprises is 169. Then the third criterion enables to focus on the 169 small enterprises and to obtain data contained in Fig. 3.

Finally for each of the obtained domains, a reference model could be defined. For instance, a study of Construction enterprises (29) would facilitate a generalization to all enterprises of the domain: secondary sector, small enterprises, and construction activity.

GRAI-SSE would serve for doing carbon management. A sub-module GRAI-CARB is being developed by using the ADEME (French Agency in charge of environmental questions) database for carbon footprint management. GRAI-SSE

**III - Activity: Small Enterprises**

| Activity Code | Activity | Number |
|---|---|---|
| C | CONSTRUCTION | 29 |
| IA | Automotive Idustry | 8 |
| IAFB | Agribusiness Industry and Drink manufacturing | 11 |
| IBFM | Wood Industry | 7 |
| ICFPCPM | Chemical Industry and non metallic manufacturing | 14 |
| IFPIEO | Electronic, Computer and Optic Industry | 25 |
| IMFPM | Metallic Industry | 49 |
| IPCI | Industry of paper | 3 |
| IRIME | Technical services and machines implatation Industry | 19 |
| ITHCC | Clothes manufaturing industry | 4 |
| Small Enterprises | | 169 |

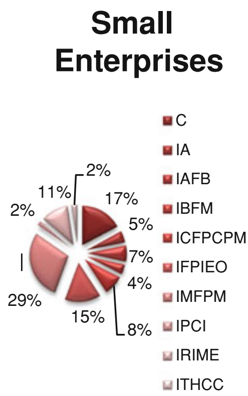


**Fig. 3** Example of enterprise typology

would also serve for implementing ISO 26000, managing ergonomic practices, managing how to make employees happy at work, and more efficient for the enterprise. The societal aspect could also be managed. The tool would also serve for improving local authorities.

To conclude, the study extended to Vendee department has been undertaken. The first step will be finished for February 2013. Then the typology elaborated will be adjusted and reference models developed for each new class. The next step will be modeling of the enterprises which will start using specific models in order to improve the reference models defined. Simultaneously, the elaboration of another economic model more adapted to the actual context and able to protect enterprises in the future will be developed.

## 6 Conclusion

Everyday there are a lot of enterprises which unfortunately cease their activities because of the crisis both in France and throughout Europe. There are also enterprises which have laid off staff in order to reduce the number of their employees. It is difficult to convince them that they should rather reorganize to become more efficient and reducing costs is not necessarily the right way. Enterprise modeling allows to prepare them for the post-crisis period and to show them really how they could integrate different new parameters for being adapted to the future. Environmental, social, and societal dimensions as a performance criterion are not just a fashion, but a real need. GRAI Methodology allows to improve to the global performance of Enterprises and particularly SMEs.

For supporting this methodology GRAIMOD is being elaborated by Icam Vendee in order to be more efficient during the improvement. The addition of carbon management as the fourth criterion with quality, cost, and delay is now acted. Then in this paper we propose to define especially for this criterion a module for facilitating the management of changes due to environmental, social, and societal dimensions. GRAICARB is the module dedicated for this management.

In this paper, we also propose to define reference models as an ideal for improving progressively an enterprise of a given activity sector. An enterprise typology is proposed with the objective to give the best ideal model to each enterprise which desires to improve its performance. A second type of reference model is being studied with the particularity to be alternative solutions for liberal economic model.

The proximity of Icam Vendee to enterprises will allow to enrich the case base of GRAIMOD by making modeling of them but also to improve the reference models and the typology elaborated.

## References


1. Aamodt A (1994) Case-based reasoning: foundational issues, methodological variations, and system approaches. Artif Intel Commun 7(1):39–59
2. Rad AMM (2006) The impact of organizational culture on the successful implementation of total quality management. TQM Mag 18(6):606–625
3. Brown DC, Chandrasekaran B (1985) Expert system for a class of mechanical design activities. Knowledge engineering in CAD. Elsevier, Amsterdam
4. Jed E, Bonni S (2000) The nature of returns, a social capital markets inquiry into the elements of investments and the blended value proposition. Harvard Business School, Boston, MA
5. European commission (2011) Responsabilité sociale des entreprises: une nouvelle stratégie de l'UE pour la période 2011–2014, Brussels, Belgium, 2011
6. Bressy G, Konkuyt C (2011) Management et économie des enterprises, Edition Sirey, 10ième edition, Paris, 2011 (ISBN: 9782247112203)
7. Doumeingts G, Ducq Y (1999) Enterprise modelling techniques to improve enterprise performances. In: Proceedings of the international conference of concurrent enterprising: ICE'99, The Hague, The Netherlands, 1999
8. Dossou PE, Mitchell P (2010) Carbon reduction: new criteria of supply chain performance. In: Proceedings of FAIM 2010, Oakland, East Bay, USA, 2010
9. Dossou PE, Pawlewski P (2010) Using multi-agent system for improving and implementing a new enterprise modeling tool. In: Proceedings of PAAMS2010, Salamanca, Spain, 2010
10. Dossou PE, Mitchell P (2012) GRAI methodology—a rudder in the economic storm for the SMEs. In: Proceedings of FAIM 2012, Helsinki, Finland, 2012
11. Thomas R (1999) L'entreprise partagée? Une pratique différente des relations sociales, Maxima-Laurent du Mesnil éditeur, Paris, 1999 (ISBN: 2-84001-173-5)
12. Xia Q et al (1999) Knowledge architecture and system design for intelligent operation support systems. J Expert Syst Appl 17(2):115–127

# Process Performance Assessment in Collaborative Manufacturing Environments: A Role Oriented Approach

**António Almeida, Filipe Ferreira, Américo Azevedo and Álvaro Caldas**

**Abstract** Due to the increasing globalization process and the current economic situation, the power has shifted from the producer to the costumer, forcing companies to become more aware of the market needs. In order to become more customer-oriented, companies have been enhancing their management capabilities by shifting from a functional oriented approach to a process centered strategy, where core inter-firms processes can be seamlessly monitored and controlled. Since it is not possible to manage a system if its performance cannot be measured continuously during its entire life cycle, it is necessary to explore flexible and agile performance measurement and management systems as they are important tools capable of supporting the achievement of the strategic goals on the operational side. In the recent years several research projects have developed techniques and tools that support the collaboration. However they are restricted to the business level. In order to achieve the goals with the best performance, innovative and appropriate process monitoring and control mechanisms are needed. Consequently, this research provides an innovative solution that facilitates not only the gathering of operational and strategic information but also the assessment of collaborative manufacturing processes behavior following a fuzzy approach.

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## 1 Introduction

Due to the increasing globalization process and the current economic situation, the power has shifted from the producer to the costumer, forcing companies to become more aware of the market needs. To capitalize business opportunities, manufacturing organizations need to improve their business processes and operations in order to become more flexible, manage shorter product life cycles, and thus satisfy their customers by continuously adapting themselves to meet the needs and expectations of the market [1]. Furthermore, in order to become more customer-oriented, companies have been enhancing their management capabilities by shifting from a standalone functional oriented approach to an inter-firm process centered strategy, where collaborative processes need to be seamlessly designed, monitored and controlled [2, 3].

In this context, SMEs need to re-invent the concept of enterprise by collaborating with outside partners in order to continue competitive and achieve business goals, enter in new market segments and quickly answer to business opportunities with special and innovative requirements, taking into account that chirurgical improvements can present important competitive advantages [4, 5]. In order to gain such competitive advantages, decision makers are more and more interested in developing strategies designed to provide companies with resources and capabilities that will allow them to implement quantitative systems and risk analysis methodologies so that they can control their processes in a more proactive way. As a consequence, process-based companies are enhancing their decision-making capabilities by evaluating risks, uncertainties and variability within this important task.

Even though process management is a valuable tool for operations analysis, its potential in the strategic scope is also large and perhaps still untapped. Thus, in order to efficiently achieve the goals enumerated before, organizations must be able to implement and maintain the ability to continuously monitor and foresee the behavior of the production chain by tracking the performance of their core partners. However, it is necessary to explore flexible and agile performance management systems for collaborative manufacturing processes, recognizing that each partner has a specific role in the process execution. Using a proper combination of leading and legging Key Performance Indicators (KPIs), as well as a tool capable to collect, analyze, and show real time structured performance information, it possible to holistically monitor and control production chains in a proactive way.

This paper presents an innovative approach for collaborative process performance assessment, based on a fuzzy description of partners' expected behavior. The main advantage of this proposal is that it becomes possible to evaluate partners' in a more reliable way due to the fact that partners are assessed taking into account their specific type of activities. For instance, for the machinery industry, during the design and implementation of a new type of machine, different partners collaborate with different expertise following a specific workflow. Hence, each partner should be evaluated according to its type of activity and maturity within this collaborative environment. In this context, the paper presents a solution developed in the scope of a European project [6], composed by three main modules (partner's behavior definition, KPIs processing and partners' alignment assessment) which synergies allow to bridge the gap between operational and strategic layers in collaborative manufacturing environment.

Aiming to contextualize and describe this performance assessment approach, the paper here presented is organized as follows. Section 2 provides the foundations concerning the research topics addressed during the process performance management approach presentation. Following, Chap. 3 presents the architecture of the developed framework, as well as the detailed description of its components. Finally, Sect. 4 concludes the paper explaining which should be the next steps to be followed in future researches around this issue.

## 2 Foundations and Research Topics

### *2.1 Collaborative Manufacturing Environments*

Due to the global competitiveness, a diversity of new organizations based on collaboration have emerged (the so-called collaborative networks). These coalitions between firms were created to face market challenges and overcome the limitations by joining abilities. Thus, companies with specific knowledge and competencies, seek to align with other companies to meet requirements and thus exploit and quickly answer to emerging business opportunities, forming a Collaborative Network in the form of Virtual Enterprise [2, 4].

The definition of Virtual Enterprise (VE) used in this paper is based on the definition proposed by Camarinha-Matos et al. "A Virtual Enterprise represents a temporary alliance of organizations that come together to share skills or core competencies and resources, in order to answer to a specific business opportunity" [2].

The establishment of a VE is triggered by a new business opportunity. Consequently, partners with the skills needed for product development and manufacturing are selected. After the negotiation of contracts for signature, the virtual enterprise is ready to start its operation [2, 7]. Normally there is an entity which performs the processes of partner search and selection, and configures suitable infrastructures for VE formations and commitment. This entity is normally the one that identifies the business opportunity as is known as the VE Broker [2].

Temporality is an important characteristic of virtual enterprises because it seeks to operate in the short run, and aims to achieve business opportunities in the short and medium term. Virtual enterprises are expected to overcome geographic and temporal barriers, bringing together dispersed firms. The prevailing feature of the virtual enterprise is the complementarity of skills between partners, i.e., each network partner dominates a sub-process or has a specific knowledge about a process or product. All partners have to contribute directly or indirectly in creating value. Thus, the combination of skills provides synergy and greater flexibility to meet customer requirements.

## 2.2 Business Activity Monitoring

Business Activity Monitoring describes the processes and technologies that provide real-time situation awareness, as well as access to and analysis of key performance indicators, based on event-driven sources of data. Business Activity Monitoring (BAM) is used to improve the speed and effectiveness of business operations by keeping track of what is happening now and raising awareness of issues as soon as they can be detected. BAM applications can emit alerts about a business opportunity or problem, drive a dashboard with metrics or status, make use of predictive and historical information, display an event log and offer drill-down features. BAM also "drives the innovation by detecting events, filtering them and triggering business process management (BPM) solutions". BAM may enable new ways of performing vertical applications that will result in significantly increased revenue or cost savings for an enterprise [8].

Although the purpose of BAM technology is to provide business users with real-time access to, and analysis about, key performance indicators, the level of complexity in the solution can widely vary. BAM functionality is based on a relatively simple architecture. Alerts and frequently updated displays are driven by a processing and analytic engine that is supplied with a stream of events that is received or collected from a variety of sources working in real time. BAM must address the general requirements and each the basic features of four architectural categories: Event collection, filtering and transformation, Delivery and display, analysis and processing, and Operational databases.

The current challenge is to bring BAM functionalities to the Manufacturing SMEs field, through a web based platform. Thus, SMEs can manage their collaborative processes without the need of large ICT investments as in many cases they are not capable to do such type of investments [6].

## 2.3 Partner Alignment

A process is a set of activities implemented in order to transform one or more inputs into valuable outputs (e.g., products or services for customers). Based on the concept that process oriented organizations must put their effort in supplying their costumers with products/services that respond to their needs, when it comes to processes risk assessment it is possible to define a risk factor as the deviation probability of the real process's result compared with the expected target from the costumer's point of view, both in terms of efficiency and effectiveness.

This deviation can be caused by a series of internal and external disturbances, such as the uncertainty of the business environment, the complexity of the customers' requirements for products or services, and the limitations of the company's experience, or the staff's skills to manage the company's weaknesses. In sum, three clusters of risk factors can be defined [9]:

- Risks from process operational environment: mainly related with internal and external environmental changes in which the company has been developed (e.g., economic risks, cooperative partner risks or risks imposed by competitors.
- Risks from the process's object: related with factors that disturb the outcome of the business processes (e.g., operational perform oscillation risks, product price and quality risk, risks from demand forecasting).
- Risks from the business process participants: mainly related with the limitation of the organization's strengths and staff's abilities including capital, technological, personal, and operational risks.

Since risk analysis in process management presents specific requirements and characteristics, it is necessary to shape the risk management process described before so that it is possible to handle process management risk factors described above. During a process performance management the three main pillars related with efficiency and effectiveness are evaluated: cost, time, and quality. From these three factors it is possible to build a perspective according the stakeholders' requirements. During a risk analysis these perspectives should also be taken into account.

For organizations to survive and prosper they must fit their resources and capabilities to the opportunities created by the external environment. Therefore, the Fit concept was explored in order to enhance the linkage between business environment, organizational structure and internal processes. This relationship or alignment between the requirements of the business environment and the strategy applied by the organization is called Strategic Fit.

Therefore, in the scope of these Virtual Enterprises, organizations explore relations that are normally the result of negotiations based on mutual trust and based on heterarchy architectures focused on a certain goal. In fact, adopting a contrasting network approach, organizations focus not only on the company, but also on the value-creating system itself, within which different partners work together to co-produce value [10]. However, it has been depicted that an ad-hoc collaboration by itself is not enough. Because of this observation, it was necessary explore the concept of alignment in order to assess whether an organization is able to participate in a network by adding value to the overall objective, envisioning the strategy defined by the network.

Although it has other connotations, the term 'alignment' is usually defined as an arrangement of groups or forces in relation to one another. Therefore, in the context of VEs it is possible to understand that this term can be interpreted as an adjusted relationship between the performance achieved by participants and the strategic goals of the VE considering that each partner must contribute with self-operation efficiency in order to achieve inter-organizational alignment. According to Francisco et al. [11], there are three main instants in the VE's life cycle which can be determined to measure inter-organizational alignment, which are: partner selection, agreement, and operation management. Therefore, the alignment should be measured primarily during partner selection and repeated during the entire life cycle of the VE, including the instant of agreement, and especially when the network is running (operation).

Internal fit is usually related with performance improvements to ensure a higher level of alignment. Therefore, the state of the internal fit in VEs can be represented by the relationships between intra- and inter-organizational processes. Moreover, in the management context this term can be used properly to conceptualise a situation where inter-organizational structures, stakeholders, stockholders, and whichever existing participant or process in a business environment, are strictly combined under strategic decisions to achieve specific objectives and goals.

## 3 Inter-firm Alignment Assessment

Due to the fact that more and more process performance management tools and methodologies are considered as being essential for the continuous improvement of enterprises, new approaches have been developed. However, most of them are limited to create virtual manufacturing enterprises at a business level and in many cases they concentrate on the partner-finding and factory-building processes. Thus the current approaches do not allow for innovation and higher management and operational efficiency in networked operations and thus, we explicit the need of a holistic environment to help virtual manufacturing enterprises move beyond existing operational limitations by providing concrete tools and approaches for leveraging the information exchange.

In general, a Process Performance Measurement System can be seen as an information system that supports organizations so that they can visualize and continuously improve process performance, controlling its execution by comparing process models with data collected. In order to achieve the main goals defined for a process performance management system, two fundamental mechanisms need to be explored:

- Process performance measuring mechanism capable of extracting performance-relevant data from operational information systems; it populates this data into a dedicated process data warehouse and provides mechanisms for flexible analysis of business processes.
- Mechanism capable of translating process analysis results into recommendations for appropriate improvements in the process design. Improvements are implemented by refining the respective process models, which in turn triggers another Plan-Do-Check-Act (PDCA) cycle.

However, in order to successfully implement a process performance management system, the following issues must be taken in account: (1) identify business process goals, (2) define indicators for each process goal, (3) broaden goals and indicators; (4) ensure acceptance; (5) define target values and data source; (6) evaluate technical feasibility and economy efficiency; (7) improve inter-firms process; and (8) update assessment behavior curve continuously.

Thus, this work proposes an inter-firms process assessment framework for partners alignment, developed in the scope of a European project [6] that includes loosely coupled ICT platform with the applications such as collaborative manufacturing process designer, partners profile provision and discovery, process execution engine, process monitoring, process optimization, forecasting and simulation, which are all integrated and accessible via an holistic dashboard. The inter-firms process assessment framework is following presented in the IDEF0 diagram depicted in Fig. 1.

As inputs, this framework receives from the Process Designer the process description in a XML file. A new Process Model is created in the Process Designer either as an empty model or based on a ready-to-use template from templates repository. As the Virtual Enterprise broker starts to design (edit) the process, the model enters its 'in design' phase. This is the core phase for the Process Designer and the designer can perform several types of tasks in it, such as: manage process metadata with the goal to enable automation and make the process discoverable; design process models, e.g., add/configure/remove process activities or other process model elements, using the BPMN 2.0 notation and semantics supported by the Process model design tool; define KPIs based on the internal process variables and on imported variables from sensors and legacy systems. When a process model design is ready to be executed, e.g., process activities have services bound to them, the VE broker can request a new instance of the model to be executed by the Process Execution Engine. At this time, the Process Monitoring tool retrieves all static information from the BPMN2.0 file and stores it at the cloud-based data storage.

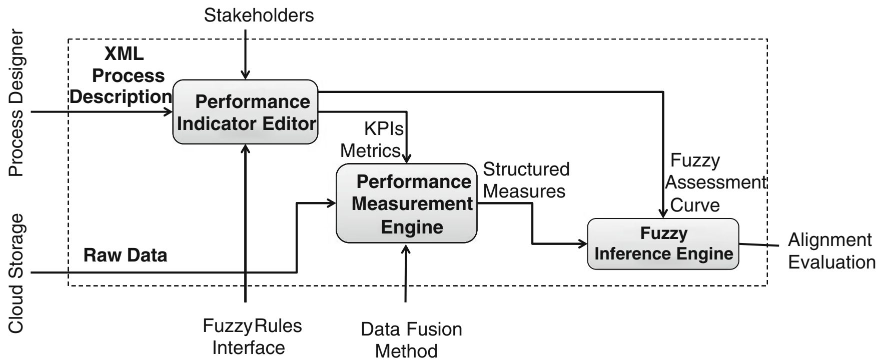


**Fig. 1** Inter-firms processes assessment

During the execution period, the Events Receiver captures the events produced by the Process Execution Engine and stores the relevant event data. Most process analyses are based on the aggregation, correlation and evaluation of events that occur during the execution of a process. These events represent state changes of objects within the context of a business process. These objects may be activities, actors, data elements, information systems, or entire processes, among others. For example, activities can begin and end, actors can log on and off, the values of data elements may change, and many other events can occur over the typical lifespan of a process instance. The scope of events considered for analysis determines the context envelope of the analysis. In other words, a narrowly scoped process analysis might focus on a single activity, by examining just those events that originated from this activity, its performers, and the resources that are input in and output from the activity. In contrast, a more widely scoped process analysis might include events from multiple processes; involve data sources outside the organization, and events from non-process-centric information systems.

After receiving all this information, the Performance Indicator Editor (PIE) is the first entity of this framework. Trough this tool, the VE broker should be capable to understand which are the main goals to be achieved by a specific process as well as the role of each partner in the process execution and, define the relevant KPIs and its metrics. This means that, in order to achieve a holistic and global vision of the process behavior, the different mind-sets of the stakeholders involved in the process execution should be standardized, aiming to evaluate each partner according to its role. Therefore, adopting a fuzzy logic approach, the different strategic objectives and paradigms are aggregated and, the non-linearity's imposed by this multi-role performance assessment tool can be modelled.

As it is possible to see in Fig. 1, one of the outputs of the PIE block is a series of fuzzy assessment curve instances that will be used by the fuzzy engine as kernel for the overall process alignment assessment. This means that, for each partner, a fuzzy assessment curve should be designed, according to its role in the process execution. However, in order to have a reliable evaluation result it is important to gather operational data in real time. Therefore, a performance measurement engine captures and structures the dynamic data related with the process execution, and consequently generates rich performance information that allows evaluating the process execution against the defined objectives.

At the end, through the integration of these three components (Fig. 1) it is expected to achieve a qualitative evaluation that will synthetize the general overview of the process, taking into account each specific partner role. Moreover, due to a wisely selection of a series of indicators (combination of lagging and leading indicators), and the capability to understand and model the process non-linearity's, through the fuzzy technology adoption, it should be possible to achieve a proactive performance management approach and consequently support decision makers to take the right decisions at the right time due to the drill-down capability.

## 3.1 Linking Performance to Strategy

Similarly to the product development process, process based manufacturing systems should be permanently adapted for changing products, markets and technologies in order to fulfil economic, social and ecologic requirements. Following the paradigm that a manufacturing system is simply a very complex type of product, a functional modelling approach from product design has been adapted to model the strategic goals of a factory (Fig. 2). Function Oriented Product Description (FOPD) defines that, in order to achieve a high quality product capable to fulfil the market needs, it is critical to assure that product functionalities are aligned with the requirements envisioned for the market [12].

In line with this paradigm, when defining a manufacturing system process-based, at the strategic level it is important to define not only the functional requirements, defining the specific behaviors or functions, but also the means (non-functional requirements) that will support the achievement of these functional requirements [9]. Nevertheless, regarding control issues, if decision makers are not capable to evaluate, in a formalized way, if the behavior of the process designed is aligned with the objectives then it is not feasible to guarantee that its control. Thus, two different concepts were explored: key performance indicators and metrics. While a key performance indicator is responsible by represent a certain non-functional requirement by a measurable concept, capable to evaluate quantitatively a certain object in a specific scope, as well as target behavior to be achieved, a metric is a characteristic of a KPI responsible by formulate it into a mathematical way, with a well-defined objective function.

Thus, the PID is mainly responsible by providing the Key Performance Indicators (KPIs) related to the manufacturing processes and partners, as well as the metrics that will support its calculation. Following the concept that, by building rich and aggregated KPIs it is possible to build business intelligence, through the user interface of this platform, users are allowed to manipulate data and create KPIs metrics to be continuously calculated at the Process Performance Measurement engine.

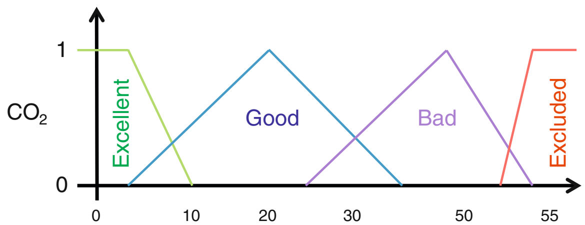


**Fig. 2** $CO_2$ membership functions

### *3.2 Process Performance Measurement*

Aiming to support the performance behavior assessment, a performance measurement engine (PME) for gathering, processing, and analyzing quantified information on performance was built. This engine was designed not only to measure the performance of specific processes but also to be generic enough to be easily integrated in any environment, integrating data from multi-sources in a user-friendly way, interpreting the production system structure, calculating indicators in a dynamic way according to the formula specified and comparing the values obtained with the expected values (target values).

In order to guarantee the integration between this module and the Broker, a metric definition based on a hierarchical approach was adopted. By using this innovative approach, users not only become capable to built aggregated KPIs using drag and drop functionalities, but also allows them to visualize the KPI structure together presenting the actual performance values for the indicators calculated. This way, it becomes possible to drill-down a problem and determine which is the root cause of a problem.

Aiming to achieve this hierarchical approach, three levels of indicators have been defined: Raw Data, Performance Indicators (PI) and Key Performance Indicators (KPI). The Raw Data level gathers the information available on the production system, providing meaning to the measurements obtained from the different data sources available. Therefore, the measurements available in several sources at different levels such as Office applications, Enterprise resource Planning Systems, Manufacturing Execution Systems, Shop Floor Controllers or Smart Sensors attached to products, capable to send information directly to the cloud storage, can be located and modelled to be reused every time this kind of information is required in order to calculate indicators affected by them. On the other hand, PI are mainly responsible by fuse Raw Data in order to, from this enormous quantity of unstructured data, create information with an associated meaning. Finally, KPI should be used not only as an aggregation of PI, but also as a way of compile tactical and even strategic information. In line with this, KPI should be designed aiming at aggregate huge quantity of information that can be easily interpreted by the decision makers. In sum, with this hierarchical metric definition, it is possible to guarantee that operational, tactical and strategic information can be fused within a single but rich aggregated performance indicator, combining different performance perspectives.

After the calculations phase finish, the software generates performance reports in a high-resolution view (ability to increase the level of detail of a system's performance snapshot) that can be broadcasted by stakeholders.

### 3.3 Fuzzy Alignment Assessment

The objective of this last step is using Fuzzy Logic to evaluate the level of alignment of the collaborative manufacturing process, based on the overall stakeholder's point of view. Indeed, one of the main advantages of this decision support tool is its ability to compile, in an iterative way, the different vision and goals of the actors responsible by each activities of the process and attribute a qualitative rate, taking into account the information captured in real time from the cloud storage.

Initially, for each KPI defined in the scope of a process objective, the broker should identify which are the boundaries of each indicator, as well as the different intervals and respective classifications (fuzzification process). It is important to underline that, this should be an iterative process, aiming to take into account the requirements and specifications of each stakeholder with responsibilities during the process execution. In the following table, it is depicted an example, from an Engineering to Order (ETO) company in the machinery sector, where two PIs [$CO_2$ emissions per order ($CO_2$) and Months per Order (MPO)] from different perspectives were used in order to evaluate the sustainability (SUS) KPI.

For the fuzzification process, both triangular functions and special trapezoidal membership functions (R-function and L-function) were used. As presented in Fig. 2, the entire $CO_2$ universe was clustered, taking into account the vision of the partners involved into the process execution.

| KPI | Intervals | | | |
|---|---|---|---|---|
| $CO_2$ (ton/order) | 0–0.5 | 0.51–1 | 1.1–1.5 | 1.5–2 |
| | Excellent | Good | Bad | Excluded |
| MPO (months/order) | 0–2 | 2–3 | 3–4 | 4–5 |
| | Excellent | Good | Bad | Excluded |

Following, based on a fuzzy rules editor, the broker is responsible by configure the fuzzy logic that will combine the different fuzzification process instances for each KPI. In this specific case, in order to achieve an understandable IF–THEN mind-set of the case, a verbose approach was adopted. An example of an if–then rule following a verbose approach is the following: IF ($CO_2$ is Good) AND (HPI is Bad) THEN SUS is OK. In fact, the Fuzzy Logic, which is normally used when there is not enough knowledge and certainty about the system to be controlled, presents interesting characteristics that make it possible to model nonlinear systems more easily. With this nonlinear system modeller, it is possible to achieve a better definition, decrease the modulation error and control more complex systems. At the end of this process, it was possible to achieve a 3D graph (Fig. 3) that represents the nonlinearity desired for the partner behavior during the process execution.

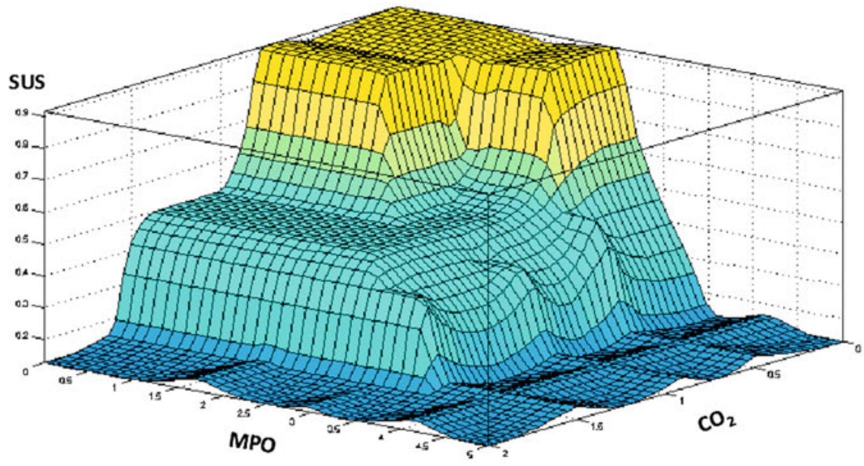


**Fig. 3** Matlab® fuzzy tool and the 3D graph results

As it is possible to see in the following image, as the PI values increase, there is a decrease in the alignment rate of the partner. In this 3D graph, the navy blue color means that a certain partner is rated as "excluded" and in terms of sustainability issues it is completely misaligned, while the color yellow means that it is highly aligned with the expected inter-firm process behavior and represents an added value for the goals achievement.

Finally, after an individual analysis of the partner performance, according the Broker requirements, it is necessary to study the global alignment of the partners involved in the process execution. Thus, aiming to achieve this, a new iteration of the fuzzy logic was applied. However, at this stage, the main objective is to use the KPIs resultant from the evaluations performed for each partner in order to obtain the global alignment rate for the process execution. In fact, the methodology is similarly to the previous one, being the main difference the fact that the intervals defined during the membership function designing should represent the role of a partner in the process execution. For instance, it is expected that a certain partner more related with production should produce more $CO_2$ than another partner mainly responsible by product design.

In line with this information, the Broker can not only determine how partners can improve their performance to benefit the process execution, by simply making a KPI analysis. Evidences must be produced so that they can support decision makers to replace a specific partner in order to meet the overall behavior of the process or avoid to select a specific partner in the future. In fact, if this methodology automatically retrieves performance data in real-time from the cloud storage, this could be an important asset to the system management because it makes possible to drill down a problem and understand which is the partner that is not aligned with the process execution vision.

## 4 Conclusion and Further Research

This paper presents a proactive performance management approach capable of supporting Virtual Enterprise brokers in controlling their collaborative manufacturing processes by using a process alignment evaluation tool as part of a broader platform developed within a European project.

Since processes should be seen as an important inter-organizational managerial tool, where partners' alignment is critical for the success of the VE, we propose a proactive performance evaluation solution based on an intelligent system approach.

Three modules compose this new approach: Performance Indicator Editor, Performance Measurement Engine, Fuzzy Engine. The Performance Indicator Editor is responsible by receiving the static information concerning the process execution (strategic and tactical information), iteratively compile the different stakeholders mind-sets in order to achieve a global vision of the process objectives (Functional Requirements) and establish the mapping between these objectives and KPIs. On the other hand, the PME is responsible for understand the KPIs metrics, gather raw data related with the process instance log and generate the KPI's measures in real time. With all this information, the Fuzzy Engine is able to provide a qualitative assessment of the process behavior, based on a fuzzy logic. Adopting this technology, it becomes possible to manage complex situations where there isn't a total clear vision of the expected system behavior, due to the capability to manage the subjectivity imposed by the different stakeholders. Moreover, through the selection of a wisely combination of legging and leading indicators, it is possible to not only assess the partners alignment with measures related with past performances, but also integrate indicators that allow to foresee future behaviors. Thus, VE's Broker become capable to have in real time a qualitative assessment of the collaborative process execution that can be used as pillar for decision makers. Due to the granularity imposed by this approach, a drill-down analysis can be performed when misalignment is registered, in order to identify which partner is not corresponding to the expectations.

As next steps, we intend to implement this approach as part of process monitoring module to be applied in the machinery industry based on collaborative manufacturing processes. With this validation proof, we intend to measure the performance of the different partners involved in a machine development processes and consequently continuously validate their alignment.

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## References

1. Yusuf Y, Gunasekaran A et al (2004) Agile supply chain capabilities: determinants of competitive objectives. Eur J Oper Res 159(2):379–392
2. Camarinha-Matos LM, Afsarmanesh H, Galeano N, Molina A (2008) Collaborative networked organizations: concepts and practice in manufacturing enterprise. Comput Ind Eng 57(1):46–60
3. Barney JB, Clark DN (2007) Resource-based theory: creating and sustaining competitive advantage. In: Sirmon DG, Hitt MA, Ireland RD (eds) Oxford University Press, New York
4. Osterwalder A, Pigneur Y, Tucci CL (2005) Clarifying business models: origins, present and future of the concept. Commun Assoc Inf Syst 16:1–29
5. Koren Y (2010) The global manufacturing revolution: product-process-business integration and reconfigurable systems. Wiley, New York
6. Adventure project (http://www.fp7-adventure.eu). Accessed on 16 Jan 2013
7. Molina A, Velandia M, Galeano N (2007) Virtual enterprise brokerage: a structure-driven strategy to achieve build to order supply chains. Int J Prod Res 45(17):3853–3880
8. Gassman B (2005) Selection requirements for business activity monitoring tools. Gartner Research
9. Kefan X, Jieming L, et al. (2007) A theoretical and empirical analysis of risk management in business process. International conference on in wireless communications, networking and mobile computing
10. Peppard J, Rylander A (2006) From value chain to value network: insights for mobile operators. Eur Manage J 24(2–3):128–141
11. Azevedo A, Francisco RD (2007) Dynamic performance management in business networks environment. In: Cunha FP, Maropoulos PG (eds) Digital enterprise technology: perspectives and future challenges. Springer, New York, pp 401–408
12. da Piedade Francisco R, Azevedo A, Almeida A (2012) Alignment prediction in collaborative networks. J Manuf Technol Manage 23(8):1038–1056

# Measuring Job Satisfaction of Shift Workers Based on Fuzzy Systems Approach

**Tuğçen Hatipoğlu, Mehlika Kocabaş, Atakan Alkan and Ahmet Cihan**

**Abstract** Companies are supposed to be aware of the parameters of job satisfaction to retain a greater motivation and reduce the staff turnover. Shift workers have non-routine work hours which lead to some social disadvantages, higher levels of various disorders, and lower concentration level. From this point of view, it is inferred that measuring job satisfaction of shift workers plays an important role for companies on the way to reduce the work-related stress. Hence, a questionnaire consists of sleepiness and fatigue, health and well-being, social and domestic situation is submitted to 60 shift workers. The results are analyzed and it is seen that there are both linguistic and numerical data which cause some complexity. In order to overcome the uncertainty, fuzzy multiple criteria decision-making method is adopted which addresses approximate reasoning. The main aim of the study is to emphasize the importance of adverse effects of shift work and propose a model to measure the job satisfaction. In the context of shift working, the findings of the study provide managers prominent results on how to enhance the job satisfaction of their employees. In the light of the obtained results, companies should focus more on "sleep and fatigue" to increase productivity.

## 1 Introduction

Measuring job satisfaction, understanding its role, and evaluating its impact on work-related issues have crucial importance in order to retain an adequate and qualified workforce. The companies which can provide high job satisfaction, survive successfully otherwise it is inevitable that work productivity and work effort will decrease in these companies towards the future. Job satisfaction is

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defined as how people feel about their jobs. It is clear that job satisfaction has more importance in shift work because it is a significant occupational stressor. Another reason for selecting shift work as a study area is having high staff turnover rates in shift work. Hence this study concentrates on assessing job satisfaction of shift workers. Paying attention to job satisfaction supplies benefits both for employers and shift workers. For employers; they get more profit from lower staff turnover and higher productivity. On the other hand, workers may also cope with shift work's negative effects easily and thus their motivation level will increase.

Job satisfaction is measured in many different ways in surveys, with a wide variety of questions and wordings. There is no consensus about the best or standard way to measure job satisfaction. Most of the academic research focused mainly on two areas: measuring the overall satisfaction of the workers surveyed and measuring the workers' satisfaction in different aspects of their job (for example, working conditions, working hours, and income) [1]. The questionnaire prepared to survey the shift workers includes 3 main parameters which are "sleepiness and fatigue", "health and well-being", and lastly "social and domestic situation".

Overall, job satisfaction provides an increasing morale of employees and quality of work life, improvement in working conditions and a more productive workforce. There are several issues to be considered like job intensification, deteriorating work-life balance and increasing expectations on individuals in the workplace arising from greater competitive pressures and globalization [1].

The rest of this paper is organized as follows: Sect. 2 includes an overview of job satisfaction. In Sect. 3, fuzzy AHP method is briefly explained. Then in Sect.4, the steps of the proposed approach are summarized. Finally in Sect. 5, the results of the application of the approach are presented and some suggestions for future studies are mentioned.

## 2 Literature Review

In the previous section, the importance of measuring job satisfaction is explained. To the best of our knowledge, due to the fact that job satisfaction is always popular subject; there are lots of studies about the topic in the literature. The researchers have used many different methods to evaluate the effects of job satisfaction. For example, Ilies and Judge investigated the within-individual relationship between mood and job satisfaction, and examined the role of personality characteristics in moderating this relationship by using an experience sampling methodology (ESM); 27 employees completed the mood and job satisfaction surveys at four different times during a day [2] . Liu et al. examined the level of job satisfaction among pharmacists and pharmacy support personnel working in Australian hospitals, and they compared the level of job satisfaction with career satisfaction, investigated the key factors determining job satisfaction of the hospital pharmacy staff and their relative importance, and identified the influential factors on their perceptions related to the ideal job. They used descriptive statistics, analysis of variance, factor analysis, and multiple linear regression methods to analyze the data [3]. Ko focused on the relationship among professional competence, job satisfaction, and career development confidence for chefs, and examined the mediators of job satisfaction for professional competence and career development confidence in Taiwan by using 180 questionnaires [4]. Delfgaauw searched that whether workers' satisfaction with various job domains affects where workers search for another job by using Heckman's two-step sample selection model, which has been modified by Van de Ven and van Praag [5]. Zalewska examined the relationship between anxiety and job satisfaction from the perspectives of three distinct approaches to well-being, i.e., 'bottom-up,' 'top-down,' and 'transactional' (boosted with elements which have greatest significance in the former two approaches by using MANOVA) [6]. Spagnoli et al. tried to find job satisfaction with job aspects that have been changed over time. Therefore, they examined the evolution of job satisfaction in a service organization over a six-year period by using factor analysis and a series of ANOVA methods [7]. Unlike previous work–life research, Georgelis et al. investigated the effect of personal events like marriage or having a child on job satisfaction by using British Household Panel Survey (BHPS) [8].

In the literature, research studies mostly focus on statistical techniques such as regression analysis, ANOVA ,etc. However these methods aren't adequate to explain the weight of each determined criteria. Hence, this study concentrates on assessing job satisfaction of shift workers by using a Fuzzy Analytic Hierarchy Process (FAHP). In the traditional formulation of the AHP, human's judgments are represented as exact numbers. However, in many practical cases, human preference is uncertain and decision-makers are unable to assign exact numerical values to their comparison judgments. The traditional AHP couldn't be applied to uncertain decision-making problems. In order to eliminate this disadvantage, the fuzzy analytic hierarchy process, which is capable to overcome the uncertainty and imprecision of evaluation process is used [9].

## 3 Resarch Methodology: Fuzzy Extended AHP

Many studies in the literature show that researchers need an effective and intuitive synthesis of decision methods for each different application area. In order to be successful on this synthesis, multiple criteria decision making (MCDM), a powerful concept, is used. The analytic hierarchy process (AHP), which is one of the useful tools in MCDM, has been widely used in practice. However, it has generally been criticized because of the use of a discrete scale of one through nine which cannot handle the uncertainty and ambiguity present in the prioritization process of different attributes. The hierarchy of the decision variables is the subject of pair-wise comparisons in the AHP. The pair-wise comparisons are established using a nine-point scale which converts human preference between alternatives [10]. The linguistic assessment of human feelings and judgments are vague and it is not reasonable to represent them in terms of precise numbers. It is more confident to use interval judgments rather than fixed value judgments. Hence, triangular fuzzy numbers are used to decide the priority of one decision variable among others. Synthetic extent analysis method is used to decide the higher priority weights based on triangular fuzzy numbers and so-called fuzzy extended AHP [9].

Let $X = \{x_1, x_2, \ldots, x_n\}$ be an object set, and $U = \{u_1, u_2, \ldots, u_m\}$ be a goal set. According to the method of Chang's extent analysis, each object is taken and extent analysis for each goal, $g_i$; is performed, respectively. Therefore, m extent analysis values for each object can be obtained, with the following signs:

$$M_{g_i}^1, M_{g_i}^2, \ldots, M_{g_i}^m \quad i = 1, 2, \ldots, n \tag{1}$$

where all the $M_{g_i}^j$ ( $j = 1, 2, \ldots, m$ ) are triangular fuzzy numbers.

The steps of Chang's extent analysis can be given as in the following:

Step 1: The value of fuzzy synthetic extent with respect to the *i*th object is defined as

$$Si = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \tag{2}$$

To obtain $\sum_{j=1}^{m} M_{g_i}^j$, perform the fuzzy addition operation of m extent analysis values for a particular matrix such that

$$\sum_{j=1}^{m} M_{g_i}^j = \left( \sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{3}$$

and to obtain $\left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1}$ perform the fuzzy addition operation of $M_{g_i}^j$ ($j = 1, 2, \ldots, m$) values such that

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j = \left( \sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \tag{4}$$

and then compute the inverse of the vector in Eq. (4) such that

$$\left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} = \left( \frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right) \tag{5}$$

Step 2: The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as

$$V(\mathrm{M}_2 \geq \mathrm{M}_1) = \sup_{y \geq x}\left[\min \mu_{M_1}(x), \mu_{M_2}(y)\right] \tag{6}$$

and can be equivalently expressed as follows:

$$V(\mathrm{M}_2 \geq \mathrm{M}_1) = \mathrm{hgt}(\mathrm{M}_1 \cap \mathrm{M}_2) = \mu_{M_2}(d)\begin{cases} 1, & \textit{if } m_2 \geq m_1 \\ 0, & \textit{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \textit{otherwise} \end{cases} \tag{7}$$

where d is the ordinate of the highest intersection point D between $\mu_{M_1}$ and $\mu_{M_2}$. To compare $M_1$ and $M_2$, we need both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ (See Fig. 1).

Step 3: The degree possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i = (1, 2,\ldots, k)$ can be defined by

$$\begin{aligned} \mathrm{V}(\mathrm{M} \geq \mathrm{M}_1, \mathrm{M}_2, \ldots, \mathrm{M}_k) &= \mathrm{V}[(\mathrm{M} \geq \mathrm{M}_1) \quad \text{and} \quad (\mathrm{M} \geq \mathrm{M}_2) \quad \text{and} \quad \ldots \quad \text{and} \quad (\mathrm{M} \geq \mathrm{M}_k)] \\ &= \min \mathrm{V}\left(\mathrm{M} \geq \mathrm{M}_i\right), \ \mathrm{i} = 1, 2, \ldots, \mathrm{k} \end{aligned} \tag{8}$$

Assume that

$$\mathrm{d}'(\mathrm{Ai}) = \min \mathrm{V}(\mathrm{S}_i \geq \mathrm{S}_k), \tag{9}$$

For k = 1, 2,…, n; k ≠ i. Then the weight vector is given by

$$\mathrm{W}' = \left(\mathrm{d}'(\mathrm{A}_1), \mathrm{d}'(\mathrm{A}_2), \ldots, \mathrm{d}'(\mathrm{A}_n)\right)\mathrm{T}, \tag{10}$$

where $A_i$ (i = 1, 2,…, n) are n elements.

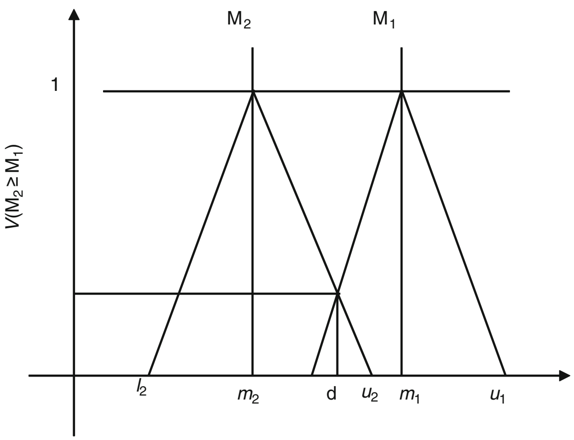


**Fig. 1** The intersection between $M_1$ and $M_2$

Step 4: After normalization, the normalized weight vectors are

$$W = (d(A_1), d(A_2), \ldots, d(A_n))T \tag{11}$$

where W is a non-fuzzy number.

## 4 Case Study: Evaluating Job Satisfaction of Shift Workers

The data used in this study were obtained from a survey which comprises of 12 sub-criteria and three main criteria that represent all these sub-criteria filled by the shift workers in Kocaeli. The evaluation criteria for job satisfaction are determined as sleep and fatigue, health and well-being, and social and domestic situation. Sleep and fatigue includes five sub-criteria which has showed sleep patterns, the amount of sleep, whether feeling rested/exhausted after sleep during the day time and effects of sleep on work and daily life. Health and Well-Being is designed to measure the condition of health and well-being. It is related to the health problems as a result of shift work, the effects of shift work on nutritional patterns/concentration level and changing attitudes. The last section was developed to find scores about social and domestic situation. It was constructed to measure whether shifting causes any problems with family or childcare responsibilities, or satisfaction with the amount of time the shift system leaves.

The survey, which had a response rate of 78 %, is distributed to 77 shift workers in different manufacturing sectors. Shift workers' ages ranged from 20 to 65 years with a mean age of 37.79 (SD = 8.02). For overall satisfaction with shift work, 26 % of shift workers reported being pleasant where 74 were unpleasant. However 93 % of shift workers reported that they had satisfied with their job. The workers' work experience ranged from 2 to 40 years with a mean of 13.2 (SD = 6.91) Also years of experience as a shift worker ranged from 2 to 34 years with a mean of 10.62 (SD = 6.51). As to marital status, 86 % of workers are married.

This study mainly purposes on evaluating job satisfaction of shift workers through the determined criteria, demonstrating the effects of criteria on job satisfaction and ensuring high levels of job satisfaction. Firstly AHP hierarchy is constructed as shown in Fig. 2. The triangular fuzzy conversion scale, given in Table 1, is used in the evaluation model of this study.

The decision structure has two levels;

First level (level of determinants); Determinants of job satisfaction are determined as Sleep and Fatigue (SF), Health and Well-Being (HW), Social and Domestic Situation (SDS).

Second level; this level consists of 12 sub-criteria. Five sub criteria about Sleep and Fatigue are Sleep pattern (SP), the amount of sleep (AS), Feeling rested (FR), Fatigue (F) Adverse sleep effects (ASE). Four sub criteria about Health and Well-

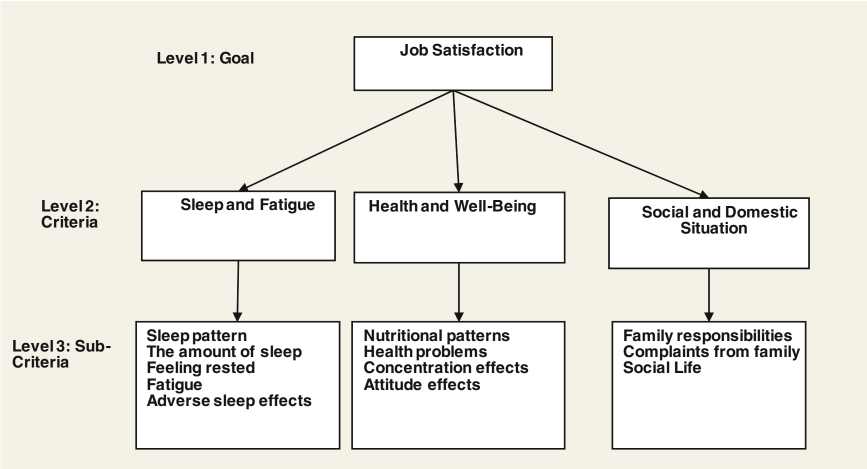


**Fig. 2** Hierarchies in the AHP

**Table 1** Triangular fuzzy scale of preference

| Relative importance | Definition | Fuzzy scale | Fuzzy reciprocal scale |
|---|---|---|---|
| 1 | Equally importance | (1,1,1) | (1,1,1) |
| 3 | Moderate importance | (1,3,5) | (1/5,1/3,1) |
| 5 | Strong importance | (3,5,7) | (1/7,1/5,1/3) |
| 7 | Demonstrated importance | (5,7,9) | (1/9,1/7,1/5) |
| 9 | Extreme importance | (7,9,9) | (1/9,1/9,1/7) |

Being are Nutritional patterns (NP), Health problems (HP), Concentration effects (CE), Attitude effects (AE). Three sub criteria about Social and Domestic Situation are Family responsibilities (FRE), Complaints from family (CF), and Social Life (SL).

Fuzzy pair-wise comparisons of three main decision criteria of "job satisfaction" are presented in Table 2. Then the sub-criteria are pair wise compared in Tables 3, 4 and 5, respectively and the weights are calculated.

**Table 2** Pair wise comparison matrix and fuzzy weights for three main criteria with respect to the goal and its priority vectors

| | Sleep and fatigue | | | Health and well-being | | | Social/Domestic situation | | |
|---|---|---|---|---|---|---|---|---|---|
| Sleep and fatigue (SF) | 1 | 1 | 1 | 1 | 3 | 5 | 3 | 5 | 7 |
| Health and well-being (HW) | 0,2 | 0,33 | 1 | 1 | 1 | 1 | 1 | 3 | 5 |
| Social and domestic situation (SDS) | 0,14 | 0,2 | 0,33 | 0,2 | 0,33 | 1 | 1 | 1 | 1 |

**Table 3** Fuzzy comparison matrix of five sub-criteria with respect to sleep and fatigue and its priority vectors

| | Sleep pattern | | | The amount of sleep | | | Feeling rested | | | Fatigue | | | Adverse sleep effects | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sleep pattern(SP) | 1 | 1 | 1 | 1 | 3 | 5 | 3 | 5 | 7 | 3 | 5 | 7 | 1 | 3 | 5 |
| The amount of sleep (AS) | 0,2 | 0,33 | 1 | 1 | 1 | 1 | 1 | 3 | 5 | 1 | 3 | 5 | 1 | 1 | 1 |
| Feeling rested (FR) | 0,14 | 0,2 | 0,33 | 0,2 | 0,33 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0,2 | 0,33 | 1 |
| Fatigue (F) | 0,14 | 0,2 | 0,33 | 0,2 | 0,33 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0,2 | 0,33 | 1 |
| Adverse sleep effects (ASE) | 0,2 | 0,33 | 1 | 1 | 1 | 1 | 1 | 3 | 5 | 1 | 3 | 5 | 1 | 1 | 1 |

**Table 4** Fuzzy comparison matrix of four sub-criteria with respect to health and well-being and it's priority vectors

| | Nutritional patterns | | | Health problems | | | Concentration effects | | | Attitude effects | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nutritional patterns (NP) | 1 | 1 | 1 | 5 | 7 | 9 | 3 | 5 | 7 | 3 | 5 | 7 |
| Health problems (HP) | 0,11 | 0,14 | 0,2 | 1 | 1 | 1 | 0,14 | 0,2 | 0,33 | 0,14 | 0,2 | 0,33 |
| Concentration effects (CE) | 0,14 | 0,2 | 0,33 | 3 | 5 | 7 | 1 | 1 | 1 | 0,2 | 0,33 | 1 |
| Attitude effects (AE) | 0,14 | 0,2 | 0,33 | 3 | 5 | 7 | 1 | 3 | 5 | 1 | 1 | 1 |

**Table 5** Fuzzy comparison matrix of three sub-criteria with respect to social and domestic situation and it's priority vectors

| | Family responsibilities | | | Complaints from family | | | Social Life | | |
|---|---|---|---|---|---|---|---|---|---|
| Family responsibilities (FRE) | 1 | 1 | 1 | 0,2 | 0,33 | 1 | 0,14 | 0,2 | 0,33 |
| Complaints from family (CF) | 1 | 3 | 5 | 1 | 1 | 1 | 0,2 | 0,33 | 1 |
| Social life (SL) | 3 | 5 | 7 | 1 | 3 | 5 | 1 | 1 | 1 |

As seen in Table 2; $S_{SF} = (0.22, 0.61, 1.52)$, $S_{HW} = (0.1, 0.29, 0.82)$ and $S_{SDS} = (0.06, 0.1, 0.27)$ are calculated. Then $W' = (1, 0.65, 0.09)$ is obtained and priority weights vector of each main criteria is $W = (0.58, 0.37, 0.05)^T$. Similarly priority weights vector of each main sub-criteria is seen in Table 3, $W = (0.4, 0.26, 0.04, 0.04, 0.26)^T$, in Table 4 $W = (0.52, 0, 0.17, 0.31)^T$ and in Table 5 $W = (0.05, 0.37, 0.58)^T$. Table 6 shows overall or global importance levels of the main criteria and the sub-criteria.

According to these results, the effects of shift work on "job satisfaction" are evaluated as following:

It is observed that the priority of the main criteria "Sleep and Fatigue" is highest with 58 % followed by "Health and Well-Being" with 37 % while for "Social and Domestic Situation" it is just 0.05 %. In the case of the sub criteria, the priority ranked highest are; "Sleep pattern", "The amount of sleep"and "Adverse sleep effects" respectively under "Sleep and Fatigue"; "Nutritional

**Table 6** Global importance levels of sub-criteria

| Global importance of three main criteria | Global importance of sub-criteria | Weights |
|---|---|---|
| Sleep and fatigue (SF) (0.58) | Sleep pattern (SP) (0.4) | 0.24 |
| | The amount of sleep (AS) (0.26) | 0.15 |
| | Feeling rested (FR) (0.04) | 0.02 |
| | Fatigue (F) (0.04) | 0.02 |
| | Adverse sleep effects (ASE) (0.26) | 0.15 |
| Health and well-being (HW) (0.37) | Nutritional patterns (NP) (0.52) | 0.19 |
| | Health problems (HP) (0) | 0 |
| | Concentration effects (CE) (0.17) | 0.06 |
| | Attitude effects (0.31) | 0.12 |
| Social and domestic situation (SDS) (0.05) | Family responsibilities (FRE) (0.05) | 0.0025 |
| | Complaints from family (CF) (0.37) | 0.0185 |
| | Social life (SL) (0.58) | 0.029 |

patterns" under "Health and Well-Being"; "Social life" and "Complaints from family" under "Social and Domestic Situation".

## 5 Conclusion

This study presents an evaluation model for job satisfaction of shift workers in different manufacturing companies. In line with this issue, three main criteria are determined as "sleep and fatigue," "health and well-being," and "social and domestic situation." Then 12 sub-criteria are defined related to these main criteria. The main purpose of the study is to emphasize the prominent parameters of job satisfaction for shift workers and reduce the adverse effects of the mentioned criteria. Evaluation process of job satisfaction can be thought as a complex multi criteria decision making problem considering multiple factors and sub-factors affecting the evaluation strategy. Hence, FAHP approach which constructs a hierarchical structure and effective vague assessments of main and sub-criteria weights having different characteristics is adopted. Most of the prior studies applied regression models to measure job satisfaction. However, in the present study, a fuzzy structure is applied to determine and prevent the negative effects of shift work on job satisfaction. Moreover, apart from measuring job satisfaction, this study explored factors that focus on job satisfaction of shift workers. The lack of studies which apply fuzzy multiple criteria decision making for the assessment of job satisfaction is a remarkable issue. The aimed contribution of this study to the literature is to provide a different perspective to reduce work-related stress which occurs when employees are unable to cope with shift work and job pressures.

There are several essential limitations that can be considered in the context of job satisfaction in shift works. For further research, the current problem can also be applied to different occupational sectors and to different job positions.

Investigating job satisfaction in different occupational sectors will enhance the understanding of the variations in satisfaction by dissimilar working arrangements. Another possibility would be to consider a fuzzy decision making model consisting of bidirectional analysis for both shift workers and managers. Evaluation of managers' opinion will also be crucial for performance improvement. Additionally, further attention needs to be given to determine whether and how working conditions, income, job safety, job involvement, etc. will affect job satisfaction which can easily be found by extending the survey.

## References

1. Measuring job satisfaction in surveys (2007) Comparative analytical report; European Foundation for the Improvement of Living and Working Conditions
2. Ilies R, Judge TA (2002) Understanding the dynamic relationships among personality, mood, and job satisfaction: a field experience sampling study. Organ Behav Hum Decis Process 89:1119–1139
3. Liu CS, Pharm B (Hons), White S (2011) Key determinants of hospital pharmacy staff's job satisfaction. Res Soc Admin Pharm 7:51–63
4. Ko WH (2012) The relationships among professional competence, job satisfaction and career development confidence for chefs in Taiwan. Int J Hospitality Manage 31:1004–1011
5. Delfgaauw J (2007) The effect of job satisfaction on job search: Not just whether, but also where. Labour Econ 14:299–317
6. Zalewska AM (2011) Relationships between anxiety and job satisfaction—Three approaches: 'Bottom-up', 'top-down' and 'transactional'. Personality Individ Differ 50:977–986
7. Spagnoli P, Antonio Caetano A, Santos SC (2012) Satisfaction with job aspects: do patterns change over time? J Bus Res 65:609–616
8. Georgellis Y, Lange T, Tabvuma V (2012) The impact of life events on job satisfaction. J Vocat Behav 80:464–473
9. Chan FTS, Kumar N (2007) Global supplier development considering risk factors using fuzzy extended AHP-based approach. Omega 35(4):417–431
10. Kwong CK, Bai H (2003) Determining the importance weights for the customer requirements in QFD using a fuzzy AHP with an extent analysis approach. IIE Trans 35(7):619–626

# Performance Heterogeneity Within a Group: An Empirical Study

**R. Folgado, P. Peças and E. Henriques**

**Abstract** Due to a change in the manufacturing paradigm, manual work is often preferred to automation while assembling products. Nonetheless, the human performance is variable by nature and from worker to worker there can be considerable differences in performance, which are commonly disregarded for the sake of simplification when analysing system performance. Heterogeneity of performance has been pointed out in earlier studies. However, there is a gap in the literature regarding the heterogeneity of performance quantification and systematization, which both researchers and industry can refer to for a more accurate assembly system performance prediction. With the objective of contributing to the knowledge on heterogeneity of performances within a group, a laboratorial experiment was set up. Several subjects were evaluated assembling LEGO parts simulating a product for the automotive interiors, based on an actual product produced by a supplier of the Automotive Industry. The results of this experiment show that the performance varies significantly from subject to subject in terms of speed and variability. A mapping approach is proposed to systematize the quantification of those differences, as well as the identification of the most typical types of performances, contributing to the knowledge on the human factor.

## 1 Introduction

Back in the 1980s there was a strong trend to automate assembly tasks as much as possible. Fully automated factories that would not have to consider the cost or variation problems caused by human involvement have been the ultimate goal of many researchers and companies. The leaders of this trend were automotive

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companies ranging from Volkswagen to Fiat and General Motors. In the end most failed to produce the desired results despite massive investments [1]. Since then high automation in production has been rethought for a more efficient use of qualified workforce and manual systems, which demonstrated to have several advantages regarding flexibility to adapt to production volumes variations, product variants and reduced product lifecycles. While automation has made some stages of the product manufacturing very efficient and less dependent on manual work cost, the manual processes are especially preferred in the final assembly of products [2–4]. This preference is due to the adoption of a strategy which favours the postponement of customization, to the last stages of production, namely to the assembly [5].

In any type of job which involves human factors, there will be naturally some amount of variability in the performance. In fact, due to changes in the business paradigms, the focus on performance was broadened from simply looking for an average performance to extending the interest into variability. Variability reduction in systems has become the prevalent priority in many manufacturing and service organizations throughout the world for quite some time [6, 7]. Nonetheless, within the field of operations and production management it is frequent to find the assumption that the workers will perform their tasks all at the same pace and with the same amount of variability, under all conditions. Simplification is a required step when designing or modelling a system, nevertheless, if researchers and managers do not have more solid information on the extent of these variations, they might not be aware of the consequences of these simplifications. According to Boudreau et al. [8] there are several assumptions which are commonly used regarding the human elements in the manufacturing systems, such as:

- The workers are not a major factor of impact on systems performance;
- The workers are independent, meaning that they are not affected by each other;
- The workers task times are deterministic and all identical, and they respond to same incentives.

Assumptions like these might simplify the analyses, although such simplifications can have a significant impact on the accuracy of system performance prediction [9]. Differences in workers' average task times can cause blocking and starving in tightly-coupled systems and underestimating variability will cause the models to underestimate congestion and consequently be too optimistic in predicting system performance [10]. As proposed by Baugous [11], it should be accepted that the workers typically are not isolated but rather integrated in a system and their performance most often contributes to the performance of a system. Furthermore, an increased understanding of the human factors in production and operations research is of great importance, and the human behaviour should not be seen as good or bad, but rather as a field in which an increased knowledge is needed for effective operations design [12]. There is some descriptive empirical work which investigates the magnitude of individual differences in work-rate variability, proposing that the worker performing the task may be the most significant source of variability in task completion times, even when the tasks vary a great deal [13]. However, even if several authors [9, 14] underline the lack of homogeneity in performance, there seems to be missing the characterization and quantification of heterogeneity in a systematic way, that both companies and researchers can actually refer to. In this paper, a contribution to the knowledge on manual work is given, namely on workers performance heterogeneity, and an approach to characterize such heterogeneity is proposed.

When an assembly system is in operation, workers perform the assembly tasks with some degree of variability, since in one repetition the worker may be quicker and in the next slower. These variations are often disregarded in the early system design stage. On top of that, the workers are different from one another: there may be differences in the speed and variability while performing assembly tasks, some workers might be slower than others, and some workers might have task times more variable (or the other way around). Given the nature of manual processing it is expected some degree of heterogeneity in the performance, in terms of average time and variability. In this paper, it is proposed to assess the significance and magnitude of these differences among a group of subjects under the same experimental conditions. It is also proposed a mapping approach to assess the differences between performances, contributing to the characterization of heterogeneity.

Within the scope of this research, the LEGO® building blocks were used to mimic the type of assembly tasks carried out in a system observed in an actual industrial context. The use of LEGO® has been a common practice in research studies concerning manual assembly tasks in the last years. Researchers have been using these building blocks to investigate phenomena like the effect of grouping parts in the reduction of the average time to assemble parts [15], assembly training procedures [16], physical and mental fatigue when performing manual repetitive tasks [17] and virtual reality training in assembly tasks [18].

## 2 Laboratorial Experiment

In order to assess the performance heterogeneity among a group of subjects performing assembly tasks, a product which is often found in the automotive interiors was used as an example. The interaction with a manufacturing company located in Portugal allowed the observation of an industrial reality where, beside other manufacturing processes, there is an area dedicated to the assembly processes. The assembly processes within this company rely mostly in manual work tasks, as a large number of manufacturing companies do. One of the products manufactured at the company are radio panels which are supplied to integrators, which then supply the final automotive OEMs. It was possible to gather information about the selected product characteristics and the assembly procedure used to obtain the final product. The actual radio panel has several components (a total of 14 push buttons, two rotary buttons and dozens of rear individual parts) that have to be assembled to the radio bezel (Fig. 1).


**Fig. 1** Radio panel

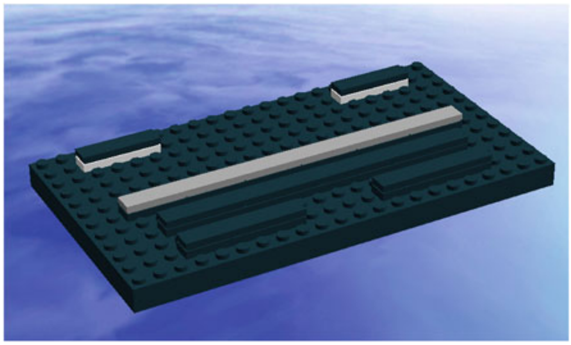


**Fig. 2** Model of the LEGO® kit representing the radio panel

A LEGO® kit was built resembling the dimensions and components location (push buttons) where the components should be assembled on an actual radio panel. In Fig. 2 the model of the described kit with the components assembled can be observed, and in Fig. 3 the schematic diagram with the main dimensions and indication of components location (buttons in grey).

It was observed that in the actual radio panel the components are assembled from top to the bottom and from the sides to the center, using both hands

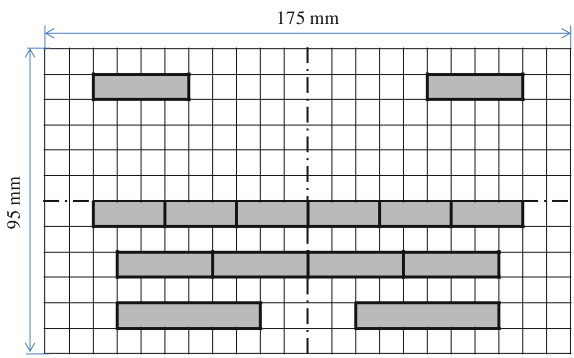



**Fig. 3** Schematic diagram of the LEGO® kit representing the radio panel

**Table 1** Basic motions elements required to assemble the LEGO® kit

| Work elements description | Basic motion elements |
|---|---|
| 1. Approach one hand to the box with the kits to be assembled placed in a fixed position | Reach (R) |
| 2. Pick one kit with one hand from the box | Grasp (G) |
| 3. Move the kit to the table and place it there | Move (M) |
| 4. Approach both hands to the components dispensers placed in a fixed location | Reach (R) |
| 5. Pick one component with each hand from the components dispenser | Grasp (G) |
| 6. Move the two components close to the jig where the product is placed | Move (M) |
| 7. Position the components in order to assemble them to the product | Position (P) |
| 9. Apply small pressure with thumbs in order to assemble components to product | Apply pressure (AP) |
| 10. Repeat steps 4–9 for the next two pairs of components (7 in total) | – |
| 11. Move the kit from the table to the box with the assembled kits | Move (M) |
| 12. Approach one hand to the box with the assembled kits placed in a fixed position and places the assembled kit there | Reach (R) |

simultaneously. This configuration of movements is common practice in manual work design [19]. In the laboratorial experiment with the LEGO® kit, the assembly process followed the same logic. It was also assured that the experiment follows the same work elements (composed by the same basic motion elements) required in the industrial assembly of the push buttons in the radio bezel (Table 1).

## 2.1 Sampling Process

For the experiment a total of $k = 28$ subjects ($IDL_i$, $i = 1$ to $k$) were gathered, representing undergraduate students (22) from the Production Management course, graduate students enrolled as PhD students (3), and professors from Instituto Superior Técnico (3). None of the subjects had experience in performing assembly tasks of this type in an industrial context. Moreover, previous published research [14] indicates that there are no substantial differences in the task times due to formal training (high school, vocational school, or college level) involving manual assembly of LEGO® parts, therefore it was considered that the sample was homogenous regarding this matter.

To become familiar with the experimental equipment and procedures, the assembly instructions were posted in front of the workstation at the eye level, the assembly process was explained to each one of the subjects and demonstrated by the analyst. In order for the subjects to be acquainted with the assembly process, they were able to experiment the assembly process for approximately 3 min. The subjects were informed that there would be a camera recording only their hand movements (Fig. 4). The subjects were requested to assemble the kits, following

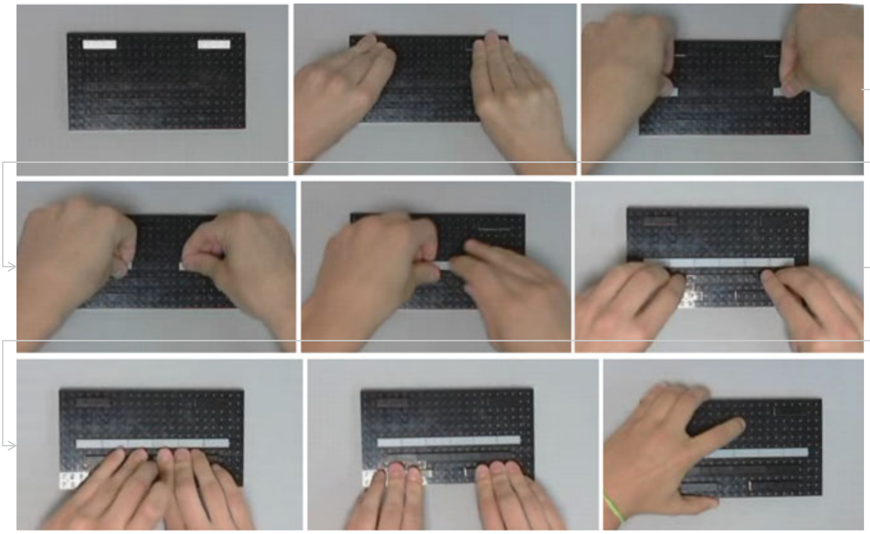


**Fig. 4** Snapshots of the assembling process of the LEGO® kit

the instructions, for 15 min. It was also underlined during this short briefing that the objective was not to perform as much parts as possible within that time, but to work at a rhythm they felt comfortable with. The objective was to capture the subjects' task times, without them being constrained by time or any other pace rather than their own. The recorded sessions were then analyzed and the assembly times registered in Excel format.

## 2.2 Observed Task Times

The task times for the $k$ subjects were registered and treated in order to analyze the differences in performance from subject to subject. After collecting the task times of the observed subjects, it was verified that the average time of all the observed subjects was 23.16 s and the average standard deviation in the times was 2.20 s. It was also verified that the difference between the slower and the faster subject was quite large (8.85 s) and between the least variable and most variable subject there was also considerable amplitude (2.18 s). Appropriate statistical tests were then used to investigate the significance of these differences. Before analyzing the significance of the observed differences in the task times, it was required to test for the normality and homogeneity of variance of the task time distributions, to choose the appropriate testing procedure correctly. All the statistical tests were run using the SPSS version 18.0, software commonly used for statistical analysis.

To test the assumption of normality it was used a well-known test of normality: Shapiro and Wilk Test [20]. The Shapiro and Wilk test is more appropriate for small sample sizes ($n < 50$ measurements) but can also handle sample sizes as large as 2,000. This test checks the normal assumption by constructing the $W$ statistic. The null hypothesis considers that the population is normally distributed. If the probability, $p$, of obtaining a test statistic at least as extreme as the one that was actually observed is below the significance value, $\alpha$ (in this study it is considered 0.05 as acceptable), then the data significantly deviates from a normal distribution. The test results demonstrated that for two of the 28 subjects the null hypothesis had to be rejected (Subject $IDL_1$: $W(n = 16) = 0.872$, $p = 0.029$, $\alpha = 0.05$; Subject $IDL_{20}$: $W(n = 22) = 0.909$, $p = 0.046$, $\alpha = 0.05$). In other words, for these cases the time distributions significantly deviate from a normal distribution, therefore the use of a parametric testing procedure is not advisable.

In order to verify if the observed individual dispersions are significantly different, the Levene's test was used. In statistics, the Levene's test is an inferential statistic used to assess the equality of variances in different samples [21]. It is the most practical test for heteroscedasticity, since it is less dependent on conditions of normality in the population [22]. It tests the null hypothesis that the population variances are equal. The significance of the test statistic $F$, is calculated from the F-distribution with degrees of freedom $df1 = k-1$ and $df2 = w-k$ ($w$ is the total number of samples, in this case, total number of registered task times, subtracted by the number of observed subjects). If the resulting $p$ value of Levene's test is less than the critical value ($\alpha$), the null hypothesis of equal variances is rejected. The test result indicate the violation of the assumption of homoscedasticity ($F(df1 = 27, df2 = 536) = 3.117$, $p < 0.0005$, $\alpha = 0.05$). This means that the variability from subject to subject is significantly different.

The previous stated evidences demonstrate that a parametric testing procedure is not suitable to evaluate the differences between the subjects' task times. In such cases, there are testing alternatives, such as the Kruskal and Wallis test [23]. It is a distribution-free (non-parametric) test since it uses rank-transformed data, and therefore does not assume a normal population. The test statistic, $H$, approximates a Chi square distribution with $k\text{-}1$ degrees of freedom. After running this test for the 28 observed subjects, it was verified that there is a significant difference among the time distributions within the group ($H(df = 27) = 286.669$, $p < 0.0005$, $\alpha = 0.05$).

In the observed sample, there were both female and male subjects. In order to compare the performances between these two groups, their average task times were compared using a $t$ test. The calculated test statistic, $t$, is compared with the Student's t-distribution for $df = kf + km - 2$, where $kf$ is the number of female and $km$ *is* the number of male subjects. To use this test the variables should be normally distributed and equal variance. Note that the distribution of the averages within each group is, according to the results of the Shapiro and Wilk test, normally distributed: Male subjects: $W(km = 15) = 0.930$, $p = 0.271$, $\alpha = 0.05$; Female subjects: $W(kf = 13) = 0.916$, $p = 0.223$, $\alpha = 0.05$; and the Levene's test results ($F(df1 = 1, df2 = 26) = 3.983$, $p = 0.057$, $\alpha = 0.05$) assure equal variances on the averages between groups. Therefore, the assumptions of normality and homoscedasticity when using the $t$ test are not violated. The obtained results of the $t$ test indicate that there are no significant differences between the female subjects' average task times ($M_f = 23.56$ s, $SD_f = 2.94$ s) and the male subjects ($M_m = 22.82$ s, $SD_m = 1.96$ s) average task times ($t(df = 26) = -0.791$, $p = 0.436$, $\alpha = 0.05$).

From the analyses performed up to this point it can be concluded that: the subjects' task times cannot be considered normally distributed; the variability on task times is significantly different from subject to subject; the subjects have significantly different task times when compared between them. The main issue is the quantification of those differences in a systematic way, which would help to increase the knowledge about the characterization of heterogeneity.

## 3 Quantification of the Heterogeneity Between Subjects

Considering that the expected average time, $\overline{X}$, is the global average of the $k$ subjects observed (1), it's then possible to calculate the percentage deviation, $\Delta\overline{x}_i$, of the average task time of the subject $i$, to that expected time (2):

$$\overline{X} = \frac{\sum_{i=1}^{k} \overline{x}_i}{k} \quad (1)$$

$$\Delta\overline{x}_i = \frac{\overline{x}_i - \overline{X}}{\overline{X}} \times 100 \quad (2)$$

Since the variability from subject to subject is significantly different, there is also the need of characterizing this measure of performance. The expected variability, $\overline{S}$, is calculated by calculating the average of the variability of the $k$ observed subjects (3). Similarly to the analysis made to the average task time, the deviation, $\Delta s_i$, of the subject $i$ variability to the expected variability is also calculated in terms of percentage (4).

$$\overline{S} = \frac{\sum_{i=1}^{k} s_i}{k} \quad (3)$$

$$\Delta s_i = \frac{s_i - \overline{S}}{\overline{S}} \times 100 \quad (4)$$

Given that workers performance can be described in terms of deviations to the expected average task time and variability, makes it possible to define classes of workers performance based on these two dimensions. Therefore, four types of performance can be considered in terms of deviations to the average values obtained for the workers population:

- The worker is slower completing the assembly task and the task times are more variable than the expected;

- The worker is faster completing the assembly task and the task times are more variable than the expected;
- The worker is faster completing the assembly task and the task times are less variable than the expected;
- The worker is slower completing the assembly task and the task times are less variable than the expected.

In order to visualize the relation between these two types of deviation, a graphic is proposed where the origin represents the expected performance, considering the average time required to fulfil the assembly tasks as well as the expected variability, based on the *k* sampled subjects. The horizontal axis represents the deviation of a subject average time to the expected average time; and the vertical axis represents the deviation of the variability of a subject to the expected variability. Therefore, there are four quadrants, each one representing one of the possible situations previously described, being the Quadrant I (QI) populated with the subjects with $\Delta\bar{x}_i > 0$ and $\Delta s_i > 0$ and Quadrant III (QIII) with the subjects with $\Delta\bar{x}_i < 0$ and $\Delta s_i < 0$.

Representing the performance in such way, allows the evaluation of the different observations in terms of percentage deviations to the expected performance within the group of subjects and the distribution and frequency of each type of performance can be compared. In addition, by using the proposed mapping, it is possible to investigate if there is a relation between the two types of deviations.

With the objective of characterizing the subjects' performances heterogeneity, the data points for the 28 subjects were calculated in terms of deviations to the expected average time and expected variability (Fig. 5). From this calculation it could be verified that the observed subjects deviation to the expected average varied between −13 and +25 %, while in terms of deviation to the expected

**Fig. 5** Representation of the four types of performance in terms of individual deviations to the expected performance

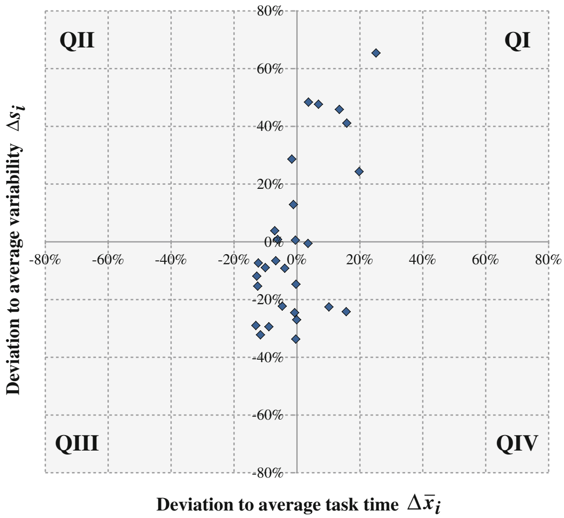
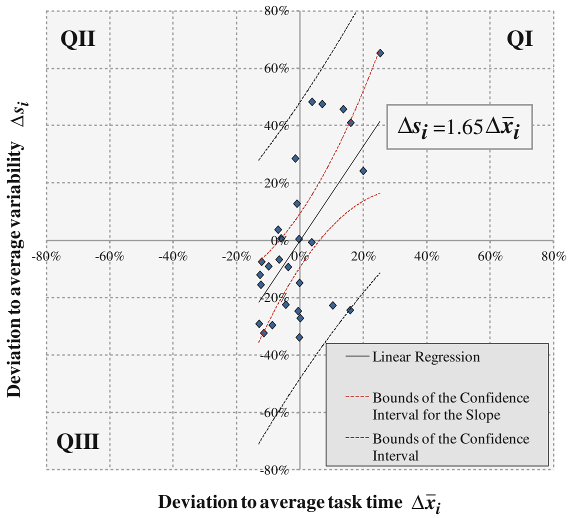


**Table 2** Average distance to the origin and frequency of occurrences per quadrant

| Type of performance | Average distance to the origin* (pp %) | % of occurrences |
|---|---|---|
| QI | 47.6 | 21.4 |
| QII | 9.9 | 17.9 |
| QIII | 20.7 | 50.0 |
| QIV | 18.6 | 10.7 |

* $d_i = \sqrt{\Delta\bar{x}_i^2 + \Delta s_i^2}$

**Fig. 6** Performance map




variability this variation was even larger (between −34 and +65 %). Moreover, when the average distance to the origin per quadrant is calculated, it could be observed that the subjects with performances of the type QI, were more distanced to the origin, than in any other quadrant (Table 2). However, there were more occurrences in QIII. These results indicate, that there's a tendency for more subjects to be faster and less variable than the average, however, when they are slower and more variable, they tend to be more deviated from the average performance (in absolute terms) when compared with the opposite situation.

In order to verify the strength of the correlation between the two types of deviations to the expected performance considered, it was used a bivariate test procedure which calculates the Spearman Rank Order Correlation coefficient, $r_s$. This is a non-parametric measure of the strength and direction of association that exists between two variables measured on an ordinal scale [21]. The correlation test result indicates that there is a medium positive correlation and that is significant ($r_s\,(k = 28) = 0.447, p = 0.017, \alpha = 0.05$). In Fig. 6, this correlation can be observed: the dashed black lines indicate the prediction interval where it is expected that 95 % of all data points to be located, and the red dashed lines the confidence interval where it is 95 % sure to contain the best-fit regression line (slope = 1.65, $CI_{95\ \%}$ = [0.8;2.49]). In fact, the positive correlation between the variables and the observed confidence interval for the slope indicates that there is a significant tendency for a subject, which is slower than the average to also have more variability than the average performance. This means that, these subjects have a tendency to be slower than the other subjects but work with higher speed variations when compared to the others. Alternatively, workers which are faster than the average performance tend to be less variable.

## 4 Conclusions

In the present context of the manufacturing paradigm, the use of manual work is often an attractive choice for the assembly of products, nonetheless, the human element is variable by nature and systems should be managed/studied taking these variations into account. However, there is a gap in the existent literature requiring further research about the heterogeneity of performances that can be found within a group of subjects, namely its systematic quantification. The results of the laboratorial experiment described in this paper, demonstrated that there is a significant amount of heterogeneity, both in terms of average time as in terms of variability in the task times, between subjects performing assembly tasks. Moreover, by mapping the time performances in the proposed way it was possible to verify that there are subjects which: are slower completing the assembly tasks and the task times are more variable than the expected (which is the worst case scenario); are faster and more variable than the expected; are faster and less variable than the expected (the best case scenario); are slower and less variable than the expected. However, even if the best case scenario is the most frequent one, the subjects who have a less desirable performance tend to be more distanced from the expected performance. In addition, there is a significant correlation between the two types of deviations, indicating that subjects with slower performances are also more variable than average. The proposed mapping approach enables the visualization of the different behaviors within a group of subjects and the quantification of those differences. This approach can also be used to study the performances of industrial workers. It should be stressed that, the subjects were observed working independently. If there is interdependence between workers (e.g., serial assembly line with reduced buffer levels) the workers performance become constrained and possibly heterogeneity might be reduced. Therefore, the influence of such working conditions on speed and variability are an interesting topic to explore.

Overall, the results of this empirical research contribute to add knowledge on the human element on assembly systems. Moreover, this study stresses the importance of considering workers performance heterogeneity for a more accurate manufacturing system performance prediction. Further research should address the modelling of systems considering heterogeneity and the assessment of its impact.

## References

1. MacDuffie JP, Pil FK, IMVP (1996) From fixed to flexible: automation and work organization trends from the international assembly plant survey, [Cambridge, Mass.], International Motor Vehicle Program, Massachusetts Institute of Technology
2. Butala P, Kleine J, Wingen S, Gergs H, Leipzig G (2002) Assessment of assembly processes in European industry. In: Proceedings of the 35th CIRP-international seminar on manufacturing systems, Seoul, Korea
3. Bley H, Reinhart G, Seliger G, Bernardi M, Korne T (2004) Appropriate human involvement in assembly and disassembly. CIRP Ann—Manufact Technol 53(2):487–509
4. Michalos G, Makris S, Papakostas N, Mourtzis D, Chryssolouris G (2010) Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP J Manufact Sci Technol 2(2):81–91
5. Yang B, Burns ND, Backhouse CJ (2004) Postponement: a review and an integrated framework. Int J Oper Prod Manage 24(5):468–487
6. Shunta JP (1997) Achieving world class manufacturing through process control, Prentice Hall PTR, New York
7. Tan B (1998) Agile manufacturing and management of variability. Int Trans Oper Res 5(5):375–388
8. Boudreau JW, Hopp W, McClain JO, Thomas LJ (2003) On the interface between operations and human resources management. Manufact Serv Oper Manage 5(3):179–202
9. Siebers PO (2004) The impact of human performance variation on the accuracy of manufacturing system simulation models, Doctor of Philosophy PhD, Cranfield University, Cranfield, UK
10. Juran DC, Schruben LW (2004) Using worker personality and demographic information to improve system performance prediction. Simul Stud Oper Manage 22(4):355–367
11. Baugous AM (2007) More than a mean: Broadening the definition of employee performance, Doctor of Philosophy, The University of Tennessee, Tennesse, USA
12. Bendoly E, Croson R, Gonçalves P, Schultz K (2010) Bodies of knowledge for research in behaviorial operations. Prod Oper Manage 19(4):434–452
13. Doerr KH, Arreola-Risa A (2000) A worker-based approach for modeling variability in task completion times. IIE Trans 32(7):625–636
14. Schultz KL, Schoenherr T, Nembhard D (2006) Equity theory effects on worker motivation and speed on an assembly line, Working Paper, SC Johnson Graduate School of Business
15. Madan M, Bramorski T, Sundarraj RP (1995) The effects of grouping parts of ready-to-assemble products on assembly time: an experimental study. Int J Oper Prod Manage 15(3):39–49
16. Schlüter M, Stodtko I (2011) Changeability training for employees in manual assembly. In: Proceedings of 56th international scientific colloquium, Ilmenau, Germany
17. Zadry HR, Dawal S, Tah Z (2009) Investigation of upper limb muscle and brain activities on light assembly tasks: A pilot study. In: Proceedings of 2009 international conference for technical postgraduates, pp.1-4, Kuala Lumpur, Malaysia
18. Adams RJ, Klowden D, Hannaford B (2001) Virtual training for a manual assembly task, Haptics-e. Electron J Haptics Res 2
19. Niebel BW, Freivalds A (1999) Methods, standards, and work design, WCB/McGraw-Hill, US
20. Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). Biometrika 52(3/4):591–611
21. Levene H (1960) Robust tests for equality of variances, Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling, Stanford University Press, pp 278–292
22. Sheskin D (2004) Handbook of parametric and nonparametric statistical procedures, Chapman and Hall/CRC
23. Kruskal W, Wallis A (1952) Use of ranks in one-criterion variance analysis. J Am Stat Assoc 47(260):583–621

# Gender Equality in Entities Setup in Spanish Science and Technology Parks

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**Abstract** The constant social, political, and economic changes require business organizations to continuously readjust. Sensitivity regarding gender equality has been determined by factors such as the entry of women into the work market, changes in business management proposals, which have started to appraise human capital as the companies' main assets or the implementation of measures to reconcile working, family, and personal life. This effort not only guarantees compliance with the applicable regulations but also an increase in productivity and satisfaction both of the workforce of the organization and of its customers/suppliers. The aim of this study is to shed light on gender equality and the degree of satisfaction of employees of technology-based companies of Science and Technology Parks (STPs), members or partners of the APTE (Association of Science and Technology Parks of Spain), trying to identify good practices carried out in these entities, extracting success factors that show how to guarantee the specific procedures to achieve the aforementioned gender equality, and indicating those aspects that can be improved in order to reach effective equity. To this end, an empiric, quantitative analysis is performed using the survey technique, with the participation, via an online questionnaire, of mid- and top-level managers of all the companies set up in the 49 partner STPs of the APTE. An analysis of the results of this phase provides a clear vision of the success elements in favor of gender quality in STPs, which can also be generalisable to other companies.

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# 1 Introduction

Gender equality-related sensitivity has developed enormously over the past few decades. The mass entry of women into the work market between the 1970s and 1980s was accompanied by attitudes of scepticism, rejection, and even infantilization by society, hindering the integration of this group, and denying their value as professionals. The direct result of viewing the entry of women into the working world as a threat had serious consequences on the form of discrimination (assignment of work with low salaries and without promotion), and in some cases, it was looked upon as sexual exploitation. Thus, sexual favors and submission to sexually offensive behavior were considered as employment conditions, existing in recruitment phases, preservation of the actual job, as well as in changes to other jobs or promotion.

Certain events led to the gradual achievement of social visibility of this type of gender discrimination, which favored the involvement of different European and national administrations, supporting the establishment of the bases for effective equality between men and women in the work sphere. The 1990s, in Europe, were an especially fruitful time in that sense, as different Directives and Recommendations were promoted, which included clauses in collective bargaining, preventive measures, training programmes, as well as clear and precise procedures to deal with gender-based discrimination problems that might occur in the work sphere. These regulations were consolidated in 2006 with Directive 2006/54/EC of the European Parliament and Council [1], related to the implementation of the principle of equal opportunities and equal treatment of men and women in matters of employment and occupation [1]. Making an evaluation of this directive, it takes into account the proportional distribution of men and women that exists at the different organization levels, taking specific measures that will contribute to improving the situation through agreements established with the workers' representatives. This council considered that, although some Member States still did not contemplate this, it was an important boost to foster the equality of men and women in the work spheres, as the measures that were defined therein defended intervention in the business spheres and in labor relations, forcing the States to encourage employers to foster gender equality through specific and systematic planning. This European Directive also deals with the appointment of organizations responsible for promoting, analysing, monitoring, and supporting equal treatment. An example of this was the creation of the European Institute for Gender Quality in 2007.

In the case of Spain, the appearance of Organic Law 3/2007, 22 March, on the effective equality of men and women [2], one of the pioneers in this sense, represented a gigantic step forward regarding active policies for achieving the effective equality of men and women in the work sphere. In article 45 of this law, it establishes that companies are compeled to respect equal treatment and opportunities in the work sphere and, for this purpose, they must adopt measures geared at avoiding any type of labor discrimination between men and women, and that these measures must be negotiated, and where appropriate agreed upon, with the workers' legal representatives, as determined in the labor legislation. In the case of companies with more than 250 workers, these quality measures must include the preparation and implementation of an Equality Plan, which must also be negotiated in the way determined by the labor legislation. In companies with less than 250 workers (SMEs), the regulation specifies that they must draw up and implement an equality plan when thus established in the applicable collective agreement, under the terms foreseen therein, and that this is a recommendable instrument for all entities.

Derived from this and other initiatives of the member states, in September 2010, the European Commission approved the "Strategy for equality between men and women 2010–2015" [3]. Here it specifies that, bearing in mind known data in the majority of the Member States of the European Union, women are still under-represented in decision processes and positions, above all at higher levels. In this regard, a report presented recently by the European Commission [4] points out that just 13.7 % of the board members of large corporations in Europe are women. The figure drops to 3.2 % when we talk about women who hold executive posts.

In Spain, despite the obligation of large corporations to have at least 40 % of women on their Boards by 2015, the situation continues to be very unfavorable for this group. In 2005, there were no Chairwomen or female Secretaries on the Boards of the IBEX 35 companies, and the percentages of Vice-Chairwomen and female Members amounted to 2.5 % and 2.3 %, respectively (Castaño and Laffarga) [5]. According to the Ministry of Health, Social Services and Equality, following the appearance of this law, the figure increased slightly, to about 6 %. In 2012, pursuant to data of the European Commission, although the figures have improved substantially (approximately one percentage point increase per year), Spain is still below the European average, with 11.5 % female board members of large corporations, and 2.9 % top managers. These data, according to the European Commission, confirm the impossibility of Spain reaching the figure of 40 % women in posts of responsibility of large corporations by 2015, as stipulated by the Equality Act.

Bearing in mind these figures, the European Commission defends the implementation in member countries of this 40 % share already imposed by Spain on large corporations (European Commission) [4], justifying this criterion not only in terms of non-discrimination and social conscience, but also due the results obtained by companies when they favor this effective equality. Thus, studies such as those of Barsh and Yee [6] verify that risk management in entities with a balanced management team is better and that the profits they achieve are 56 % higher than those that only include men.

As we have already commented, in order to achieve greater representativeness of women in companies, the regulation establishes the Equality Plan as the main instrument, which is defined by the Spanish legislation as *an orderly set of measures, adopted after having performed a situation diagnosis, whose aim is to obtain equal treatment and opportunities for men and women in companies, and to eliminate gender-based discrimination. The equality plans will establish the specific equality objectives to be reached, and the strategies and practices to be* *adopted to achieve them, and they will also establish efficient monitoring and assessment systems of the objectives established.* (Organic Law 3/2007, of 22 March for the effective equality of men and women, art. 46) [2]. These plans include measures relating to access to employment, professional hierarchy, promotion and training, pay, organization of work time, in terms of equality between men and women, to favor work, personal and family reconciliation and the prevention of sexual harassment and gender-based harassment.

Bearing in mind the figures that may be useful to assess the incidence of the Equality Plans in the companies, as well as those relating to the representativeness of women in decision posts, that we have already referred to, we can analyze other aspects such as, if there are differences in pay between men and women, or the facilities provided by these organizations to reconcile work, personal and family life. In the first case, according to the National Institute of Statistics—INE [7], it can be observed that male workers obtain 23.2 % more salary than female workers, and that this difference is especially relevant in sectors such as Industry (28.4 %) and Services (31.0 %) (Table 1).

With respect to reconciliation, 39.6 % of men and 42.4 % of women state that in their companies it is generally possible to flexibilize the working day for family reasons, while around 27 % of people of both sexes point out that it is not possible to modify the working hours for these reasons (Table 2).

Continuing with the data provided by the INE [7] on this topic, it is observed that the reduction in working hours to be able to care for a family member is a practice that predominantly affects women, as around 25 % of female workers used this right, compared with only 4 % of men (Table 3).

In 2010, 36 % of the collective agreements included the drafting and implementation of an Equality Plan, involving a total of 5.3 million workers (Research Centre on Economy and Society—CIES) [8]. However, the fact that this figure is not very high, despite the legislative imposition may be due to the fact that the start-up of a Plan of this type represents an estimated expenditure of 12,000 Euros for each company; and this volume increases to 50 million when expenses associated with paternity leaves and training of substitutes for the workers who are on leave are added (CIES) [8]. This cost, combined with the current economic crisis could explain the indifference of many of the large corporations with respect to their obligation to implement a strategy of this type.

**Table 1** Gross annual salary. Classification by gender and activity sector (in Euros) 2010

| | Women | Men | Percentage difference |
|---|---|---|---|
| National total | | | |
| Industry | 20,926.07 | 26,871.48 | 28.4 |
| Construction | 20,189.84 | 22,239.83 | 10.2 |
| Services | 19,607.32 | 25,676.99 | 31.0 |
| Total | 60,723.23 | 74,788.3 | 23.2 |

*Source* National Institute of Statistics 2010
Compiled by authors

**Table 2** Percentage of salary-earners between 16 and 64 years who may or may not modify the start or end of their working day, by at least one hour, for family reasons. Classification by gender and type of working day 2010

| | Have flexible hours | Generally possible to change them | Rarely possible to change them | Possible to change them | Does not know |
|---|---|---|---|---|---|
| Percentage | | | | | |
| Men | | | | | |
| Total | 6.13 | 39.57 | 20.06 | 27.96 | 6.29 |
| Women | | | | | |
| Total | 6.67 | 42.41 | 18.34 | 27.05 | 5.52 |

*Source* National Institute of Statistics 2010
Compiled by authors

**Table 3** Percentage of people between 16 and 64 (*), who have reduced/reduced their working hours or not, to provide care, and if they did so, the amount of working time reduced. Classification by gender and relationship with the activity 2010

| | Yes, reduced by one month or more | Yes, reduced by less than one month | Yes, reduced, but time not known | Not reduced |
|---|---|---|---|---|
| Percentage | | | | |
| Men | | | | |
| Employed | 2.11 | 1.29 | 0.14 | 95.84 |
| Women | | | | |
| Employed | 23.92 | 0.95 | 0.76 | 74.12 |

*Source* National Institute of Statistics 2010
Compiled by authors

Focusing on the group of companies that concerns us, those belonging to the Association of Science and Technology Parks of Spain (APTE), they add up to a total of 4,900 entities distributed in 80 parks and with a total of 127,000 male and female workers. With reference to the effective equality between men and women, despite the fact that there are currently no studies that have dealt with this topic in this type of entities, the initiative Objective 15, must be highlighted. This is an initiative fostered by the Ministry of Health, Social Services and Equality and by the APTE. It is a pioneer strategy in our country and it has emerged to facilitate the access of female talent, integrated in the centres and companies of the parks, to the Boardrooms of Listed Companies. More specifically, it favors the existence of a channel that permits contact between these companies and highly qualified female workers of these parks so that they can contribute, with their expertise, to the development and innovation process of major Spanish companies. The aim of this is to reach the aforementioned equality in the boardrooms by the year 2015 (APTE) [9].

We can see, therefore, that in Spanish companies in general, and in those pertaining to Science and Technology Parks in particular, there is a will to change towards parity between men and women in the work sphere and towards an active leadership of women in the business environment. However, although this type of initiatives, which emerge under the umbrella of the Equality Act, represent a step forward to combat gender discrimination in the labor environment, all public and private organizations should have the desire, not only derived from legislative impositions, for the conditions of men and women at work to be on an equal level, to not just pay lip service to the Act and not draw up specific plans, ending a long way from the aforementioned Objective 15, which is to achieve total parity between members of the boards of directors. Therefore, this objective must not be understood as a political strategy with a simplistic vision, but rather as a step toward social cohesion. Social cohesion, which is especially necessary at times of economic recession, based on three pillars, according to the Ministry of Health, Social Services, and Equality [10] insofar as preventing gender discrimination in the work sphere is concerned: equal opportunities in access to employment and in working conditions; positive action regarding gender rebalance at work; and the search for structural changes that overcome the already latent dichotomy between predominantly male posts and those reserved for women.

This move toward gender equality in the work sphere must be based on a planning that bears in mind the evidence of the current situation of this group in the business field. Focusing on technology-based companies of the STPs, below, we propose an analysis of the work context of women who work in these centers, trying to identify good practices and extracting success factors that bear in mind how specific procedures to achieve gender quality are guaranteed, and pointing out those aspects that can be improved upon to achieve effective equity.

## 2 Method

A questionnaire was designed to analyze entities in STPs and it was sent to all the organizations set up in the 49 associate member STPs of the APTE. In other words, out of the total of 80 STPs in Spain, the ones which, according to the APTE, satisfied the minimum requirements to be associate members, were selected. After identifying the entities—1600—e-mails were sent out during the third week of November 2012. Given the low response rate observed, a reminder was sent a week later. The final response rate was 21 %. The survey includes several types of questions. First, there are questions related to the characterization of the entities, such as which STP they belong to, the type of entity, the size, or the existence or not of equality plans. There are also questions related to qualitative evaluation, mainly about the perception of female and male workers on the discrimination level of women in aspects related to working conditions, the treatment of female employees during pregnancy or return to work after maternity leave. More specifically, the Likert scale from 1 to 5 has been used for this second type of question. Finally, the female respondents were invited to answer a series of questions about discrimination and their level of satisfaction with their entity.

## 3 Results

The sample analyzed is described below where the distribution of frequencies can be seen. Second, the main variables are summed up and then the main results of the Chi square independence contrast are presented for a 0.05 alpha significance level (Table 4).

The figures show that women make up approximately half the workforce (52 %) of the total male and female workers of the respondent entities, while men represent 47 % (Fig. 1).

**Table 4** Characterisation of the sample

| Variable | Descriptor | $n_i$ | $f_i$ | $N_i$ | $F_i$ |
|---|---|---|---|---|---|
| *Gender of the respondent* | | | | | |
| | Women | 183 | 52 | | |
| | Men | 162 | 47 | | |
| *Type of entity* | | | | | |
| | Company | 290 | 83.8 | | |
| | R&D Center, Technology Center | 46 | 13.2 | | |
| | University | 10 | 2.8 | | |
| | ICTs | 120 | 34 | | |
| *Activity Sector* | R&D Centres | 41 | 11.6 | | |
| | Aeronautics, Automotive | 15 | 4.2 | | |
| | Training, Human Resources | 16 | 4.5 | | |
| | Engineering, Consulting and Advisory Services | 65 | 18.5 | | |
| | Industrial | 27 | 7.6 | | |
| | Energy-Environment | 27 | 7.6 | | |
| | Medicine, Biotechnology | 26 | 7.4 | | |
| | Electronics | 9 | 2.5 | | |
| | <10 | 240 | 68 | 240 | 68 |
| *Size of the company: in number of employees* | 10–49 | 64 | 18 | 304 | 86 |
| | 50–99 | 21 | 5.9 | 325 | 92 |
| | 100–149 | 11 | 3.1 | 336 | 95 |
| | 150–249 | 11 | 3.1 | 347 | 98 |
| | >249 | 4 | 1.1 | 351 | 100 |
| | Owner | 90 | 25.9 | 90 | 259 |
| *Post of respondent* | Management | 79 | 22.7 | 169 | 48.6 |
| | Middle manager | 141 | 40.5 | 310 | 89.1 |
| | Administrative, technical | 38 | 10.9 | 348 | 100 |

$n_i$ absolute frequencies; $f_i$ relative frequencies; $N_i$ absolute cumulative frequencies; $F_i$ relative cumulative frequencies

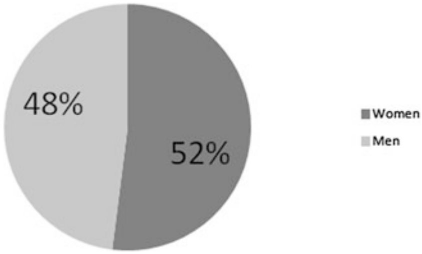


**Fig. 1** Percentage distribution of workers by gender

In the majority of the cases, the person answering the questionnaire was a middle manager (40.5 %), followed by male or female owners and male or female executives, with 25.9 and 22.7 % respectively. If we carry out the Chi square independence contrast between the variables ≪post in the entity≫ and ≪gender≫, the *p* value obtained is 5.3 E-15 so for the 0.05 alpha significance level, the hypothesis of independence between the variables is accepted (Fig. 2).

Statistically significant relations of dependence are also found in the variables ≪post occupied in the company≫ and ≪reconciliation between personal, work and family life≫. Noteworthy is the 37 % of administrative/technical posts that give a score of 4 (where 1 is little and 5 is a lot) to discrimination of women in the reconciliation between personal, work, and family life. Statistically significant relations have also been found between ≪post held in the company≫ and ≪possibility of promotion as a woman≫ (Fig. 3). The relevance of administrative/technical posts is worth highlighting where 26 % of the sample give a score of 5 (where 1 is little and 5 is a lot) to the discrimination of women insofar as promotion possibilities are concerned.

Another outstanding aspect is that the majority of the respondent entities are companies (83.8 %) compared with 13.8 % Technology Centres or R&D Centres and 2.8 % Universities. The main activity sectors that are distinguished are ICTs (34 %), Engineering, Consulting and Advisory Services (18.5 %); Research and Development (11.6 %), followed by the Industrial sector and Energy and Environment sector, both with 7.6 %, and Medicine and Biotechnology with 7.4 %. Finally, the Aeronautics and Electronics sectors are only represented with 4 and 2 % of the total. No statistically significant relations were found between the activity sector and the gender differentiation ($p$ value = 0.2) (Fig. 4).

The sectors that employ a greater proportion of men are aeronautics and automotive, as 81 % of the entities that comprise these sectors and that form part of the sample, have more male workers than female workers on their staff. On the contrary, in sectors such as Training-Human Resources and Medicine and Biotechnology, the percentage of entities that employ a greater proportion of men than women, is 20 and 23 % respectively.

Knowledge about whether an equality plan has been drawn up in the company is of low intensity. Only 14 % of the men and women respondents declare that there is an equality plan in their company, compared with 78 % that say no and 7 % that do not know or do not answer. This variable has a statistically significant

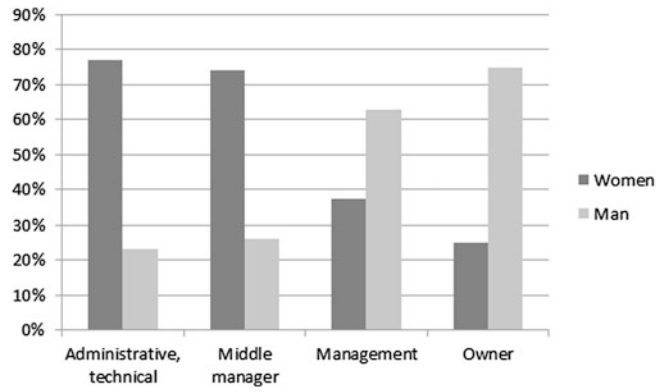


**Fig. 2** Percentage distribution of workers by gender according to post they hold in the entity

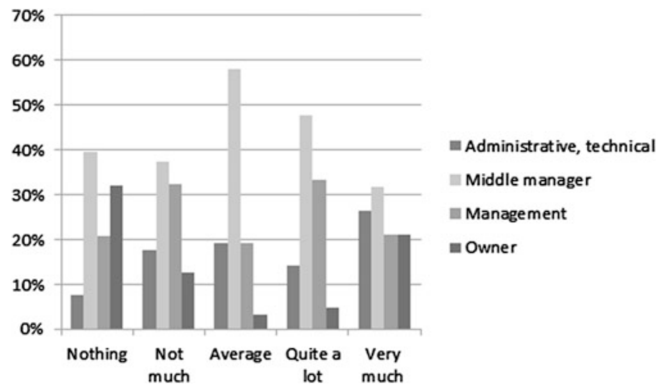


**Fig. 3** Percentage distribution of post in the company and possibility of promotion

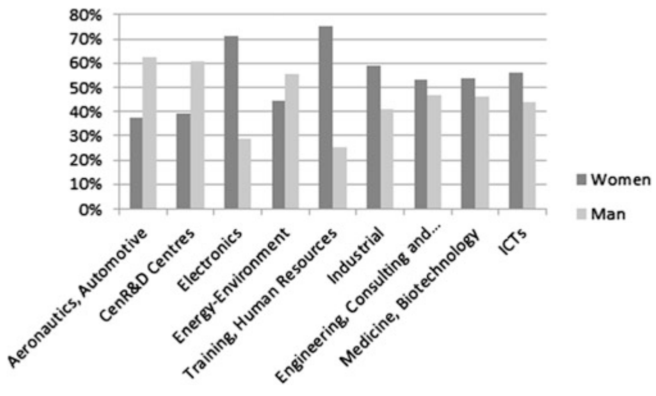


**Fig. 4** Percentage distribution of workers by gender and activity sector

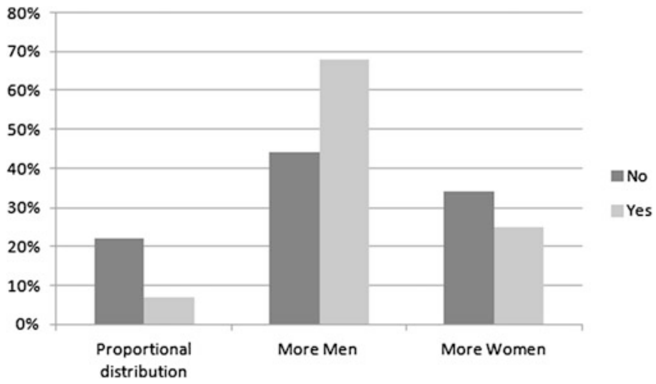


**Fig. 5** Percentage distribution of proportion of men and women and harassment at work

association with training in equality between men and women and on whether they are abreast of equality plans.

With reference to the posts held by the women respondents, 15 % hold administrative/technical posts, 57 % are middle managers, followed by 15 % in management posts, and finally 11 % of the samples are owners. With respect to economic remuneration, 54 % of the women respondents consider that the economic remuneration they currently receive is not fair or fair enough.

Noteworthy is the treatment of female employees during pregnancy, breastfeeding and reduction of working hours, when women are asked to give a score on a scale of 1–5 where 1 means "women are not discriminated" and 5 "women are very discriminated"; about 22 % give a score of 5 to discrimination with respect to the care provided by the company during pregnancy, 24 % during breastfeeding, and 21 % reduction of working hours for children under the age of 9.

Finally, 14 % of the women respondents state they have suffered some type of harassment at work. 85 % of them hold administrative/technical posts, 13 % are middle managers and finally 2 % are executives. Another significant aspect in this sense is the fact that women are more likely to suffer harassment at work when the number of male and female workers in the company is not equally distributed, as in the result of the independence contrast between variables ≪ proportion of men and women ≫ and ≪ having suffered harassment at work ≫ a $p$ value of less than 0.05 is obtained, so the dependence between these two variables is accepted (Fig. 5).

## 4 Discussion

Despite the great effort made by the different national and supra-national public administrations to make labor equality between men and women effective and real, figures show that a lot still has to be done to achieve this objective, especially if we take into account the presence of female workers in high responsibility jobs. This low representativeness of women in executive posts is combined with another type of problem in this sense, such as promotion difficulties for female employees, salary differences with respect to their male colleagues or the limited flexibility of companies insofar as reconciliation of personal and family life are concerned. This difficulty has resulted in labor stagnation for women due to the fact that, in the majority of the cases, they are the ones who are still responsible for taking care of other family members. This situation is especially paradoxical for the Spanish case, where, despite being one of the pioneer countries in enacting a specific legislation to avoid gender discrimination, including the work sphere, the reality of the different entities situate it, in this aspect, at a lower development level than the European mean.

In this research study, we have focused on Spanish STPs to analyze the situation of gender equality in entities that form part of them, bearing in mind that these business centres are normally representative with reference to good practices in the management of their human resources, given their usual commitment to corporate social responsibility.

The people who participated in the study, the majority of whom are male and female workers who call themselves “middle managers” of companies engaged in ITCs, Engineering, Consulting and Advisory Services, and Research and Development, confirm a greater presence of men in higher responsibility posts, especially in the aeronautics and automotive sectors.

Generally speaking, there is a dependence between the labor level and the evaluation of gender inequality that exists in a company, such that those male and female workers who hold posts of lesser responsibility, especially in the case of male and female operators and administrative or technical staff, perceive greater promotion difficulties for women, greater salary discrimination and they negatively evaluate the possibilities offered by the company in respect of reconciliation of personal and family life.

The male and female workers of the STPs have little knowledge of equality plans and, when they do have a knowledge of them, this is because they have been made aware of them previously, normally through training in the issue.

Female workers in the STPs notice greater discrimination in aspects such as the payment of salaries; more than half of them consider that their payment is less than what would correspond to them due to their labor activity, and in the family reconciliation opportunities that the company offers them, which are not considered sufficient in the case of labor facilities during pregnancy, breastfeeding, and care of children under the age of 9.

Finally, it is seen that, in companies where there is a greater presence of men in posts of responsibility, there is greater probability of suffering harassment at work, a consequence that, in itself, justifies decisive action to promote effective equality of women and men in the labor sphere.

Thus, it can be concluded that, although we can find entities in the STPs that decisively commit to innovation, social responsibility and good practices in the management of human resources, there are still certain pitfalls that make effective equality between men and women in the labor sphere impossible, and that must be overcome to avoid consequences such as those seen in the study, which vary from a negative perception in some sectors on the salary and labor situation of women, to the existence of a greater number of cases of harassment at work when there is less presence of women in posts of responsibility.

Due to this, bearing in mind the future perspective of this study, we consider that a transfer of experiences between companies would be necessary, regarding good practices in gender equality related matters identified in this and other studies. On the other hand, this "transfer" notion may also be extended to the relationship between the scientific and academic field, where numerous research studies relating to equality in employment and at work, are being developed, so that the results that are reached in the former (analyses of the current situation, future perspective, possible strategic lines of action, etc.) are accessible for the companies. To this end, associationism, as in this case that identified in the APTE, arises as an excellent opportunity so that through chats, courses, conferences, and other activities focused on managers and workers, examples of effective equity, which are being successful both regarding the profitability of the company and in the implementation of its social responsibility, can be disseminated.

## References

1. European Union (2012) Directive 2006/54/EC of the European parliament and of the council of 5 July 2006 on the implementation of the principle of equal opportunities and equal treatment of men and women in matters of employment and occupation. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32006L0054:EN:NOT. Accesed Nov 2012
2. Ley Orgánica 3/2007 (2012) de 22 de marzo, para la igualdad efectiva de mujeres y hombres. http://noticias.juridicas.com/base_datos/Admin/lo3-2007.html. Accesed Nov 2012
3. European Union (2012) Strategy for equality between women and men 2010–2015. http://europa.eu/legislation_summaries/employment_and_social_policy/equality_between_men_and_women/em0037_en.htm. Accesed Nov 2012
4. European Commission (2012) Special Eurobarometer 376: women in decision-making postions. European Comission 2012. http://ec.europa.eu/public_opinion/archives/ebs/ebs_376_en.pdf. Accesed Nov 2012
5. Castaño C, Laffarga J (2005) Empresarias y empresarios, Informe de Investigación. Instituto de la Mujer, MTAS, Madrid
6. Barsh J, Yee L (2012) Unlocking the full potential of women at work, McKinsey 2012. http://www.mckinsey.com/careers/women/~/media/Reports/Women/2012%20WSJ%20Women%20in%20the%20Economy%20white%20paper%20FINAL.ashx. Accessed Nov 2012
7. Instituto Nacional de Estadística (2010) Módulo año 2010. Conciliación entre la vida laboral y familiar, INE, 2010. http://www.ine.es/jaxi/menu.do?type=pcaxis&path=/t22/e308/meto_05/modulo/2010/&file=pcaxis. Accesed Nov 2012
8. Centro de Investigación de Economía y Sociedad (2010) Los Planes de Igualdad entre Mujeres y Hombres en las Empresas Españolas, CIES, 2010. http://www.grupcies.com/boletin/images/stories/PDFBoletin/ArticuloI_Edic_60.pdf. Accesed Nov 2012

9. Asociación de Parques Científicos y Tecnológicos de España (2012) Objetivo 15, APTE, 2010. http://www.objetivo15.net/. Accessed Nov 2012
10. Ministerio de Sanidad, Política Social e Igualdad (2011) Políticas de empleo y reactivación económica en España, 2011: análisis desde una perspectiva de género, Ministerio de Sanidad, Política Social e Igualdad, 2011. http://paralaigualdadenelempleo.mspsi.gob.es/repository/documents/INFORME_def_020820114.pdf. Accessed Nov 2012

# A Model to Increase Customer Loyalty by Using Bi-directional Semantic Interference: An Application to White Goods Industry

**Deniz D. Diren, Alper Göksu, Tuğçen Hatipoğlu, Hatice Esen and Alpaslan Fiğlali**

**Abstract** Adding values on products, services, or systems by responding to customers' needs quickly is a relevant issue for companies and requires them to be located competitively in their environment. In line with this issue, the demand chain approach enables companies to create user-centered designs. A demand chain is defined as a special customer-oriented supply chain network structure in the decision making process, that analyses customer demand and market conditions in order to reach an efficient distribution. The aim of this study is to examine the customer portfolio in white goods industry and find the preferences of current and potential customers in order to build and retain customer loyalty. The decision rules which help to increase the market share are obtained by using the Classification and Regression Trees (CART). After conducting a comprehensive literature survey on the demand chain approach and its applications, the required components for a network structure are determined by utilizing the bi-directional relationships between the customers and the manufacturers. Hence, eighty-five customer and twenty dealer surveys are carried out. The research methodology is then presented and the data collected from the surveys is analyzed statistically. The results of the study have prominent importance to overcome the uncertainty in demand chain and to determine which strategies should be adopted by the companies to have a loyal customer base.

**Keywords** Demand chain · Inductive learning · CART algorithm

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## 1 Introduction

The demand chain which aims to increase customer satisfaction is as important as supply chain for firms to be successful in the increasing competition conditions and to be able to answer the needs of continuously changing demands. For this reason, companies are supposed to analyze their present situation by understanding the variety in customer demands, and should have enough knowledge about what improvements should be done to increase customer satisfaction in the future. This can be accomplished only by the cooperation between the elements of the demand chain and having a continuous feedback among them. Demand chain management, being different from supply chain management which has a wide application among firms, has emerged as a concept of integrating customer value to the chain.

Lee (2002) defined demand chain as a network of commercial partnership that is extended from end customers to manufacturers. According to Lee, partners swap information and goods that are ready to use flow along the physical infrastructure of the network. A demand chain may include multiple businesses such as physical layouts, manufacturing warehouses, distribution centers of the wholesalers, warehouses of the retail chains, and retail sales places. Since the product flows along the network, the partners both undertake the costs together and make use of the profit together [1].

Walters and Rainbird [2] defines demand chain as "understanding the repeat and potential customers' demands, needs, market properties and the alternatives to meet them".

The aim of this study is to assess the customer demand in demand chain management by determining repeat and potential customers. In the study, the relationships between the customers and the manufacturing firms in the white goods sector, which has been selected as the field of application have been analyzed and it is suggested for the firms to carry out customer-oriented manufacturing with the purchase and service decisions.

A considerable number of classification studies interested in the customer behavior exist in the literature. Kim et al. [3] used genetic algorithm to predict the customer's purchase behavior by combining multiple classifiers. Choi and Kim [4] developed a customer reward program and tested the impact of customer understanding of the firm's entitlement to profit upon the degree of the customers' voluntary behavior for the firm's benefit. Wezel and Potharst [5] concentrated on ensemble learning methods for the modeling of customer choice. Kim and Gupta [6] presented a case study which examines the differences between potential and repeat customers based on mental accounting theory and information processing theory. Chen and Fan [7] developed a collaborative multiple kernel support vector machine (C-MK-SVM) approach for distributed customer behavior prediction using multiplex data. Canniere et al. [8] applied the theory of relationship quality and planned behavior to model the customer behavior using the real-life purchase behavior data of apparel and the survey information.

In this study, first, the research methods applied have been introduced, and then the components that influence the processes in demand chain management have been determined. A conceptual model has been designed for both demand chain management and raw material purchase systems. In the model, various statistical tests have been done to determine and interpret the relationships between the selected components (customer-firm). The results obtained from the collected data and the statistical analyses have been interpreted by forming decision rules based on different customer types.

## 2 Classificatıon and Regression Trees

Most of the statistical learning techniques such as Classification and Regression Trees (CART) assume that the samples are independent during the computation of classification rules. This assumption is very practical for the estimation of the quantities involved in the algorithm and for the assessment of asymptotic properties of the estimators. For practical reasons, it is often difficult to sample data over the whole studied area. Sampling units are thus often clustered. Because close observations are more similar than remote ones in the presence of spatial dependence, the spatial pattern of the sampling units is a critical issue. A direct application of supervised classification algorithms leads to biased discriminant rules because the same weight is given to every record and thus regions with high sampling density are overweighed. There are many ways to construct discrimination rules. In this paper we focus on CART; CART models have several additional advantages over other techniques: input data does not need to be normally distributed; it is not necessary for predictor variables to be independent; and non linear relationships between predictor variables and observed data can be modeled [9].

The CART method of Breiman et al. (1984) addresses the classification and regression problem by building a binary decision tree according to some splitting rules based on the predictor variables. A tree T has a root node whose descendant nodes, also known as daughters, can be divided into terminal nodes and split nodes. Throughout the paper, the terminal nodes will be denoted by rectangles and be identified with a t, while the split nodes will be denoted by ellipses and identified with an s.

Suppose that the data consists of a response variable Y and a vector of the predictor variables, with a fixed dimensionality, where can be ordered, i.e., continuous or discrete ordinal, or categorical, i.e., nominal. The tree itself can be expanded as follows. At each node do the following:

Step 1. Examine every allowable split on each predictor variable. Usually the binary splits are generated by binary questions.
Step 2. Select and execute the 'best' of these splits.
Step 3. Stop splitting on a node when a stopping rule is satisfied.

For ordered variables, the questions in Step 1 are of the form {Is} for all c in the range of. If is categorical, say taking a finite number of values { }, the questions are of the form {Is} as C ranges over all subsets of { }. Those cases in t answering 'yes' go to the left descendant node and those answering 'no' to the right descendant node. The 'best' in Step 2 is assessed in terms of goodness-of-split criterion chosen. Two popular criteria are 'least squares' and 'least absolute deviations'. Both afford a comparison based on a sub-additive 'between/within' decomposition, where 'between' alludes to the homogeneity or a loss measure applied to the parent node.

The rules for Step 3 seem not to work well in practice. The tree tends to be too big and have very few data points in each terminal node to make a study worthwhile. To overcome this problem, the trees which are very large with few data points in each terminal node are recursively pruned. Different ways of pruning are examined in Breiman et al. (1984), with the most common method being the minimal cost complexity procedure. Frequently, the pruned subtree is constrained to have more than some minimum number of data points in each terminal node.

At each node, the tree algorithm searches through the variables one by one, beginning with XY and continuing up to. For each variable it finds the best split. Then it compares the m best single variable splits and selects the best of these. Steps 1 and 2 are then reapplied to each of the daughter nodes, and so on, thus arriving at the full tree [10].

# 3 Bi-directional Semantic Interference Model in White Goods Industry

The study's main aim is to form the decision committees necessary to obtain the continuity of the loyal customers in white goods sector (refrigerator, dish-washer, washing machine, and oven group) and to gain new repeat customers among the potential customers by taking the properties that are important for them into consideration.

## *3.1 Collecting and Analyzing Data*

A bi-directional analysis method has been applied to measure the relationships between the customers and the manufacturers. The customer portfolios have been evaluated by preparing a customer questionnaire that includes the components which affect customer demand. The questionnaire was designed as an interview in order not to direct and limit the customer. To represent the firms, a dealer questionnaire that measures to what extent they usually meet the customer demands was developed for the dealers.

The customer questionnaire, which includes 20 questions, consists of 5 groups with purposes of; determination of the customer demand, measurement of the product quality and the customer satisfaction, determination of the factors that influence purchasing decision of the customers, and the customer type on the basis of brand. The dealer questionnaire, which consists of 14 questions is divided into three groups to measure; the manufacturer's sales capacity, the manufacturer's ability to answer to the customers' needs, and the factors affecting sales density.

To determine the elements that influence the customer demand, the questionnaire was administered to a total of 85 customers for each group of white goods. According to the brands that the customers use or think of using in the future, the questionnaire was administered to 20 dealers to find out the firms' level in meeting the customer demand.

The statistical analysis of the data was done by using SPSS package program. To carry out the analysis, the data obtained in the interviews, were classified into categories. To figure out the relationships between the data, the frequency analysis, crosstabs, and Chi square were applied.

Frequency analysis as seen in Table 1 was applied to determine the profile of the customers participating in the questionnaire. While determining the profile, the brand they use at the moment, the brand they used in the past, and the brand they want to use in the future were taken into consideration. If a customer answered at least one of these questions with a different brand, then the customer was evaluated as a potential or as a brand independent customer, otherwise, as a repeat customer.

The relationships between the questions on the questionnaire were searched within all the data groups. As an example, the crosstabs analysis results are as follows for the refrigerator product group (Table 2).

The purchase decision was formed on the basis of whether the customer profile is a repeat or a potential. Since a bi-directional analysis was required to be done in the study both according to the dealer and the customer, the brand is chosen as the

**Table 1** Frequency analysis for customer type

| Customer type | | | | |
|---|---|---|---|---|
| | | Frequencies | % | Potential (%) |
| Refrigerator | Potential | 44 | 51.8 | 51.8 |
| | Repeat | 41 | 48.2 | 48.2 |
| | Total | 85 | 100 | 100 |
| Washing machine | Potential | 41 | 48.2 | 48.2 |
| | Repeat | 44 | 51.8 | 51.8 |
| | Total | 85 | 100 | 100 |
| Dish-washer | Potential | 48 | 56.5 | 56.5 |
| | Repeat | 37 | 43.5 | 43.5 |
| | Total | 85 | 100 | 100 |
| Oven | Potential | 52 | 61.2 | 61.2 |
| | Repeat | 33 | 38.8 | 38.8 |
| | Total | 85 | 100 | 100 |

**Table 2** The crosstabs results for the refrigerators relations with brand

| Questions | Chi square | df | p | Relationship status with brand |
|---|---|---|---|---|
| *Determine the customer current brand choice* | | | | |
| Cause of choice | 114,066 | 90 | 0.044 | Related |
| Year of use | 42,864 | 60 | 0.954 | Not related |
| *Enable to determine customer demand* | | | | |
| Color of product | 4,484 | 10 | 0.923 | Not related |
| Extra feature request | 22,159 | 20 | 0.332 | Not related |
| *Measure product quality and customer satisfaction* | | | | |
| The number of failures | 83,006 | 40 | 0.000 | Related |
| Cause of failures | 68,183 | 50 | 0.045 | Related |
| Satisfaction of technical support | 38,099 | 20 | 0.009 | Related |
| Cause of dissatisfaction | 60,508 | 30 | 0.001 | Related |
| The problem of spare parts | 41,915 | 20 | 0.003 | Related |
| Cause of the problem | 43,574 | 20 | 0.002 | Related |
| Solution of the problem | 47,079 | 40 | 0.205 | Not related |
| Be ready to pay more for quality | 21,402 | 10 | 0.018 | Related |
| User-friendliness | 5,882 | 10 | 0.825 | Not related |
| *Determine the factors that influence purchasing decision of the customer* | | | | |
| Tracking the campaigns | 16,622 | 10 | 0.083 | Not related |
| News of campaigns | 129,104 | 50 | 0.000 | Related |
| *Customer type on the basis of brand* | | | | |
| Recommendation of brand | 26,510 | 10 | 0.003 | Related |
| Previous brand of product | 86,704 | 80 | 0.285 | Not related |
| Reason of give up previous product | 25,125 | 40 | 0.968 | Not related |
| Brand that planned to be used | 234,794 | 80 | 0.000 | Related |

common point of the two questionnaires, and the questions were criticized accordingly. Firstly the questions that reveal "related" answers were determined at the Chi square analysis, and they are directed to the customers of refrigerator, washing machine, dish-washer, and oven. The questions which were significant in the questions which are used to define the decision rule for each group, were as the number of the breakdowns, the reason of the breakdowns, the reason why they were not satisfied with the technical support sent, if they were not satisfied with it, following the status of the promotions made, the reason why they choose the brand they use and the brands used in the past. A total of six basic questions have been chosen to make the decision rule analysis. However, in the dealer questionnaire, the questions that can be regarded as equivalent to these questions have been determined with the experts' opinions. These are the questions rather asked to determine the technical support satisfaction such as whether the customers accept to pay more price for quality, the technical service availability, the easiness to provide spare parts and if providing spare parts is difficult, the problems encountered about it. These questions were matched with the customer profile. The aim is to determine, without brand dependency, whether the customers are loyal or potential by the help of the parameters such as the technical support satisfaction, the preference properties, and the easiness of using. Moreover, factors which will play a role in the determination of the customer profile were evaluated with the decision rule tree. At the end of the study, with the help of the knowledge obtained from the repeat customers, it is aimed to deduce the rules of purchase decisions to earn value from the potential customers for the firms.

In order to form the decision rules, SPSS Clementine program and CART algorithm, an inductive learning method, are used. The decision rules for the refrigerator product are as follows (Fig. 1).

For the refrigerator product, 14 decision rules were obtained, 6 of which was with the potential customers, and 8 of which were with the repeat customers.

As seen in the figure, we can easily determine the status of the refrigerator customers as either being repeat or potential according to the answer given to the question "Do you advise the brand you used?" regardless of the brand they have used. If they are satisfied with the brand they use, they will retain brand loyalty.

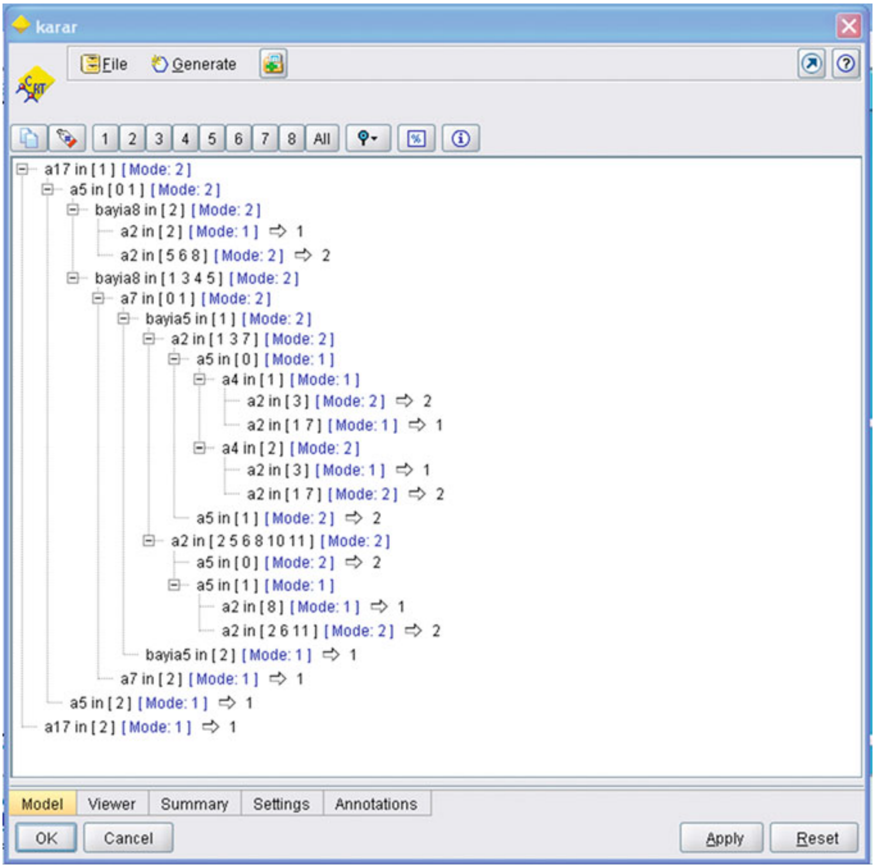


**Fig. 1** The decision rules for refrigerator

Otherwise, a branching takes place in the decision rule and the rule is subtracted from the question “number of the machine’s breakdowns” to form the decision rule. The customer is a repeat customer if the customer replied as “two times” to this question. If they answered “0” or “1” for the number of breakdowns they experienced then the decision is commented according to the answer to the question asked about customer satisfaction in the dealer questionnaire. The branching of the rules goes on like this. When the number of the rules is high, it is easier to determine the loyalty status of the customer. At the end of the decision rules for washing machine product range, a conclusion can be drawn that “if the customers recommend the brand they use and if they have preferred it for the domestic, cheap, widespread service network, and suitable payment conditions, and if they have preferred it upon a customer satisfaction and recommendation, although they experience some breakdowns, if the technical service of this brand reaches and solves the problem and the customer is pleased in terms of the price, they will stay loyal to the brand”.

The rules for the dish-washer are as follows, if the customers recommend the product they use, if the number of breakdowns is low, if the technical service reaches the customer in a short time when a breakdown takes place, if it is easy to provide spare parts when needed and after all of these if the customer is pleased with the technical service, it is clear that the customer is a repeat customer.

Finally, for the oven product, the customers’ status of being loyal or changeable depends on the reasons that customers “prefer the products”. The result of branching is as follows, if the product is easy to use, the number of breakdowns is few, and the customer is satisfied with the technical service delivered when it breaks down and consequently if the customer recommends the brand that they use then it is assumed that customer is a repeat customer.

## 4 Conclusion

Nowadays, it becomes more and more difficult to survive for firms due to rapidly changing demand levels and high customer expectations. In this respect, demand chain management has emerged as a chain of activities to provide a competitive advantage and to earn customer value for companies. In demand chain management, it is aimed to produce a suitable product for a suitable market focusing on the long term planning. Meeting the demand by spreading the customer expectations all along the chain is one of the major properties of the demand chain management.

In this study, the customer portfolio, their demands and needs in the white goods market have been determined and the capacities of the firms and the services they provide based on the dealers have been measured. In the next step in the demand chain management, by obtaining the relations between customer and firm, the result of these relations should lead firms’ decisions about service and purchase rules issues. Thus, customer value, sales, and profit rates are aimed to be increased.

While customers reached the service and products they demand, firms have an opportunity to provide improvements. By means of the two way relations determined in the study, bi-directional benefits can be obtained. For this purpose, CART algorithm, an inductive learning method, which was supported with the statistical analyses have been used. By using this algorithm, decision rules have been interpreted which help firms to understand the factors that customers pay attention to.

We can summarize the decision rules obtained as "if the customers state that they are satisfied with the technical services, if they recommend the brand they use, on the other hand, if the dealer's or the company's technical service provides good and fast solutions and provides suitable advantages in terms of the price, the customers will be loyal". If the customers recommend the brand they use, if they are pleased with the technical service provided even if there is a breakdown in the product and if the dealer or the company provides good advantages in terms of the price, the customer will be loyal. Otherwise, when there is a monetary crisis, it is inevitable for the customers to move to another brand which is more suitable for them in terms of the price. This will lead to a varying customer profile for companies. Thus, services offered to customers should have both suitable prices and good technical opportunities.

## References


1. Lee BC (2002) Demand chain optimization: pitfalls and key principle. In: Nonstop solutions supply chain management seminar, White Paper Series, pp 1–26
2. Walters D, Rainbird M (2004) The demand chain as an integral component of the value chain. J Consum Market 21(7):465–475
3. Kim E, Kim W, Lee Y (2003) Combination of multiple classifiers for the customer's purchase behavior prediction. Decis Support Syst 34(2):167–175
4. Choi S, Kim S (2012) Effects of a reward program on inducing desirable customer behaviors: the role of purchase purpose, reward type and reward redemption timing. Int J Hospital Manage 32:237
5. Wezel M, Potharst R (2007) Improved customer choice predictions using ensemble methods. Eur J Oper Res 181(1):436–452
6. Kim H, Gupta S (2009) A comparison of purchase decision calculus between potential and repeat customers of an online store. Decis Support Syst 47(4):477–487
7. Chen Z, Fan Z (2012) Distributed customer behavior prediction using multiplex data: a collaborative MK-SVM approach. Knowl Based Syst 35:111
8. Canniere MH, Pelsmacker P, Geuens M (2009) Relationship quality and the theory of planned behavior models of behavioral intentions and purchase behavior. J Bus Res 62(1):82–89
9. Bel L, Allard D, Laurent JM, Cheddadi R, Bar-Hen A (2009) CART algorithm for spatial data: application to environmental and ecological data. Comput Stat Data Anal 5:3082–3093
10. Denison DGT, Mallick BK, Smith AFM (1998) A bayesian CART algorithm. Biometrika 85(2):363–377

# A Study into Composite Laminators' Motivation

**Dennis Crowley, Carwyn Ward, Kevin Potter, Oksana Kasyutich, Kevyn Jonas and Nigel Jennings**

**Abstract** Manufacture using advanced composite materials is a predominantly manual process. Despite recent advances in automation; the manufacture of complex panels such as those found in secondary aircraft structures, is usually carried out by highly skilled human operators. A requirement for increasing build rates of aircraft structures means that a formerly low production cycle technique must now be applied to much faster and larger production runs. This is further complicated by a desire to achieve higher quality at lower cost. Increased automation and laminator aids are being employed to achieve this goal. This paper presents an initial study into the current state of composite laminators' motivation using Maslow's Hierarchy of Needs. A series of semi-structured interviews were conducted with a variety of laminators from a range of industries. The principle aim is to generate a preliminary set of recommendations based on trends gained from this initial study, with a view to later widening the study to improve motivation and thus productivity and quality.

## 1 Composite Materials and Manufacture

Composite materials are formed from two or more constituent parts in order to create a new material with the beneficial properties of both. They are also seeing rapid growth year-on-year, a trend which is expected to continue for some time [1]. The aerospace industry has the largest share of composite materials [1–3], in

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particular due to projects such as the Airbus A350 XWB and Boeing 787 Dreamliner. These aircraft have the highest proportions of composite materials (approximately 50 % by weight); however the drive toward lower weight and greater fuel efficiency will see smaller commercial aircraft making increased use of composites [4]. These smaller, single aisle aircraft are of particular interest because their replacement rate could be as high as 600 per annum [4, 5]. Thus high production rates will necessitate increased productivity in the coming years.

The principle barrier to increased use of composite materials is that their manufacture is a complex and expensive process. Raw material costs are in the region 30-150 GBP/kg [6, 7], compared to 1.50 GBP/kg [8] for Aluminium. This however only represents up to 42 % [8] of the total manufacturing cost as another 42 % is associated with labor costs. Whilst specific values will vary project to project, it can be seen that labor and manufacturing make a significant part of the final cost of a part. In order to increase the competitiveness of composite materials these costs must be reduced at quality.

The manufacture of composite parts is usually carried out by hand [3]. However there has been increasing interest in, and use of, automated methods—in particular Automated Tape Laying (ATL) and Fibre Placement (AFP) [9] as well as more mechanical techniques such as press forming and hot drape forming [10]. These methods have been developed in direct response to the need to increase manufacturing rate and reduce defect count. However these methods have certain limitations, particularly in the area of geometric complexity [5, 11, 12] and can also represent a high capital investment [13]. In the case of a typical wing ship-set the number of parts which cannot be automated presently outnumbers the parts that can at a ratio of $\sim$5:1 [4, 12]. Since up to 600 ship-sets will be required, each with over 100 panels which have to be made by hand, manual lay-up is an important area to consider.

## 2 Composite Lay-Up and Quality

The process of placing a layer of fabric or tape over a mould tool such that it covers the surface is called drape. Drape can be a complex operation, depending on the geometry, involving a number of small operations in order to get the material to conform without defect [5]. It is accepted that there are potentially infinite ways of draping a layer of material over a tool surface [14, 15] and that the materials are delicate and tacky, particularly in the case of unidirectional prepreg materials. The operators use a mixture of experience and problem solving to carry out the manufacture from an internal, tacit knowledge base. This is generally agreed to be the case as instruction sheets often do not unambiguously detail the drape routes, and there is little standardization in levels of instruction detail. More recently there have been some advances in assistive technologies for laminators. This has mainly been in the form of laser projection systems [16, 17] which project glowing outlines onto the tool or part surface and shows the operator where the next ply should be positioned. Fundamentally these templates alone do not guarantee that the ply will be positioned correctly and without surface defects.

That is not to say that manual lay-up is perfect by any means. Composites literature [18] has identified "human error" as a major source of defects and variability. Newell et al. [19] go on to state that a laminator will never drape a part the same way twice. If this assertion is correct there will always be part-to-part variation in the product. However this is also likely to be due to learning curve affects as the manual operators improve with experience. It is also worth mentioning that the majority of composite laminators are contractors. This presents the industry with an issue as the tacit knowledge base and experience isn't necessarily tied to a particular company or industry.

Because of the complexity of drape there are several quality control and assurance issues associated with composites manufacture. In the particular example of hand lay-up, the tool, incoming material, and draped ply are all inspected either by the operator or a qualified inspector. These inspectors are looking for a variety of small surface defects on an optically complex surface, such as foreign objects, wrinkles, dry spots, and other imperfections. These surface imperfections can go on to become defects later in manufacturing, meaning that the part will need to be either scrapped or enter a concession process, reducing profit margins, and costing time. Since the scrap rate for composite manufacture can be as high as 10 % [20], this represents a significant burden in cost and time and if re-enters the manufacturing loop has a significant impact on rate.

In the aforementioned areas of manufacture and quality, the "human-in-the-loop" plays a significant role. Composite lay-up in areas which still rely on manual lamination will have both the manufacture and quality control operations carried out by a single human operator. Therefore, understanding the needs of the human in the loop is of great importance if quality is to be assured and productivity increased.

## 3 Motivation Theory: Maslow's Hierarchy of Needs

Figure 1 is a schematic representation of Maslow's Hierarchy of needs [21–23] which is a needs-based theory meaning that motivation arises from unmet needs. The first four levels are deficiency needs which, once satisfied, would move the individual up to the level of growth needs, in this case self-actualization. Self-actualization arises from an individual meeting their potential and striving to be all that they can be. More recently [24] the hierarchy has grown to 8 tiers to include cognition and esthetic needs above self-esteem. The esthetic appreciation is more difficult to relate to a composite manufacturing operation. There are some esthetic elements in lay-up, when a ply "looks right", but it is not immediately clear if this is on the same level of psychology as the need for esthetics. Another addition above self-actualization is the notion of self-transcendence. This is a level above self-actualization whereby the person will go beyond themselves to help others achieve actualization. This could manifest in experienced laminators training the

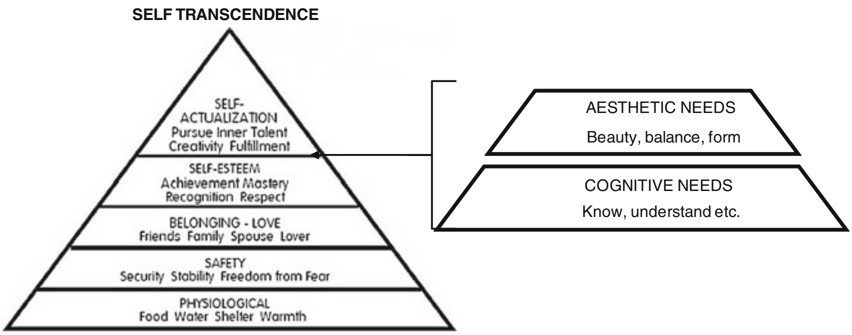


**Fig. 1** Maslow's hierarchy of needs

**Table 1** Breakdown of needs from…? with examples in composites manufacture

| Level | Needs | Examples in composite manufacture |
|---|---|---|
| Physiological | Must be met for the body to function | Drinking fountains, canteens |
| Safety | Physical safety, stability, and security | Job security, pay, no sudden job changes |
| Belonging | Identity, acceptance, and social connections | Defined role/department, teamwork |
| Self-Esteem | Recognition and respect | Promotion, performance evaluations, rewards |
| Cognitive | Understand, to know | Understand mechanics of drape |
| Esthetic | Appreciation of beauty and form | Surface quality |

next generation, for example. Table 1 gives examples of these needs and how they relate to composites manufacture.

Maslow's theory of needs was selected as the main motivational theory because it is one of, if not the, most prevalent works in the field. The 5 and latterly 8 step model is one of the most commonly used. There are other motivational theories, such as the Motivation-Hygiene Factors theory [25], and Hackman and Oldham's theory of job design [26]. Much of these theories can loosely be encapsulated in the belonging and self-esteem levels of Maslow's hierarchy, and possibly also in the cognition level of the 8-step model.

Over the years there have been some criticisms of Maslow's hierarchy. The original methodology in [1] was an autobiographical approach of people whom Maslow believed were self-actualizers. Also subject to some criticism is the hierarchical structure of the needs theory as it has been shown that in other cultures where the safety needs can be said to be partially satisfied, some degree of self-actualization can be achieved [27, 28]. Diener [28], with his large survey of 123 countries, found no real link between the needs and the order in which they are achieved. However he did find that his study did match well with Maslow's proposed set of needs. The conclusion was that, possibly for evolutionary reasons [29], there are a set of universal (or near-universal) needs which apply regardless of cultural or societal factors.

**Table 2** Needs assessed by question areas

| Experience | Industry Practices | Work Patterns | Engagement | Ownership | Craftsmanship | Other questions |
|---|---|---|---|---|---|---|
| Physiological, safety needs | | | Belonging | Esteem | Belonging/esteem | |

## 4 Methodology

Since there is little objective measurement of self-actualization or transcendence, a subjective methodology was pursued. Semi-structured interviews were used to gather information from working laminators. A mixture of open and closed questions was selected. Closed questions were used to establish facts about the sample and open questions were used to give the respondents an opportunity to give their opinions and other information around the subject. Due to the relatively small number of accessible laminators, interviews were preferred over a written survey as they would give a greater wealth of information from the limited-size sample.

Each interview lasted 30 min to an hour and often had to be carried out around other tasks. This also gave the opportunity for some observations into their hands-on work. The reasons and method for the interview was presented first as a means of engaging and assuring the respondent that there was no malicious intent or agenda. The questionnaire was steered using Maslow's needs theory and some from applicable case studies [30–32]. There were 7 sections of varying length, each aimed at a particular level of need Table 2 (see the appendix for the list of questions):

The responses were treated confidential in full. The information was gathered in the form of hand-written notes and analyzed using qualitative coding. Coding was done without the aid of software, separating the respondents by industry, employment type, experience, and then their response to the question. All respondents were from differing industries with varying levels of experience, with a mixture of permanent and contract staff.

## 5 Results and Discussion

This paper is an initial study to understand if Malsow's Hierarchy of Needs is useful for the work in motivating laminators. As a result only six laminators have been interviewed at this time, as a snap-shot study for future research direction. Of the six laminators interviewed at this initial stage, two have only worked in a production environment and one has only ever worked in a research environment. The remaining three were contract laminators and had worked in multiple sectors. All had received in-house on-the-job training, however laminator 5 had received additional external training. All predominately used pre-impregnated materials and

**Table 3** Breakdown of interview sample

| Laminator | Experience (years) | Sector (previous sectors) | Permanent/ contractor |
|---|---|---|---|
| 1 | 25+ | Research (aerospace, automotive (F1)) | Contractor |
| 2 | 25+ | Research (aerospace, automotive (luxury)) | Contractor |
| 3 | <2 | Research | Permanent |
| 4 | 10–15 | Aerospace | Permanent |
| 5 | <2 | Aerospace | Permanent |
| 6 | 10–15 | Research (aerospace, automotive (F1), space) | Contractor |

had a preference (where stated) for woven mats over unidirectional tapes. Three laminators had previous jobs which they felt contributed: carpentry and training as a mechanic. The suggestion was that technical and skilled manual jobs were beneficial to working in/as composite laminating (Table 3).

## 5.1 Permanent Versus Contract

This area was of particular interest with respect to Maslow. Half of those sampled were contractors, but had previously worked as permanent employees. The reasons for the change were: seeking a new challenge, freedom, and financial. From a needs perspective this is interesting as it can be seen that some were prepared to sacrifice security for additional challenge, or fulfil an esteem need. However this reduced security was balanced by an increased hourly wage and hours worked. The number of hours per week for a contractor varied between 36 and 90, with a $\sim$60 h per week mean. This is compared to 30–40 h per week for permanent staff. The motivation for working as many hours as possible in a week was financial, again meeting a safety need. However, working many hours in a week could cause fatigue and lead to lower productivity as well as the possibility of making mistakes, leading to a lowering of quality. There was also some reported past tension between permanent and contract staff. This tension arises from the differences in hourly wage and benefits, and possible envy of the autonomy enjoyed by contractors.

Of those surveyed, the more experienced became contractors; this could be that they felt their growth/self-actualization was being hampered by remaining as a permanent employee. It could be argued that satisfying their esteem need by contracting, whilst balancing financial security with job security, they would sacrifice a degree of belonging.

## 5.2 Engagement and Communication

All the respondents stated that they had good access to either supervisors or engineers. However this access was generally limited to clarifying the instruction set and querying ply orientations. There seemed to be little to no access to design decisions from the shop-floor for production staff. By contrast those research environment laminators had better access to the engineers in a more informal way.

The two laminators that participated in formal group meetings were both permanent staff from a production environment. From a needs perspective group meetings, teamwork, and participation, all move toward meeting the need for belonging. All other engagement is usually informal and undocumented. Informal and undocumented communication can mean that a problem is solved but not shared. It could also potentially mean that a problem solver will not get the recognition they deserve, potentially leaving an unsatisfied need for appreciation.

### *5.3 Ownership and Responsibility*

Of all those surveyed none were given any criteria for success, other than the part had to conform. As a result, there is no reward or recognition for meeting or exceeding the success criteria. There was also a sense that even a "thank you" was a rare occurrence. On the other side all were aware of the penalties for non-conformance. Repeated failures would result in re-training, reduction of hours (for contractors), removal of quality stamp (for the production laminators, akin to a demotion), and even dismissal. There was even one case where a contractor had to follow an instruction set which resulted in a non-conforming part. The result was a reduction in hours, causing the contractor to leave the job in question. The current system which provides little recognition for success and threatens the laminator's safety needs for failure should be addressed.

All responded with a high sense of responsibility, owing mainly to the certification and traceability requirements of their respective industries. This results in a paperwork burden (a bureaucracy hygiene factor in Herzberg's theory [25]). On the subject of paperwork, laminator 2 expressed the view that the entire lay-up operation, and indeed as much of the manufacture as is practicable, be done by the same person or team, to simplify the paperwork. This would also lead to a higher sense of responsibility since it would be more difficult to blame others for a non-conforming part. This is interesting from a manufacturing perspective as both the Toyota Production System (TPS) and Just In Time (JIT) facets of lean production [33] both emphasize a production flow, rather than control by a single employee.

### *5.4 Craftsmanship*

Laminator 5 disagreed with the notion of craftsmanship in the role of a composite laminator. The reasoning in this instance was due to the increasing use of lay-up aids such as laser projectors. This follows Maslow as it diminishes the sense of mastery in the esteem-level of need. As with flow manufacturing, lamination aids are seen as improving productivity and quality. Further work should be done to find the balance between aiding the laminator and eroding their sense of craftsmanship.

However there was general agreement from the other (mostly more experienced) laminators that they were, or at least identified with the notion of craftsmen. Their rationale was that lay-up is a complex operation that requires intuition, they have the freedom to work in their own way and that they possess certain skills and know-how. This is a good sign as it shows there is recognition of what they do and an identity, meeting both belonging and esteem needs. However given the previously mentioned increasing labor costs it is likely that de-skilling will be an objective of production environments.

When asked if the industry saw their role as craftsmen the answers were less definitive. Both laminators with around 15 years' experience said that the industry did not see them as craftsmen. One of the reasons was in industry preferring semi-skilled workers and using assistive technologies such as laser projection. The other it was due to the split between engineering and shop-floor, due in part to some preconceived ideas by both parties. For those that agreed it was because there was an appreciation of their skills and a degree of autonomy. From this it can be shown that autonomy can be an important motivator, particularly for the more skilled laminators. This shows that the recognition need is met in some but not others.

## 5.5 Summary of Needs and Initial Trends

Table 4 highlights the satisfiers/dissatisfiers for composite laminators. It can be assumed that physiological needs are met to a high enough degree that they do not need further inspection. From these first few results it can be seen that among composite laminators there are some divisions, notably between contractor and permanent staff, and between engineering and production. It can also be seen that

**Table 4** Pros and cons of each level of need

| Need | Pros | Cons |
|---|---|---|
| Safety | Contractor: better paid than permanent<br>Permanent: better security<br>Aerospace: consistent hours | Contractor: lack benefits<br>Contractor: longer hours<br>Contractor: no overtime<br>F1: ramp-up and lulls in production |
| Belonging | High levels of craftsmanship identity<br>Production: group meetings | Contractor/permanent split<br>Engineer/laminator split<br>Limited engagement with other areas |
| Esteem | High levels of craftsmanship<br>High levels of responsibility<br>Pride in job well done<br>Level of autonomy | Limited positive feedback<br>Feedback primarily negative<br>No reciprocal recognition of skills<br>No rewards<br>Feedback offered up not acted upon |

contractors appear to suffer somewhat more when it comes to meeting their needs. Enhancing positive feedback and giving credit and recognition would reduce the esteem drawbacks; and this could be carried out in formal, recorded meetings, also enhancing belonging by bringing together engineers and laminators to solve production problems and improve manufacturability.

## 6 Conclusions and Further Work

There are three principle objectives for composite manufacturers: retain key personnel, improve productivity, and improve quality. This is possible through better fulfilling their needs according to Maslow and these are summarized in. This preliminary survey, while not yet statistically significant due to the small population size, hints at a larger trend of unmet needs with composite laminators. These are chiefly in the esteem and belonging regions. If the industry is to keep up with the increasing demand in the future these needs must be met in order to prevent high staff turnover (or escalating labor costs due to a limited labor pool) and low productivity.

It is difficult to say what the precise impact implementing these suggestions will have on productivity. However since there is likely to be an increase in output required over the next few years, steps must be taken to improve motivation. It is also important to not undervalue the tacit knowledge gained through training and experience which will be lost if the employee leaves to pursue contract work. That said a needs-based motivation theory is clearly of some benefit to this process.

Further work in this work will be to expand the number of respondents to get a wider industry picture. This would also be helpful for determining how laminators' needs affect the deployment of a quality management system such as lean or six-sigma for TQM etc. (Fig. 2).

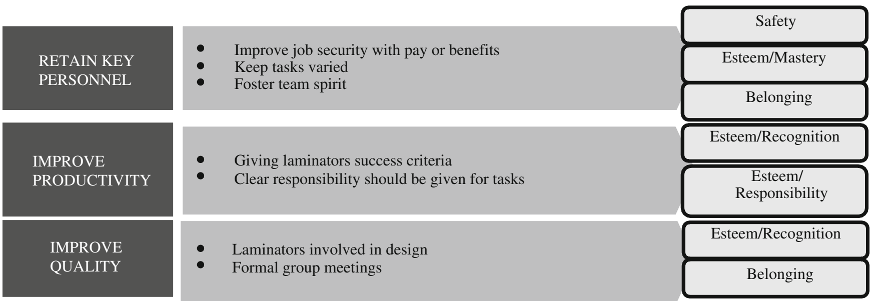


**Fig. 2** Summary of objectives, suggestions, and needs to fulfil

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# Appendix 1 Interview Procedure

## *A.1.1 Introduction*

The purpose of this interview is to gain some understanding of motivations within the lay-up environment. This is to enable me to have an understanding of what things matter the most to composite laminators to put forward some ideas of how to improve motivation, productivity, and quality of manually laid-up parts. The main areas I will be looking into are:

| | | | | |
|---|---|---|---|---|
| (a) Experience | (b) company/industry practices | (c) Working patterns | (d) Engagement with others | (e) Craftsmanship |

These areas have been selected as a starting point for getting to know the motivations and working practices within the composites industry. Any information which can be provided will be of use. If there are any questions you feel uncomfortable answering, please say so and we will move on. However any information you can give will be very helpful for this work. The information you provide will have any identifying material and information removed and will not be directly quoted from. The interviews will be recorded by handwritten notes. Any questions before we begin?

## *A.1.2 Experience*

1. So to start, how many years have you worked in composite manufacture?
2. What was/were your role(s) and responsibilities?
3. What size companies did you work in?
4. What (if any) training did you receive for this/these role(s)?
   a. External, company, self-taught?
5. What industry sector(s) have you worked in? (e.g., defense, aerospace, automotive, marine…)
   a. Why change?
6. What materials systems did you use in these roles (woven, prepreg etc.)?
   a. Which materials did you like or dislike and why?

7. Have you had any previous roles which you think might have contributed to these roles?
   a. Could you give any details?

### A.1.3 Industry Practice

1. In the industries mentioned earlier, were there any practices, in particular regarding to quality control, which you were aware of?
2. Could you talk me through a typical project/work order?
3. Information received? (Briefings, MIS etc.)
   a. What do you think could be done in the future? (Computer simulations?)
4. Feedback to design/supervisors?
5. Quality control
   a. Process
   b. Measures
   c. Tolerances
6. Number of people/size of part/area
   a. What is the largest part which could be made by a single operator?
   b. What are the timescales for the manufacturing operation?
7. Inspection
   a. Who inspects?
   b. How long for?
   c. When? (ply-by-ply, de-bulk)
   d. What are you inspecting for? (Measurement devices, tolerances etc.)
8. Did the material type influence how any of this was carried out?
9. Paperwork
10. Have you noticed any differences between industries/companies in these processes? (If worked for more than 1)

### A.1.4 Work Patterns

1. In a typical week how many hours did you work?
   a. Were there opportunities to do overtime work?
2. Were these hours arranged in shifts or 9-5?
   a. How did you prefer to take your shifts?
3. Do you think this spread is typical for this role/industry?

4. How were breaks organized?
5. Was there any night shift work?
6. Did you work individually or in teams? Which did you prefer?
7. Was there any information flow between teams, shifts, individuals?

### *A.1.5 Engagement*

1. In a typical project was there a mechanism to feedback concerns or difficulties to a supervisor or to the designers?
   a. Do you think this worked well?
2. What, if any, feedback mechanisms were there between the shop floor and designers (two-way)? Were there supervisors, or meetings for example?
3. Were there any discussions between operator teams/individuals?
   a. How do you feel these were handled?
   b. Could it be done better?

### *A.1.6 Ownership*

1. What was the level of accountability or traceability for your own work?
   a. How was this carried out?
2. Were there any personal success criteria given to you at the start of a project?
3. What was the result of failing to meet the criteria?
4. Were there any rewards for meeting/exceeding the criteria?
5. How do you feel this structure worked, or affected your motivation?
6. How much did you feel like you "owned" your task and outputs?
   a. How responsible did you feel for your own work?
7. Do you think you would have benefitted from more or less ownership?

### *A.1.7 Craftsmanship*

1. How much do you feel that your role (or those similar to it) compare to a "craftsman"?
2. Do you think that the industry sees or treats you as craftsmen?

### A.1.8 Other

1. So with all the things we've discussed in mind, when was working in your role best for you?
2. What has changed during your career?
   a. Has academia had an impact?
3. If you were to run your own production line, from a blank sheet, how would you do it?
4. How do you feel about increased use of automation?
   a. For lay-up/assisting laminators?
5. Can you think of any other sources of motivation for yourself or those in a similar role?

### A.1.9 Concluding

Thank you very much for your time. Your responses will be of great help to me in this study. Is there anything you would like to ask me at this point?

## References

1. Anon (2009) The UK composites strategy. Department for Business Innovation and Skills Report
2. Anon (2009) Aerospace industry outlook—implications for composite demand. In: AeroStrategy management consulting presentation, composites industry investment forum 2008, New York City
3. Anon (2006) HYBRIDMAT 3: advances in the manufacture of advanced structural composites in aerospace—a mission to the USA. In: Report of a DTI global watch mission
4. DeLong DJ (2007) Global market outlook for carbon fiber 2006 and beyond. SAMPE J 43(1):39–46
5. Ward C, Harza K, Potter KD (2011) Development of the manufacture of complex composite panels. Int J Mater Prod Technol 42(3/4):131–155
6. Anon (2009) The UK carbon fibre composites industry—market profile. Department for Business Innovation and Skills Report
7. Weitao M (2011) Cost modelling for manufacturing of aerospace composites. M.sc research thesis, School of Applied Sciences, Cranfield University
8. http://www.indexmundi.com/commodities/?commodity=aluminum&months=300&currency=gbp. Accessed 14 Jan 2013
9. Lukaszewicz DHJ, Ward C, Potter KD (2012) The engineering aspects of automated prepreg layup: history, present and future. Compos Part B 43:997–1009
10. Ward C (2012) Personal communications
11. Buckingham RO, Newell GC (1996) Automating the manufacture of composite broadgoods. Compos Part A 27A(3):191–200

12. Ward C (2010) Manufacturing quality assessment through in-process inspection. In: 31st SAMPE Europe international technical conference, Paris, France
13. Marsh G (2011) Automating aerospace component production with fibre placement. REINFORCED Plast 55:32
14. Hancock SG, Potter KD (2006) The use of kinematic drape modelling to inform the hand lay-up of complex composite components using woven reinforcements. Compos Part A 37:413–422
15. Hancock SG, Potter KD (2005) Inverse drape modeling—an investigation of the set of shapes that can be formed from continuous aligned woven fibre reinforcements. Compos Part A 37:947–953
16. Anon (2010) LPT100 laser RADAR projector. Laser Projection Technologies Brochure
17. Anon (2012) LASERGUIDE: the next generation. Assembly Guidance Systems Brochure
18. Miracle DB, Donaldson SL (2001) ASM handbook, vol 21: composites. ASM International, Ohio
19. Newell CG, Buckingham RO, Khodabandehloo K (1996) The automated manufacture of prepreg broadgoods components—a review of literature. Compos Part A 27A(3):211–217
20. Kujinga A (2006) Organisation of in-process inspection and control of the lamination process in carbon fibre composites manufacturing. MRes Thesis, School of Industrial and Manufacturing Science, Cranfield University
21. Maslow A (1943) A theory of human motivation. Psychol Rev 50:370–396
22. McLeod SA (2007) Maslow's hierarchy of needs. http://www.simplypsychology.org/maslow. Accessed 18 Jan 2013
23. Huitt W (2007) Maslow's hierarchy of needs. Educational psychology interactive, http://www.edpsycinteractive.org/topics/regsys/maslow.html. Accessed 18 Jan 2013
24. Maslow A, Lowery R (1988) Toward a psychology of being, 3rd edn. Wiley, New York
25. Herzberg F, Mausner B, Snyderman BB (1959) The motivation to work. Wiley, New York
26. Ramlall S (2004) A review of employee motivation theories and their implications for employee retention within organizations. J Am Acad Bus 5(1/2):52–63
27. Wahba MA, Bridwell LG (1976) Maslow reconsidered: a review of research on the need hierarchy theory. Organ Behav Human Perform 15:212–240
28. Tay L, Diener E (2011) Needs and subjective well-being around the world. J Pers Soc Psychol 101(2):354–365
29. Kenrick DT, Griskevicus V, Neuberg SL, Schaller M (2010) Renovating the pyramid of needs: contemporary extensions built upon ancient foundations. Perspect Psychol Sci 5(3):292–314
30. Bentley TW (1994) Factors affecting the motivation of skilled craftsmen in the United States Air Force. M. sc Thesis, University of Texas at Austin
31. Parkes KR, Clark MJ (1997) Part IV The offshort environment in the mid-1990s: a survey of psychosocial factors. Health and Safety Executive—Offshore Technology Report
32. Lam SYW, Tang CHW (2003) Motivation of survey employees in construction projects. J Geospatial Eng 5(1):61–66
33. Shah R, Ward PT (2007) Defining and developing measures of lean production. J Oper Manage 25:785–805

# Relationships of Factors in a Manual Assembly Line Environment

**Jaakko Peltokorpi, Sampsa Laakso, Juho Ratava, Mika Lohtander and Juha Varis**

**Abstract** This study makes a proposal and then presents the information required to describe operations and human resources management factors in a manual assembly line environment. This information is needed since the purpose of this study is to increase the understanding of the effects of the factors and their interrelationship on system performance. Because of the complex nature of the socio-technical assembly environment the present study focuses on task- and worker-related matters as a basis for conceptual-level analysis and factor connections flow. The study uses the Gephi software for analyzing factor clusters, occurrences, and connections by means of a relationship network. As a result, the software produced four different factor clusters, each characterized by strong mutual relationships between the factors comprising them. Further, the results of this study help to identify the factors that are to be used in more thorough analysis, from assembly environment development up to semi-intelligent decision-making systems.

## 1 Introduction

The development and maintenance of a competitive manufacturing system is a widespread issue in global production markets. In order to achieve highly performing and profitable production the description of product and device resources and their interconnectedness should be the starting point for method comparison [1], the development of expenses [2], production planning [3, 4], and the performance of optimization [5]. According to Newness [2], budgeting in the design

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phase requires the presentation of factors relating to production and the product itself, as does process optimization.

There are at least two points of view on cost-effectiveness in the manufacturing context, namely cost-effective total product, and cost-effective manufacture [6]. A typical response to decreasing cost-effectiveness in western countries is that companies concentrate on those actions that add the most value to the product they are able to with great efficiency. With a view to the present paper, such effectiveness potential has been seen in assembling mass customized products in varying production circumstances in which line design and the manual workforce play a major role. When assembly production is designed in such a way that the task-, system- and worker-related properties are taken into account throughout, a significantly higher degree of value added can be incorporated into a product, while minimum production costs and good employee satisfaction can also be maintained.

Many previous approaches to analyzing and developing the performances of manual assembly systems have been undertaken, advisedly or unknowingly, with inadequate information to handle a socio-technical system. Instead of the necessary and thorough understanding of the assembly environment, these academic studies or practical case studies from several disciplines mostly concentrate on separate subsystems or problems to be solved. Although the incremental improving of assembly processes can improve efficiency and productivity, in the longer term all the essential factors, both in the operations and human resources management fields, should be handled together. Therefore, when analytical methods are being selected the nature of the system must be taken into account. Furthermore, it is impossible to create an optimal technological design, as stated by Wang [7], unless the characteristics of the processes are known.

The purpose of this study is to increase understanding of the manual assembly line environment. As a research method the study makes a conceptual and relationship-level analysis of task- and worker-related factors in the proposed environment. Because of the complex nature of such a socio-technical system, the environment is described on a level that is suitable for examination. Then the information based on the literature is presented to describe the interrelationship effects of the factors. This information is needed for analyzing a highly-performing assembly production and for the further development of expert systems.

The rest of the paper is organized as follows. "A Framework for Optimising Product Performance Through Using Field Experience of In-service Products to Improve the Design and Manufacture Stages of the Product Lifecycle" deals with the traditional problems and methods when an assembly environment is being designed and analyzed. "Advanced Product and Process Design Through Methodological Analysis and Forecasting of Energy Consumption in Manufacturing " proposes the assembly environment to be examined by defining the factors and explaining their effects on the other factors on the basis of the previous literature. "Cost-based Evaluation for Product Selective Disassemblability" presents and analyzes the results as a relationship network generated by the Gephi software. Finally, "Risk Management Methodology Covering the Entire Product Lifecycle" draws the conclusions.

## 2 Methods for Analyzing Assembly Processes

Designing and analyzing manufacturing systems involves the handling of essential matters and the use of suitable methods. As an example, companies have traditionally integrated the master production scheduling and detailed capacity planning of production design. Production design, as well as all other design functions in manufacturing, including drafting, operation, and mechanics, should be increasingly combined under one overall system in order to improve profitability. Regardless of the development trend, it is inevitable that the portion of automatic and semi-intelligent systems will increase. The development of smarter systems requires several separate functions, practices, and disciplines to be gone through. This is used for designing systems that are capable of presenting the information people need at the right time and with suitable accuracy. In this paper, the authors present the fields deemed the most central, required or in need of development in order to design intelligent systems for assembly operations.

Once a model for an assembly process is formulated, there may be multiple ways of attempting to find an optimal solution or analyze it as a function of its sub-processes. However, in order to get a broad understanding of the whole socio-technical system, the information on the factors and the effects of their interrelationships, and all the loops in the entire process should be studied. From that point of view many previously studied processes, such as assembly task re-organizing, job scheduling, worker selection or assembly line balancing by means of workload or worker allocation can be seen as separate sub-processes or problems of the assembly environment. As an example of that, it has been proven by Rekiek et al. [8] that the assembly line balancing (ALB) problem itself is an NP-hard problem (non-deterministic polynomial-time hard), and in order to acquire an integrated solution from production design to highly performing production, it is but a single part of the environment. Therefore, solving the problem for complex assembly production will take large amounts of computation time if conventional means are used. Some of the solution methods may apply on multiple levels of the problem, whereas some may be unique to a specific part of the problem.

The exact formulation of the model of the assembly environment imposes specific requirements for the solving method to be applied. Most notably, solving, e.g., the ALB problem requires optimization in a discrete space. If measurements are used, care must be taken in data assimilation (model fitting), as all data must be considered noisy. All models are ultimately approximations, adding another source of imprecision to the system. Finally, in order for an appropriate method to solve the problem to be selected, the nature of the system must be taken into account.

The programing method must be able to deal with nonlinearities and discrete decisions in order to solve the problems in processes. As the assembly process is ultimately stochastic, many approaches use statistical and stochastic methods [9]. In addition, genetic algorithms and fuzzy logic are used. As a result of the discrete solution spaces, Multi-Attribute Decision-Making (MADM) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) may be used to select the correct combination. Other approaches may locally linearize the problem or use methods such as simulated annealing. Some approaches use an agent-based solution, such as in the study of Sabar et al. [10], though in general, branch-and-bound type solvers are used, e.g., for ALB problems.

Since the literature deals comprehensively with solving and analytical methods for problems and decision making the focus in this study is on a broader understanding and analysis of the assembly environment. Therefore the information that is needed and an analytical method that considers the factors involved with a suitable level of accuracy are proposed in the following papers.

## 3 Proposed Assembly Line Environment

Typically, when manual assembly performance is being examined the focus is on task- and worker-related matters. However, central issues in developing a socio-technical system are the goals the company has set and the way the system is to be managed in order to reach these goals. Hopp and Oyen [11] summarize that agile companies typically set such targets as reducing Work-In-Process (WIP), increasing throughput per time unit, and maintaining a minimum product cycle time or good employee satisfaction. Whatever the target is, system decision makers are at the interface between operations and human resources management, an approach that was handled in a comprehensive study by Boudreau et al. [12]. According to this paper, managers in both fields in industry should know the value of their connection when working together. The paper also notes that authors in the research fields of both operations and human resources management mostly handle these aspects as separate subjects in separate communities of scholars.

The assembly system design in this conceptual study is a serial mixed model assembly line, in which several variations of the same base product are assembled in a single line as discussed in [9]. The customization of physically relatively large products with low-volume processes influences the variation in workload and processing times between the stations and makes it possible for workers to help others in teams [13]. Figure 1 introduces the different assembly line environment factors and their connections on a conceptual level on the basis of the literature and partly on the authors' own view.

In Fig. 1, the operations management factors are shown against a dark gray background and human resources factors are shown against a light gray background. An arrow between the factors simply indicates a preceding factor affecting another. A factor against a changing dark gray and light gray background indicates that it can be characterized as both an operations and human resources factor in this context. The following paragraphs define the factors and explain their interconnections. First, work unit and task characteristics, then the system characteristics, followed by the individual characteristics, contribution and outcomes, and finally operational costs are examined. Because of the nature of the environment,

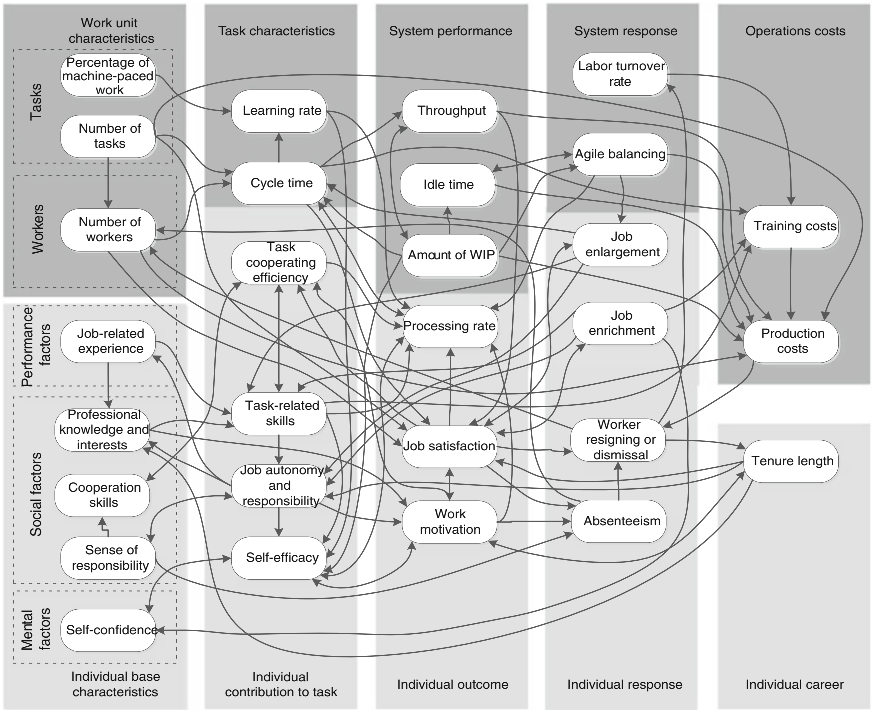


**Fig. 1** Assembly line environment flow chart

only directional effects are explained and the assessment of their magnitudes is omitted. Thus Fig. 1 does not present any values or weights.

A *work unit* consists of a number of serial *tasks* and a group of *workers* in a line segment. Each task is performed at their own station by one primary worker. Although the tasks are mainly processed manually, the number of machines and the level of automation affect the work. Therefore, the *percentage of machine-paced work*, indicating the shares of tasks in which machines are pacing labor at work, affects the *learning rate* [14].

When the number of workers differs from the number of tasks, it also affects the *cycle time* for tasks. An increased work unit size (through increased numbers of tasks and workers) increases not only *production costs* but also *absenteeism* and *labor turnover* because of lower group cohesiveness, higher task specialization, and poorer communications [15]. Importantly, *job satisfaction* is connected to both absenteeism and labor turnover, the latter specifically through *worker resignations*.

The *learning rate* is determined as the speed of the decrease in the average time for a task when the task completions are doubled on the basis of Wright's learning curve [14]. In general, the learning rate depends on the task type, which comprises task characters (i.e., cycle time) and overall task complexity. This factor has a major influence on the task *processing rate* and also on individual *self-efficacy,* determined in [16].

Operationally, the cycle time is the average total time it takes a job to queue to and be processed at a workstation [17]. From a worker's point of view, the cycle time can be defined as a repeated work cycle [18]. A study in [19] reviewed that with a relatively short cycle time (2.5–5 min) the level of labor dissatisfaction in assembly work was the highest. By contrast, a cycle time of 15–20 min results in optimum job satisfaction as a result of the reduced machine pace and leaving room for individuals to make their own decisions at work. However, an advantage of a suitable short cycle time is its ability to keep an efficient, increased pace (processing rate) on the assembly line [19]. In production management, the cycle time has a connection to the *amount of WIP* (Work-In-Process) and *throughput*, according to Little's Law [17]. Another effect is that the longer the cycle time (greater task content for one worker) is, the higher the *training costs* are.

Since the system in this paper enables workers to cooperate by means of agile helping, *task cooperation efficiency* is defined as the ability of one worker to provide help to another. This ability is, on the one hand, based on task properties such as task space congestion or constraints in tools [20], but also on individual abilities such as *cooperation* and *task-related skills*. That cooperation efficiency affects the processing rate, and it is notable that when workers are accustomed to working together, it affects their individual skills. The system performance indicates how productive a work unit is in terms of system throughput, utilization of resources and efficiency. The *throughput* rate for the system is determined as the number of completed jobs leaving the system (work unit) in a unit of time [17]. As a clear measure for cost-effective production, throughput affects production costs. Moreover, throughput makes a general if somewhat ambiguous contribution to job satisfaction [21].

A paced assembly line (in which products move to the next station in a synchronized manner) is not suitable for a mixed model assembly system because of the varying processing times between the stations. In a mixed model system, varying cycle times are balanced by using work-in-process buffers between the stations [22]. Work-in-process (WIP) is the average number of jobs within a system that are either undergoing processing or waiting for processing in a buffer [17]. The amount of WIP contributes to production costs because of the capital invested in temporary WIP inventories. The amount of WIP also affects the *idle time*, defined as the time when a worker cannot work because of blocking or starving [22]. Idle time increases production costs as a result of the non-value-adding time of a worker. However, an idle worker can help other stations, which here is denoted by the term *agile balancing*. An idle worker can be allocated to a bottleneck station in order to increase the efficiency of the whole line. A visible amount of WIP affects the working pace (processing rate) of an individual worker [12], assumedly through self-efficacy. The processing rate is determined as the number of completed items per time unit [23], thus contributing greatly to the cycle time.

The *system response* covers the ways in which the system re-organizes in order to maintain efficiency and good performance. A well-organized agile balancing is generally beneficial, though excess worker movement between stations, especially when setup times in the station they have moved to are taken into account, may increase production costs. In practice, temporary agile balancing can be characterized as individual *job enlargement*. Job enlargement means widening the range of tasks performed by a worker [24], which may increase the cycle time for a task. The increasing variety of work affects the individual processing rate through task-related skills, with learning (skilling) [14] and forgetting (deskilling) [25] effects. Job enlargement has a positive impact on *job autonomy and responsibility*.

The very basis of human resources management is the fact that individuals differ in what skills they possess, how fast they perform and many other characteristics [12]. When workers' base characteristics are being evaluated, the criteria can be classified into performance, social, and mental factors. This classification was used in a study of the worker placement problem in an industrial environment [26]. In this paper, the most relevant factors from these three categories are selected to determine individual base characteristics in the present assembly system.

*Job-related experience* is selected as a performance factor. It covers all the previous experience influencing the current job a worker has. This experience has an impact on performance through individual task-related skills [27]. The essential factors in a social context from [26] are selected as *professional knowledge and interests.* In this paper this term stands for the individual's professional know-how and interests in their current work. This fact contributes to *tenure length*, as reported in [28], which, in this paper, is supposed to occur through work motivation and job satisfaction. Job-related experience has a positive impact on professional knowledge and interests, which again affect task-related skills. Other social factors in this study are *cooperation skills*, meaning skills in joint action [24] taken by two workers and a *sense of responsibility*, describing awareness of one's obligations [24]. Both these social factors affect task cooperation efficiency. Moreover, a sense of responsibility contributes to job autonomy and responsibility and the level of absenteeism, as well as cooperation skills. Mental factors in workers' base characteristics are filled with self-confidence from [26], which means a belief in oneself or one's abilities [24]. Self-confidence basically affects self-efficacy with tasks.

*Individual contribution to task* covers the factors of individual abilities and performance of a given task. A skill is defined as an ability that has been acquired by training [24]. Task-related skills have a major impact on the individual processing rate as a result of the learning process described in [14]. These skills also have a negative effect on training costs. Task-related skills contribute to self-efficacy [24] and job autonomy and responsibility. Job autonomy means increased worker discretion and independence to schedule one's work and the ways work is done [29]. Job responsibility is simply defined as a given responsibility over work. Job autonomy and responsibility affect many factors, i.e., job-related experience, professional knowledge and interests, sense of responsibility, self-efficacy, and work motivation.

Self-efficacy is determined as beliefs in personal ability, skills, knowledge, previous task experience, and completion of the task to be performed. Moreover, the motivation theory is also built from the aspects of these personal and situational factors [24]. First of all, good self-efficacy contributes positively to the processing rate. Another meaning is increased self-confidence. An *individual outcome* is characterized as a result or consequence of how a worker perceives his job or position with the current task. Motivation is a psychological feature that arouses an organism to action toward a desired goal [24]. Therefore a motivated worker performs better than a worker without any goals or targets and thus good motivation indicates an increased processing rate. Work motivation affects job satisfaction and self-efficacy [24]. Moreover, a motivated worker is more interested in working at the company and therefore may achieve a long tenure. By contrast, a worker with motivation problems is absent more often [30].

Job satisfaction indicates the extent to which a worker's hopes, desires, and expectations about the employment he is engaged in are fulfilled [24]. In other words, job satisfaction embodies how contented a worker is in his job. This includes a sense of achievement, advancement, growth, recognition, and responsibility, as well as the work tasks [31]. Job satisfaction contributes to the processing rate, as well as the efficiency of the cooperation on an individual task. Continuous job dissatisfaction can lead to absenteeism and finally to the worker resigning from the job. Absenteeism itself is a habitual pattern of absence from a duty or obligation [24]. Temporary, when a worker is absent from work there may be a shortage of workers in a work unit. In the worst case absenteeism leads to *workers resigning or dismissal* from a job, which affects labor turnover.

*Individual response* describes the ways in which a worker's position in his current job is changed. When a change is needed, care should be taken to improve workers' tasks or working conditions through re-organization. Otherwise a worker's commitment to the job may decrease decisively. Job enlargement may be a solution to low job satisfaction, if dissatisfaction is caused by repetitiveness at work [32]. By contrast, a solution for low job satisfaction and work motivation resulting from work tasks not being challenging enough may be providing a range of tasks and challenges of varying difficulties by means of job enrichment [24]. A previous study in [33] connected job enrichment to positive personal and work outcomes. For example, new tasks, a decreased amount of control, special assignments, and increased authority were observed to lead to increased worker autonomy. The authors assume that special tasks influence the self-confidence of individuals through job enrichment. However, job enrichment increases training costs.

Labor turnover is the rate at which an employer gains and loses employees [24]. That turnover can be affected by any employee- or employer-driven reason that leads a worker to leave the job. Operationally, the turnover rate contributes to the training costs of new workers. Tenure length means the time a worker has held his current job position. It is assumed to contribute to work motivation and job satisfaction since a review study in [34] summarized that after a certain length of tenure labor turnover decreases. Tenure length also affects job autonomy and responsibility, as well as professional knowledge and interests [27].

Finally, operation costs include the costs of training and production. Training costs include training new workers or training current workers for new tasks. Production costs cover all the costs, direct or indirect, affected by the described assembly production itself. The costs of production can affect the numbers of worker dismissals for individual or for economic and productivity reasons.

## 4 Results and Discussion

The factors and relationships discussed in "Advanced Product and Process Design Through Methodological Analysis and Forecasting of Energy Consumption in Manufacturing" above were imported to the Gephi software suite presented in [35] to analyze the assembly environment being studied by means of a relationship network. Figure 2 below presents the self-organized network by visualizing factor clusters, occurrences, and connections. The figure is followed by analysis and discussion of the results.

In Fig. 2 a thick line between factors indicates a two-directional effect, whereas a thin line indicates only a one-directional effect. Four different clusters of factors are identified in the assembly environment. These clusters consist of the factors with the strongest relationships together and are marked in similar colors, characterized as follows: white, light gray, gray, and dark gray. The size of the points and text reflect the number of connections between each factor in the system.

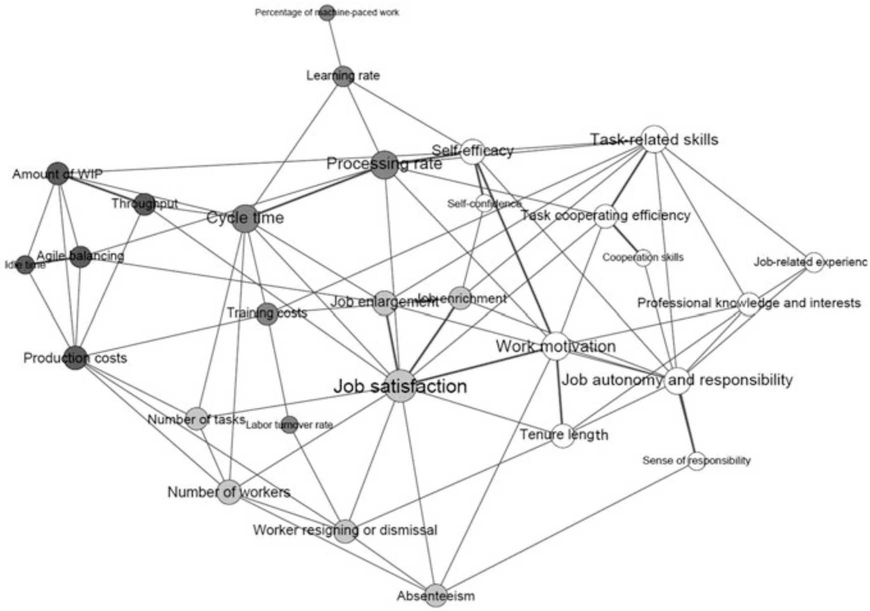


**Fig. 2** Relationship networks of manual assembly factors

The white cluster consists of ca. 38 % of the factors, covering all the factors from individual base characteristics and contribution to the task. In addition, work motivation, and tenure length are involved in this cluster. Major factors here are work motivation, self-efficacy, and task-related skills, as well as job autonomy and responsibility.

The light gray cluster covers about 24 % of the factors. The factors in this cluster represent work unit characteristics, as well as job satisfaction affecting the factors of individual response, as discussed in Sect. 2.2. Job satisfaction has the largest point of the network (Fig. 2), indicating the factor that occurred most frequently, with 15 incoming and outgoing connections in total. As mentioned, job satisfaction embodies the worker's contentment with his job, meaning, i.e., how the hopes, desires, and expectations connected with the job are fulfilled [24]. On the basis of the figure above, it is a major connective factor in a socio-technical system in contributing to the operational and human resource processes and targets set for the present manual assembly system.

The gray cluster consists of ca. 21 % of the factors covering all the operations management levels in the flow chart in Fig. 1. The factors in this cluster are related to task challenges, processing speed, and the training costs and labor turnover rate. Major factors here are the cycle time and processing rate.

The factors in the dark gray cluster (ca. 17 % of all the factors) consist of system performance factors, as well as agile balancing and production costs. A remarkable point about this cluster is that all the other factors affect the major factor, production costs.

According to the above analysis, the factors in the process flow levels of individual outcomes and individual contributions to tasks (Fig. 1) have the most connections. One explanation for this is that in the upstream of the process flow chart human resources factors are slightly more widely represented than operations management factors. Although the factors and connections presented, found in the literature or partly based on the authors' view, can be interpreted in various ways, the generated network, however, increases the understanding of the assembly environment and also gives insights for further developments of suitable analytical methods.

## 5 Conclusions

This study made a conceptual-level analysis of operations and human resources management factors and the effects of their interrelationships in a manual assembly line environment. The proposed socio-technical system was studied in order to see how both these types of factors affect system performance from the operational and individual workers' points of view. Because of the extremely complex research field, only task- and worker-related base characteristics were used as starting points in the process flow. A literature review was conducted to find out the factors and their possible directional effects on each other. Because of the unique approach and selection of factors in the assembly environment, some of the effects were also based on the authors' own view. All the effects were imported to the Gephi software suite to analyze factor clusters and occurrences. Four different clusters were identified as a result of the analysis. The largest cluster represents individual base characteristics and contribution to the task. In addition, work motivation and tenure length are involved in this cluster. The second largest cluster represents work unit characteristics, as well as job satisfaction and the factors of the individual response. The other two clusters consist of operations management factors: the first connects system performance factors and agile balancing to production costs, and in the second the factors are related to task challenges, processing speed, training costs, and labor turnover rate.

The results from the system that was studied show that the job satisfaction factor contributes most frequently to the other factors, being a major link between operations and human resources management processes and targets. Depending on the performance targets, different factor loops in the assembly process can be identified, and thus taken into account during decision making and system development. This approach does not give automatic solutions to reach the targets, but helps to identify the factors that are to be used in more thorough analysis. Different expert systems can be further developed by examining the essential factors that influence specific assembly systems. In order to get more accurate results from such analyses, the parameter values have to be identified. Although literature and experts can be used in searching for values, ultimately empirical studies are needed for realistic parameters.

## References

1. Lutters D, ten Brinke E, Streppel AH, Kals HJJ (2000) Computer aided process planning for sheet metal based on information management. J Mater Process Technol 103(1):120–127
2. Newness LB, Mileham AR, Hosseini-Nasab H (2007) On-screen real-time cost estimating. Int J Prod Res 45(7):1577–1594
3. Cuirana J, Ferrer I, Gao JX (2006) Activity model and computer aided system for defining sheet metal process planning. J Mater Process Technol 173(2):213–222
4. Hayes C (1996) P3: a process planner for manufacturability analysis. IEEE Trans Robotics Automation 12(2):220–234
5. Singh DKJ, Jebara C (2005) Feature-based design for process planning of machining processes with optimisation using genetic algorithms. Int J Prod Res 43(18):3855–3887
6. Lohtander M (2010) On the development of object functions and restrictions for shapes made with a turret punch press. Lappeenranta University of Technology, Lappeenranta
7. Wang GG, Xie SQ (2005) Optimal process planning for a combined punch-and-laser cutting machine using and colony optimization. Int J Prod Res 43(11):2195–2216
8. Rekiek B, Dolgui A, Delchambre A, Bratcu A (2002) State of art of optimization methods for assembly line design. Ann Rev Control 26(2):163–174
9. Boysen N, Fliedner M, Scholl A (2011) Assembly line balancing: which model to use when? Int J Prod Econ 111(2):509–528
10. Sabar M, Montreuil B, Frayret J-M (2011) An agent-based algorithm for personnel shift-scheduling and rescheduling in flexible assembly lines. J Intell Manuf 23(6):2623–2634

11. Hopp WJ, van Oyen MP (2004) Agile workforce evaluation: a framework for cross-training and coordination. IEEE Trans 36(10):919–940
12. Boudreau J, Hopp W, McClain JO, Thomas LJ (2003) On the interface between operations and human resources management. Manufact Serv Oper Manag 5(3):179–202
13. Hytönen J, Niemi E, Perez S (2010) The effect of worker skill distribution and overmanning on moving worker assembly lines. In: Proceedings of international conference on competitive manufacturing. Stellenbosch, South Africa, pp 171–176
14. Yelle LE (1979) The learning curve: historical review and comprehensive survey. J Decis Sci Inst 10(2):302–328
15. Steers RM, Porter LW (1973) Organizational, work, and personal factors in employee turnover and absenteeism. Psychol Bull 80(2):151–176
16. Porter LW, Bigley GA, Steers RM (2003) Motivation and work behavior, 7th edn. McGraw-Hill/Irwin, New York
17. Curry GL, Feldman RM (2011) Manufacturing systems modeling and analysis, 2nd edn. Springer, Berlin
18. W. Karwowski: Handbook of standards and quidelines in ergonomics and human factors, Lawrence Erlbaum Associates, 2006
19. Jürgens U (1997) Rolling back cycle times: the renaissance of the classic assembly line in final assembly. In: Shimokawa K, Jürgens U, Fujimoto T (eds) Transforming Automobile Assembly. Springer, Berlin
20. Sengupta K, Jacobs FR (2004) Impact of work teams: a comparison study of assembly cells and assembly line for a variety of operating environments. Int J Prod Res 42(19):4173–4193
21. Judge TA, Bono JE, Thoresen CJ, Patton GK (2001) The job satisfaction-job performance relationship: a qualitative and quantitative review. Psychol Bull 127(3):376–407
22. Bukchin J, Dar-El EM, Rubinovitz J (2002) Mixed model assembly line design in a make-to-order environment. Comput Ind Eng 41(4):405–421
23. Slack N, Chambers S, Johnston R (2009) Operations and process management: principles and practice for strategic impact, 2nd edn. Pearson Education Ltd, London
24. http://www.thefreedictionary.com/. Accessed 16 Jan 2013
25. Nembhard DA (2001) An empirical comparison of forgetting models. IEEE Trans Eng Manage 48(3):283–291
26. Yaakob SB, Kawata S (1999) Workers' placement in an industrial environment. Fuzzy Sets Syst 106(3):289–297
27. Quinones MA, Ford JK, Teachout MS (1995) the relationship between work experience and job performance: a conceptual and meta-analytic review. Pers Psychol 48(4):887–910
28. Boyd JB (1961) Interests of engineers related to turnover. J Appl Psychol 45(3):143–149
29. Helms MM (2006) Encyclopedia of management, 5th edn. Thomson Gale, Farmington Hills
30. Nicholson N (1977) Absence behaviour and attendance motivation: a conceptual synthesis. J Manage Stud 14(3):231–252
31. Herzberg F (1987) One more time: how do you motivate employees. Harvard Bus Rev 65(5):109–120
32. Hulin CL, Blood MR (1968) Job enlargement, individual differences and worker responses. Psychol Bull 69(1):41–55
33. Hackman JR, Oldham G, Janson R, Purdy K (1975) A new strategy for job enrichment. California Manage Rev 17(4):59–76
34. Globerson S, Crossman E (1976) Minimization of worker induction and training cost through job enrichment. Int J Prod Res 14(3):345–355
35. Bastian M, Heymann S, Jacomy M (2009) Gephi: an open source software for exploring and manipulating networks. In: Proceedings of 3rd international AAAI conference on weblogs and social media. San Jose, CA, USA, pp. 361–362

# Clustering for Decision Support in the Fashion Industry: A Case Study

**Ana Monte, Carlos Soares, Pedro Brito and Michel Byvoet**

**Abstract** The scope of this work is the segmentation of the orders of Bivolino, a Belgian company that sells custom tailored shirts. The segmentation is done based on clustering, following a Data Mining approach. We use the K-Medoids clustering method because it is less sensitive to outliers than other methods and it can handle nominal variables, which are the most common in the data used in this work. We interpret the results from both the design and marketing perspectives. The results of this analysis contain useful knowledge for the company regarding its business. This knowledge, as well as the continued usage of clustering to support both the design and marketing processes, is expected to allow Bivolino to make important business decisions and, thus, obtain competitive advantage over its competitors.

## 1 Introduction

The fashion industry is increasingly characterized by short life cycles, high volatility, low predictability, and high impulse purchasing [1]. In order to have manufacturing systems that support increased competitiveness in a global market, companies need complete and up-to-date knowledge about all the parts of their

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business (e.g., product development, marketing, production) and they need to integrate this knowledge into those systems. This work addresses one part of that problem. We use Data Mining (DM) approaches to extract knowledge from historical data with the goal of supporting the fashion industry in its production/design and marketing decisions.

The data that companies collect about their customers is one of its greatest assets [2]. Companies are increasingly accumulating huge amounts of customer data in large databases [3] and know that, within this vast amount of data, there are all sorts of valuable information that could make a significant difference to the way in which any company run their business and interact with their current and prospective customers. If available, this information can help them gain competitive edge on their competitors [2]. Given the additional fact that companies have to be able to react rapidly to the changing market demands both locally and globally [2], it is urgent that they manage efficiently the information about their customers. This is true in fashion as in most other industries.

One approach that is increasingly being used for that purpose is data mining. DM techniques can be used to extract unknown and potentially useful knowledge about customer characteristics and their purchase patterns [3]. This knowledge can, then, be used predict future trends and behaviors, allowing businesses to make knowledge-driven decisions that will affect the company, both short term and long term [2]. DM is also being used in e-commerce to study and identify the performance limitations, increase sales, and address issues raised by political and physical boundaries [2]. The identification of such patterns in data is the first step to gaining useful marketing insights and making critical marketing decisions [3]. In today's environment of complex and ever changing customer preferences, marketing decisions that are informed by knowledge about individual customers becomes critical [3]. Customers have such a varied tastes and preferences that it is not possible to group them into large and homogeneous populations to develop marketing strategies. In fact, each customer wants to be served according to his individual and unique needs [3]. Thus, the move from mass marketing to one-to-one relationship marketing requires decision-makers to come up with specific strategies for each individual customer based on his profile [3]. This is particularly important in highly customized industries. In extreme cases, such as Bivolino, each product is different from all the others.

In short, DM is a very powerful tool that should be used for increasing customer satisfaction by providing good quality, safe, and useful products at reasonable prices as well as for making the business more competitive and profitable [2]. One of the most important DM tasks is clustering [4, 9]. Clustering algorithms find subgroups of observations in a population that are similar among themselves but very different from the observations in other subgroups. Clustering is often used in segmentation [6]. In this paper, we show how clustering can be useful for segmentation in the textile industry, in particular for highly customized garments. Our goal is to use the clusters to support both the design and the marketing processes. The approach is tested on data provided by Bivolino, a manufacturer of custom tailored shirts. To the best of our knowledge, there are no publications on the use of this approach in highly customized industries.

We start by motivating this study in Sect. 2. In Sect. 3 we present a short introduction to clustering. In Sect. 4 we present and discuss the results. The paper finishes with some conclusions and some ideas for future work (Sect. 5).

## 2 Clustering

According to Jain [4], clustering can be defined, in operational terms, as follows: "Given a *representation* of *n* objects, find *k* groups based on a measure of similarity such that the similarities between objects in the same group are high while the similarities between objects in different groups are low."

### *2.1 K-Medoids Algorithm*

According to Velmurugan and Santhanam [5], the basic strategy of K-Medoids clustering algorithms is to find *k* clusters in *n* objects by (1) arbitrarily finding a representative object (the medoid) for each cluster; (2) associate each remaining object with the medoid to which it is the most similar; (3) update the medoids by choosing the most representative object in each of the *k* clusters; and (4) repeat steps 2 and 3 until convergence or a stopping criterion is met. Unlike the more common method, K-Means, the K-Medoids method uses representative objects as reference points. The algorithm takes the input parameter *k*, the number of clusters, to be partitioned among a set of *n* objects.

Velmurugan and Santhanam [5] present a typical K-Medoids algorithm for partitioning based on medoids, i.e., examples from the data that represent the corresponding clusters. Due to lack of space, we omit the details of the algorithm, which can easily be found in the literature (e.g., [5]). A very informal summary is:

Input: $K =$ number of clusters and $D =$ dataset containing n objects.
Output: A set of *k* clusters that minimizes the sum of the dissimilarities of all the objects to their nearest medoid.
Method: Arbitrarily choose *k* objects in *D* as the initial representative objects.
Repeat: Assign each remaining object to the cluster with the nearest medoid; randomly select a non medoid object $O_{random}$; compute the total points *S* of swap point $O_j$ with $O_{random}$; if $S < 0$ then swap $O_j$ with $O_{random}$ to form the new set of *k* medoid until no change occurs.

## 3 Case Study

This work was motivated by the need of segmenting Bivolino shirts orders, based on data from 2011. The goal was to obtain knowledge to support design and marketing business decisions. Bivolino[1] is a company that produces and sells customized shirts on the web, both for men and women.

Our goal is to demonstrate the applicability of data mining methodology, tasks, techniques, and tools to support both design and marketing processes in the fashion industry. The data mining methodology adopted was CRISP-DM.[2] The data mining task that is suitable for the problem at hand is clustering. Clustering partitions data based on a certain similarity criteria or distance measure. The distance measure used was the Mixed Euclidean Distance, given the fact that we have numerical and categorical variables. This measure uses the classical Euclidean distance for numerical variables and a binary distance for symbolic variables (i.e., distance is 0 if both values are the same and 1, otherwise). The clustering algorithm applied to the data was K-Medoids because it works well with large amounts of data, is less sensitive to outliers, and can handle categorical data. The data mining software used to segment the shirt orders was Rapid Miner.

The problem is the identification of the fashion profiles in Bivolino shirts orders to support the company in terms of design and marketing decisions. The aim is to extract useful information and obtain important knowledge about the business of Bivolino using data mining tools and techniques.

## 4 Results

We present two different analyses. The first one is focused on the perspective of production/design of shirts while the other takes a marketing perspective. The difference between them is in the inputs, i.e., the sets of attributes used to characterize the transactions. Different variables naturally lead to different results. The analysis of the first results is focused on the shirts and orders attributes, namely in the typical values they assume in each cluster, as given by the respective medoid. Due to lack of space, we do not describe the results and the data in detail. We simply illustrate the results with some examples, namely by identifying the most salient features of the clusters.

[1] http://www.bivolino.com

[2] http://http://khabaza.codimension.net/index_files/crispdm.htm

### 4.1 Clustering for Design

In these experiments, the goal is to analyze the characteristics of the shirts that were purchased, searching for knowledge that is potentially useful for shirt design and production. We try to identify the fashion trends on shirts based on customer choices of shirts and their characteristics.

Table 1 summarizes the results of the clustering performed on data concerning 10,775 shirts orders characterized by 29 attributes (4 numerical and 25 categorical), with the number of clusters $k = 6$. All the clusters obtained have medoids with at least one attribute that is clearly distinctive, i.e., that identifies each cluster in a unique way. The medoids are defined by the most "typical" value of each attributes in the corresponding cluster. For numerical attributes, the typical value is the mean while for the categorical ones it is the most common value, i.e., the mode.

Analyzing the results, we can group the clusters into two main groups. The first group is composed by clusters 1, 2, and 4 corresponding to work shirts and representing 65 % of total shirts orders. The second group is composed by clusters 3, 5, and 6 corresponding to fashion shirts and representing 35 % of total shirts orders. Analyzing these groups in more detail, we additionally observe the following: costumer choices are conditioned by a certain formal business dress code; cluster 2 represents the most common choices in terms of shirt attributes; and the binary[3] attributes (e.g., has pocket, has monogram) assume, in most of the cases, the value *no*. In terms of the second group, we conclude that costumer choices were conditioned by their physical attributes (e.g., mature men have preference for pockets on shirts unlike the young men). This relation is illustrated in Fig. 1.

These observations can be useful for the product designers because understanding what the preferences of the customers are and how they evolve will lead to the development of products which are better suited to their preferences.

### 4.2 Clustering for Marketing

In the second experiment, we focus on the customers rather than on the shirts, which is more suitable for marketing purposes. In marketing terminology, we perform a segmentation of the costumers. This perspective aims to identify and define in which segments the company should focus its efforts and marketing strategies.

First, we have to define the segmentation bases, i.e., the attributes that are used to characterize the observations. We have added to the attributes that characterize the shirt, several attributes that characterize the customers. In Table 2 we show the classical segmentation bases suggested by Kotler and Keller [6].

3 Binary attributes in Rapid Miner's terminology are binomial attributes.

**Table 1** Clustering results in a technical perspective (distinct medoids attributes values). The second line contains the number of observations and the corresponding proportion. The lines below that, contain differentiating features of the clusters

| Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
|---|---|---|---|---|---|
| 1,282 12% | 4,889 45% | 872 8% | 1,570 15% | 500 5% | 1,662 15% |
| Work_shirt | Work_shirt | Fashion_shirt | Work_shirt | Fashion_shirt | Fashion_shirt |
| Fabric_color: *Multicolor* | Fabric: *Greenwich* | Fabric_structure: *Twill* | Collar: *Italian Semi-spread* | Collar/Cuff white: *Yes* | Fabric: *Miro_3* |
| Fabric: *Sheffield* | | Fabric: *Red & Bordeaux* | Fabric: *London_4* | Fabric: *Kiwi_9* | Fabric_structure: *Herringbone* |

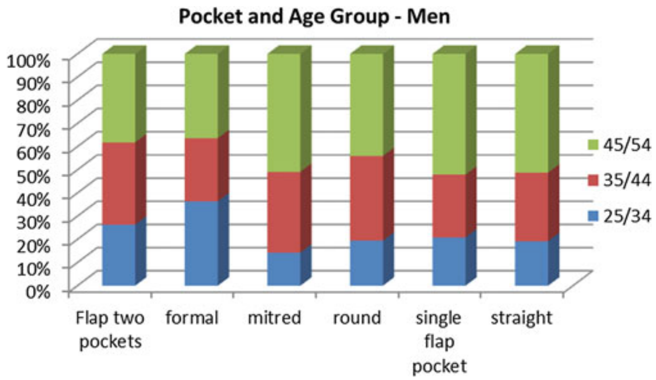


**Fig. 1** Relation between age and shirt pocket

**Table 2** Segmentation bases

| Demographic (who they are) | Geographic (where they live) | Psychographic (how they behave) | Behavioristic (why they buy) |
|---|---|---|---|
| Gender: men (91%), women (9%)<br>Age: [25-34], [35-44], [45-54]<br>Country/Nationality: UK (United Kingdom), fr (France), de (Germany) | Nationality: UK (United Kingdom), fr (France), de (Germany)<br>Postal code: any different | Lifestyle: activities—work; social events; or entertainment<br>Interests—work; fashion | Price sensitivity: has voucher (yes; no) |

So, the company can segment its customers according to the three demographic variables gender, age, and nationality. This category of segmentation variables is, according to Kotler and Keller [6], very popular in the way that these variables are often associated with consumer needs and wants and are easy to measure. If a company chooses to segment its customers by gender, it has to take into account that "men and women have different attitudes and behave differently, based partly on genetic makeup and partly on socialization" [6] and that "they have different expectations of fashion products" [7]. If a company segments its customers on the basis of the age, the shirts have to be "designed to meet the specific needs of certain age groups" because "customer wants and abilities change with the age" [6]. If a company decides to segment its customer market based on nationality, it has to pay attention to the "identity attributes because of social and cultural values that inform the self" [7].

The company can also divide its customers market into different countries and also into specific regions given the postal code. This kind of segmentation does not ensure that all customers in a location will make the same buying decision; however, it helps in identifying some general patterns [6].

A psychographic segmentation is based on variables that are inferred such as personality traits (consumerism, dogmatism, locus of control, cognitive style, and religion), personal values, and lifestyle (activities: work, hobbies, social events, entertainment, etc.; interests: family, home, job, fashion, etc.; opinions: of oneself, social issues, economics, culture, etc.). As we did not have access to such kind of personal information, we could only make some inference about it. Therefore, we propose that the company segments its customers market according to their life-style based on their activities (e.g., work and social events or entertainment) and interests (e.g., work and fashion).

Behavioral variables are considered by marketers "the best starting point for constructing market segments" [6] and "are related to buying and consumption behavior" [8]. This category comprises variables such as occasions, benefits expectations, brand loyalty, price sensitivity, usage rate, end use, attitude, preferences, etc. Some of these variables can be directly measured and others have to be inferred. As for the psychographic variables, we did not have enough information. However, we identified the price sensitivity as a behavioristic variable which can be measured by the use or not of gift vouchers that offers discount on payment.

Table 3 presents the clustering results concerning 10,775 shirts orders characterized by 59 attributes this time (30 more that in the first experiment, where 27 are numerical and 32 categorical). As before, we set the number of clusters to $k = 6$, and the algorithm returned 6 clusters with at least one clearly distinctive attribute.

Table 3, like Table 1, represents the distinctive attribute values that identify each cluster in a unique way. In this case, we can group the clusters in 3 groups. They are the work shirts (clusters 1, 4, and 5), the party shirts (clusters 2 and 3), and the fashion shirts (cluster 6). Several interesting observations can be made from these results. For instance, they show that young men (age between 25 and 34] years old) prefer shirts of slim fit, while mature men (age between 45 and 54 years old) prefer shirts of comfort fit.

Another interesting segment is given by cluster 2, which represents mostly women. The characteristics of the shirts in this segment make it possible for the

**Table 3** Clustering results in a marketing perspective (distinct medoids attributes values). The second line contains the number of observations and the corresponding proportion. The lines below that contain differentiating features of the clusters

| Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 |
|---|---|---|---|---|---|
| 2,687 25% | 5,116 47% | 2,316 21% | 80 1% | 564 5% | 12 1% |
| Work_shirt | Party_shirt | Party_shirt | Work_shirt | Work_shirt | Fashion_shirt |
| Collar group: <36 | Gender: women<br>Has voucher: yes<br>Country: fr (France)<br>Affiliate: Bivolino | Postal code: sg49aq | Postal code: co45bq | Postal code: cv313nd | Country: de (Germany) |

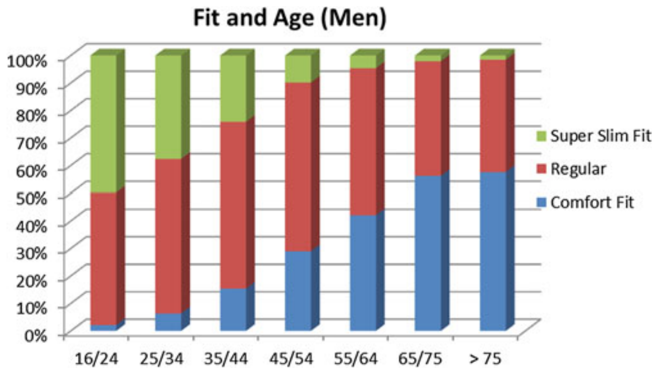


**Fig. 2** Relation between shirt fit and customer age

company to segment its consumer market on the basis of the gender of the customers, as men and women have different expectations of fashion products.

We also observe that the company can segment its market based on the age of the customers, since the changes in body characteristics and shape have a great impact on fashion choices. One example is that in terms of shirt fit (level of shirt tightness to the body) choices, the young customers prefer the "super slim fit" and the older customers the "comfort fit", although the "regular fit" remains the most common choice. This relation is illustrated in Fig. 2. Other example is that the older customers are the ones that like to use pocket on shirts the most, especially of a certain type.

The company can also segment the market geographically by country or postal code, since customers from different places have different requirements for fashion and clothing products, and their choices are often influenced by social and cultural values. We observe that the more representative country in terms of Bivolino sales in 2011 was the United Kingdom (UK). This fact is illustrated in Fig. 3.

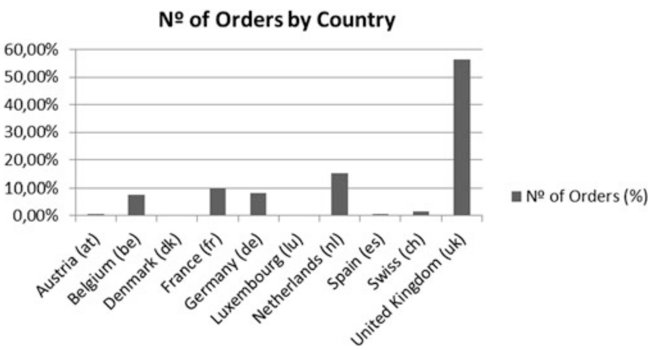


**Fig. 3** Relation between shirt fit and customer age

Another alternative for segmenting the Bivolino costumers is on the basis of the purpose or intention of buying according to, for instance, the categories "work shirt", "fashion shirt", and "party shirt" (configurator or collection type). We can then infer, for example, that their buying is motivated by professional requirements (e.g., segments 1, 4, and 5), interest on fashion (e.g., segment 6), or by social events requirements (e.g., segments 2 and 3).

We have also identified another segmentation variable that is the price sensitivity. This could be measured by the usage of gift vouchers to get a discount on payment. We concluded that women are more price sensitive than men given that more than 82 % used a voucher for payment. Women are generally more receptive to promotions of this type and more open to experimenting new products than men. However, we do not know if this was related to a specific promotion, because Bivolino only introduced the female collection in 2011. On the other hand, if this is a gender-related pattern, then the company should study other ways of attract the female public and improve sales.

## *4.3 Limitations*

During our study we faced several challenges. The first one is related to the limitations of the method adopted. The K-Medoids clustering algorithm, despite being less sensitive to outliers than K-Means because of the use of the median instead of the mean, still requires the a priori definition of the number of clusters. Deciding the optimal *k* number of clusters is well known to be a difficult task [9]. Common approaches to this problem consist of running the algorithm multiple times with different parameter values (i.e., *k*), and the best configuration obtained from all of the runs is used as the final clustering. This method is extremely time consuming. In our experiments, each clustering process took a significant amount of time (a few hours) on Rapid Miner due to the quantity of examples as well as to the number of attributes. Another difficulty concerns the evaluation of the result: how to assess whether the clustering obtained is good or not. All clustering algorithms will, when presented with data, produce clusters regardless of whether the data contain clusters or not. If the data does contain clusters, some clustering algorithms may obtain 'better' cluster than others [9]. However, in this study, this was not an important problem because, given the type of the attributes used in the study (binary and polynomial, i.e., non-numeric), the choice of algorithm was very limited. Most of the clustering algorithms available on Rapid Miner do not process categorical data (data separable into categories that are mutually exclusive, such as age groups). However, the algorithm selected proved to be suitable for the problem at hand.

In summary, the most important difficulties faced in the study were:

- Deciding the number of clusters *k*;
- High computational cost of the methods;

- Limitations imposed by the types of the attributes, which strongly constrain the selection of the algorithm;
- Subjective nature of the evaluation process;
- Insufficient data to characterize customers.

## 5 Conclusions

In this paper, we use clustering for segmentation in a textile manufacturer of highly customized garments. We investigated how the clusters obtained can be used to support both the design and the marketing processes.

The approach was tested on data provided by Bivolino, a manufacturer of custom tailored shirts, containing 10,775 examples which correspond to the number of shirt orders in 2011. The clustering was obtained using a K-Medoids algorithm with $k = 6$ clusters. Two sets of experiments were carried out. In the first, the transactions were characterized using 29 attributes that describe the orders, the shirts, and the customers, while in the second, 59 attributes were used, including attributes that characterize the customers in terms of demographic, geographic, psychographic, and behavioristic features.

In the first set of experiments, we focused on the characteristics of the shirts because the goal was to obtain knowledge (e.g., profiles and trends) that is useful for the design process. The clusters obtained represent attribute values in shirt orders that are specific to a subgroup of transactions, which can be used by the fashion designers to better perform their tasks.

In the second set of experiments, we included features that are typically used in marketing studies to describe customers. Thus, the clusters found by the K-Medoids algorithm enabled us to analyze the profile of Bivolino customers and their relation to the product (shirts). We concluded that their choices in terms of shirts attributes are greatly influenced and conditioned by numerous factors such as, their physical attributes, age, gender, nationality (country), and purpose of buying. The profiles found can be used by the company to adjust its product and marketing strategies to the different segments identified.

In summary, despite some challenges that were discussed, this study illustrates how DM tools and techniques, namely clustering, are indeed valuable instruments to better understand consumer tastes and preferences allowing companies to be more efficient and responsive to customer requests and gaining a competitive advantage, particularly in highly customized textile industries.

Taking into account the difficulties encountered during the study and the limitations they imposed on it, we find that future work is needed and should focus on the following issues, which are mainly related to the problems of the clustering process itself:

- Develop a heuristic solution to find the optimal number of clusters for any given dataset;

- Reduce the time complexity when dealing with large number of dimensions and large number of data items;
- Develop methods to support the systematic interpretation of the result of a clustering algorithm (that in many cases can be arbitrary itself);
- Transform the data to enable the use of different clustering algorithms, compare the different results, and decide which one is the best;
- Reduce the dependency of the effectiveness of the clustering method on the definition of "distance" (for distance-based clustering);
- Alternatively to the previous suggestion, it would be interesting to find a way of defining a distance measure, that is specific to the business problem and aligned with the evaluation criteria.

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## References

1. Lo W, Hong T, Jeng R (2008) A framework of E-SCM multi-agent systems in the fashion industry. Int J Prod Econ 114:594–614
2. Ahmed S (2004) Applications of data mining in retail business. In: International conference on information technology: coding and computing (ITCC'04), IEEE
3. Shaw M, Subramaniam C, Tan G, Welge M (2001) Knowledge management and data mining for marketing. Decis Support Syst 31:127–137
4. Jain AK (2009) Data clustering: 50 years beyond K-means. Pattern Recognit Lett 31:651
5. Velmurugan T, Santhanam T (2010) Computational complexity between K-means and K-medoids clustering algorithms for normal and uniform distributions of data points. J Comput Sci 6(3):363–368
6. Kotler P, Keller K (2000) Marketing management, 13th edn. Prentice Hall, New York
7. Rocha M, Hammond L, Hawkins D (2005) Age, gender and national factors in fashion consumption. J Fashion Mark Manage 9(4):390–390
8. Wedel M, Kamakura W (2000) Market segmentation: conceptual and methodological foundations. Kluwer Academic Publishers, Dordrecht
9. Jain AK, Murty MN, Flynn PJ (2000) Data clustering: a review. ACM Comput Surv 31(3):264

# Competence-Based Planning of Coupled Process Chains

**Berend Denkena, Friedrich Charlin and Helge Henning**

**Abstract** Planning of manufacturing process chains requires simultaneously the consideration of the necessary human and technological resources for producing parts. Thereby, today's planning methodologies often only focus on the technical resources of production systems like machinery, tools, or material. A systematic integration of the worker′s competencies in terms of process chain planning is often neglected. This is a major drawback which is especially critical for production systems characterized by a high vertical range of manufacturing resources like multiple types of processes and machines or knowledge intensive manual work steps. Besides assembly processes in specialized industries, forging process chains are an example for production systems of high complexity in terms of coupled processes which will be discussed in this paper. Therefore, a new method for competence-based planning of coupled process chains has been developed, merging a competence analysis with analytical technological process models and a Genetic Algorithm for optimization. Based on a set of pareto-preferable solutions, parameters for forging process chain dimensioning can be found and selected based on the planner′s experience. The developed method and software-prototype are depicted and optimization results are discussed based on a case study.

## 1 Introduction

Intelligent Manufacturing requires both a technological and a human competence perspective. The recent years have been characterized by an increasing customer demand for individualized high-performance products, further progress in manufacturing technologies, and strong market competition. Thus, manufacturing

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process chains have to be planned thoroughly with a high flexibility in order to keep up with these challenges. Thereby, the task of the process planning is the pre-determination of the optimal machining parameters within the involved technologies as well as the required number and qualification of the working personnel. Generally, the generated process plans are based on the planner's experience with detailed knowledge about the required technologies, constraints, or process chain alternatives. The overall aim is the optimal dimensioning of the manufacturing resources in the process chain. The optimization objectives range from minimizing cycle or cutting times, minimizing production costs, resource- or energy-efficient manufacturing to high flexibility, and responsiveness [1]. A survey conducted in 2012 with 43 short- and medium-sized industrial enterprises revealed that systematically integrating worker's competencies in planning bears high monetary saving-potentials in production technology (Fig. 1).

It can be concluded that the impact of the workers′ competencies on the production targets gains in importance with a growing complexity of the manufacturing tasks, i.e., production systems characterized by a high vertical range of manufacturing resources or knowledge intensive manual work steps. This leads to a high number of processes included in the process chain planning, and therefore a high amount of parameters and worker′s to be assigned. Thus, the required expertise of the work planner grows significantly which is in conflict with the aim to optimally exploit the potentials mentioned above.

Figure 2 illustrates this relation for the planning of forging process chains, which represent a demanding planning task. Thereby, a given sequence of necessary processes always requires a specific consideration of the existing technological interfaces between the processes. If the focus of the planning depends mainly on the optimization of one single process (e.g., turning), it can counterfeit

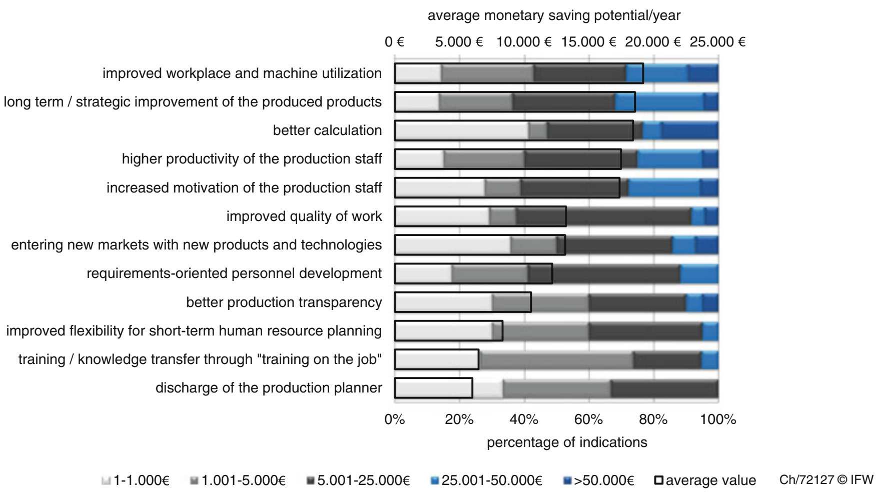


**Fig. 1** Survey: Monetary saving potentials per year for competence-based planning

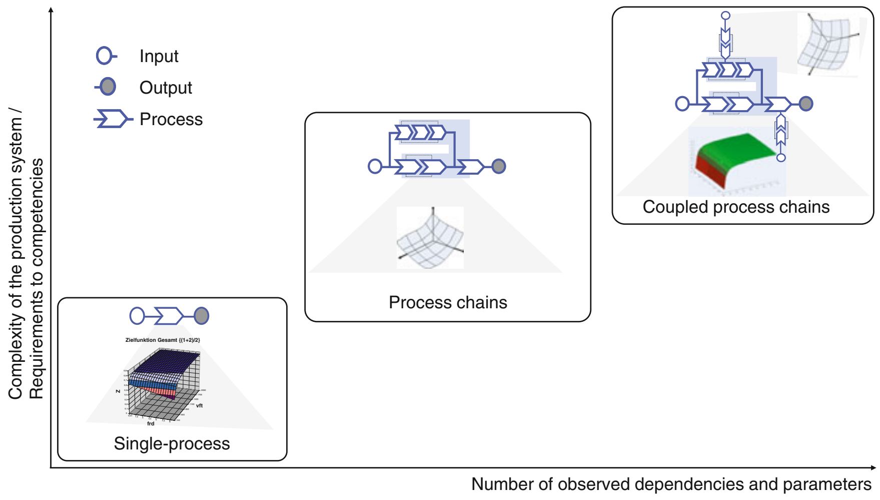


**Fig. 2** Increase of optimization complexity

the achievement of an overall optimum of a process chain [1]. Considering the dependencies of the whole process chain in planning leads to further benefits, as manufacturing processes can be adjusted to each other. Due to the proportionately high costs of the forging tool and the main contouring of the parts to be produced within the forging process, the impact of the tool on the overall costs and quality in forging process chains is significant. Therefore, the coupling of the indirect process chain of tool production into the direct (i.e., value-added) process chain bears high optimization potentials which, on the other hand, increases the amount of possible process plans. Bearing this in mind, a method for overall optimization of coupled manufacturing process chains integrating indirect process chains into the planning has been developed in the past years. The method is based on analytical and empirical process models, which model the dependencies between input and output values within and between the process chains mathematically [1, 2]. This way, an overall optimization of the process chains using optimization algorithms (e.g., linear optimization or genetic algorithms) can be performed. Tool design and manufacturing is directly linked to the resulting impacts on the total performance of the overall process chain. The monetary saving potentials achieved using the integrative approach were up to 12 % for a case study compared to a conventional optimization focussing the optimization of each single process without considering the dependencies in the process chain [3].

Although the proposed developments for coordinating the parameters of manufacturing processes in a holistic manner are very promising, they only focus on the technological resources of a production system. Worker's competencies, i.e., technical, social, and personal skills, which can have a great impact on the production targets in complex systems, are not integrated systematically into the planning yet. This separation can be observed consistently in literature, as current planning approaches either focus on technical aspects [4–6] or human aspects [7–10]. Thus, a competence-oriented dimensioning of coupled process chains bears high potentials for optimization as the impact on the production targets of both the manufacturing processes and the workers are systematically considered. In the following, the novel integrated concept is depicted and discussed based on a case study.

## 2 Competence-Based Approach for Planning of Coupled Process Chains

### *2.1 General Planning Procedure*

The starting point for process chain planning is the product specifications defined by the customer. Further input is represented by the internal target costs of the manufacturing units, the available technologies and capacities. If these specifications are determined, the selection of manufacturing processes and process parameters, usually under technological and economic criteria, is carried out. This step requires higher competence of the planner referring to technologies and processes. Additionally, the job-assignment of the workers based on the skills has to be performed. The needed competencies for performing the job have to be matched with the prevalent skills. This step has to be executed for all manufacturing process chains being included. Afterwards, the resource planning and temporal scheduling of orders is executed. Each manufacturing technology, tool, material, or production worker require specific knowledge in order to determine the best set. The planning expert has to be supported effectively by adequate methods in order to realize an optimal plan. An effective measure for this subject is a virtual model of the process chain. Analytical and empirical approaches can be used to model the dependencies in the process chains. This approach implies, however, that all significant interactions are implemented with generic process models. In practice, this can only hardly be guaranteed, since a complete modeling of the process chain is complex, expensive, and time consuming. Thus, the acceptance of the results computed by implemented algorithms is not always given by the experts. Furthermore, the integration of the worker′s competencies has to be guaranteed, as the impact on the production targets gains in importance with a growing complexity of the manufacturing tasks. Thereby, the increasing amount of parameters being included in the planning often leads to high-dimensional optimization problems of the virtual model [11]. The search for the optimal values exceed the expected time frame if every possible set of parameter is calculated separately.

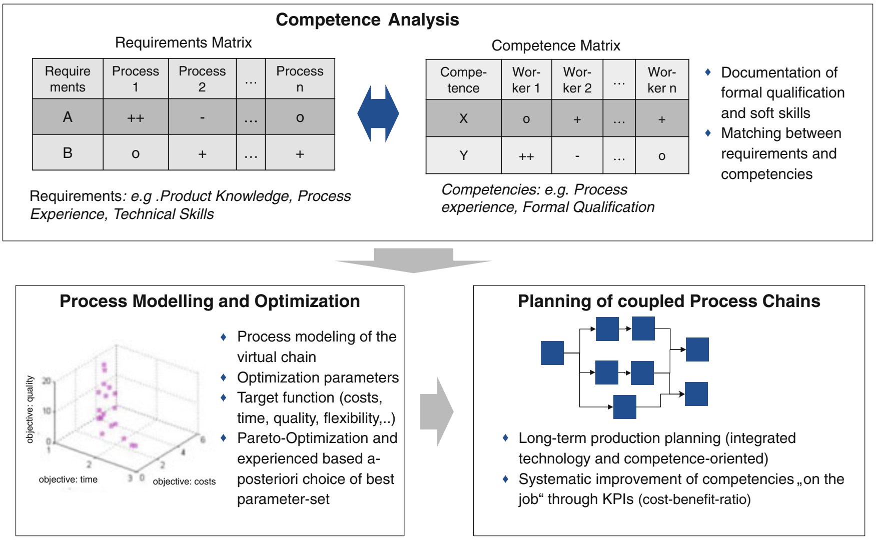


**Fig. 3** Competence-based planning approach for coupled process chains

## 2.2 *Competence-Based Approach for Process Chain Planning*

The new competence-based planning approach which has been developed combines the technological process chain dimensioning with the expertise of the working personnel (competence-oriented) by a flexible modeling and heuristic-based optimization method for integrated planning (Fig. 3).

First, the requirements regarding the needed technologies and competencies for performing the work tasks have to be categorized and evaluated. In the next step, these requirements need to be matched with the competencies of the workers for determining suitable workers for specific work tasks. In addition to the technical skills of the workers, social, and personal skills have to be considered, as these have a great impact on the degree of fulfillment of the work task. Furthermore, the impact of the competencies to the production has to be formalized and combined with the technological process models. After that, the parameters to be optimized have to be connected to a fitness function of an optimization algorithm in order to find a best set of parameters for the process chains. These parameters are, in the next step, optimized by the implemented heuristic algorithms. In order to improve the acceptance of the optimization results, the a posteriori decision making procedure for a choice of best set of parameters is fundamental. Therefore, a pareto-based optimization of the process chain parameters is performed which allows an integration of expert-knowledge. This way, the planner can select one best set of parameters offered by the heuristic which corresponds to his experience. In case a suitable set of parameters is not calculated by the algorithm, the planner can go back to the step of technological process chain planning and has the possibility to choose alternative manufacturing processes or adapt the mathematical process models. Based on these results, the planner is able to identify best possible process parameters considering both machining and worker's demands.

## 2.3 Modeling of Coupled Process Chains

As depicted, a major step within process chain planning is to specify the product requirement as well as the internal restrictions and to transfer these values into target criteria for the optimization. Thereby, the expert has to focus on the main process chain without reducing the perspective to single processes and the indirect process chains. Increasing the planning perspective leads to a balancing of process chains as interdependencies between the processes and their impact on target values are as well considered. Thus, the dependencies in the process chains need to be analyzed and modeled (Fig. 4).

Thereby, the tool making is integrated as an indirect process chain into the optimization of the direct process chain and the parameters settings are optimized simultaneously for both process chains. The interdependencies between the process chains are adjusted for the criteria of minimizing manufacturing costs. The costs of the tool and the costs of the further finishing operation are planned based on the resulting stock allowance. The modeled interdependency is as follows: The higher the permitted allowance or the lower the requirements for dimensional accuracy, the lower the manufacturing costs of the tool will be. This is due to decreasing requirements for macro- and micro-geometry of the die. On the other

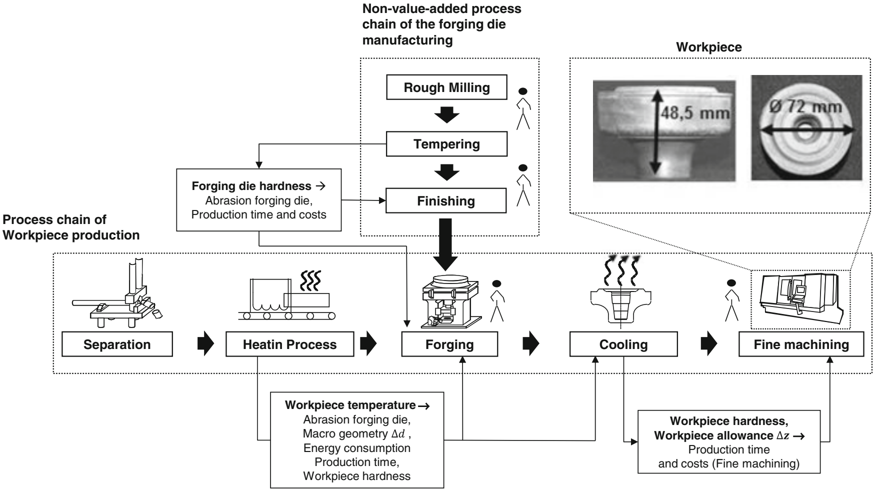


**Fig. 4** Dependency-analysis of a coupled forging process chain

side, the costs of the subsequent finishing operation increase with less precise upstream processes. In this case, the requirements for the finishing operation increase as well as the cutting time due to an increased amount of material to be removed.

In the next step of this approach, process models need to be generated for this interdependency. The macro geometry of the work piece, described by the stock allowance $\Delta z$ influences the process of fine machining regarding the manufacturing time $t_{\text{fine machining}}$ and especially the tool wear costs $C_{\text{tool wear}}$. In consequence, the manufacturing time $t_{\text{fine machining}}$ of the finishing process is influenced by the machining parameter feed rate f, cutting depth $a_p$, cutting speed $v_c$ and the stock allowance $\Delta z$.

$$t_{\text{fine machining}} = \frac{l * \frac{d}{2} * \frac{\Delta z}{a_{\mathrm{p}}}}{1000 * f * v_{\mathrm{c}} * 60} \tag{1}$$

The variables l and d represent the length and the diameter of the work piece, respectively. The processing costs for the finishing process $C_{Finishing}$ consist of the energy cost $C_{energy}$, the machine costs $C_{machine}$, the wage cost $C_{wage}$, the tool wear cost $C_{tool\,wear}$ ,and tool change costs $C_{tool\,change}$. The energy cost $C_{energy}$ are predominantly influenced by the cutting depth $a_p$, and the feed rate $f$. The wage costs $C_{wage}$ depend on the required processing time $t_{\text{fine machining}}$ and the assigned worker. $C_{\text{tool wear}}$ is further influenced by the choice of machining parameters with the related tool abrasion as described in Eq. 2 ($A_2$, $A_3$, $A_4$ as constant material describing parameters) and $C_{\text{tool}}$ representing the tool costs.

$$C_{tool\,wear} = \frac{C_{tool} + t_{fine\,machining}}{A_3 * vc^{A_2} * f^{A_4}} \tag{2}$$

From technological point of view, $C_{Finishing}$ can be formulated as a function of the cutting parameters and the stock allowance, depending on both processes from the different process chains.

## *2.4 Integrating the Competence Requirements*

The other major aspect of the depicted approach is that the human factors need to be integrated into calculation, i.e., the wage costs and the influence of the worker's qualification on the process time. Thereby, the competencies can influence the necessary time for reloading the machine, quality measurements of the part, the tool change, process installation, capacity for dealing with inconveniences, etc. In this context, the process-specific competencies (Table 1) have to be identified and documented using a simple ranking system (e.g., scale of 1–10). In this context, 1 represents a very low level of competence and 10 the maximum value.

**Table 1** Technical and Soft Skills of the workers

| Technical skills about… | Soft skills |
|---|---|
| …the machine [1–10] | motivational skills [1–10] |
| …the process [1–10] | self-management [1–10] |
| …NC-Programming [1–10] | physical condition [1–10] |
| …the products [1–10] | Capacity for Team Work [1–10] |
| …organizational issues [1–10] | willingness and ability to learn [1–10] |
| …etc. | …etc. |

Thereby, the single competence requirements $C_{Ni}$ and have to be matched with each competence level $C_{Li}$ of the workers as follows in order to perform a gap-analysis:

$$\Delta C_i = C_{Li} - C_{Ni} \tag{3}$$

The following logic can be assigned for the workers according to the demands of the enterprises:

- $\Delta C_i > 2$, highly qualified for the job, with the possibility of teaching
- $0 \geq \Delta C_i \geq 2$, well qualified
- $-2 > \Delta C_i > 0$ out of the job, with the possibility of "learning on the job"
- $-2 > \Delta C_i$ out of the job, with the possibility of learning periods (seminary, school…)

In order to be able to determine appropriate workers for the jobs, the needed and existing competencies need to be aggregated. Furthermore, the influence of the personnel on the processes has to be determined. Therefore, a parameter has been developed, which evaluates the suitability of a worker for a job for each process (e.g., fine turning) and allows for an optimization through a genetic algorithm:

$$COMP_{pr} = \left( \sum_{i=1}^{n_T} \frac{\frac{TC_{Li}}{TC_{Ni}}}{n_T} * f_K + \sum_{k=1}^{n_p} \frac{\frac{PC_{Lk}}{PC_{Nk}}}{n_p} * f_P \right) * \frac{M_L}{M_N} \tag{4}$$

with:

- $TC_{Li}$ = *i-th* technical competence level of the worker;
- $TC_{Ni}$ = *i-th* needed technical competence for the job;
- $n_T$ = the number of technical competence for the worker and the job;
- $PC_{Lk}$ = *k-th* physical competence level of the worker;
- $PC_{Ni}$ = *k-th* needed physical competence for the job;
- $n_T$ = the number of technical physical for the worker and the job;
- $M_L$ = worker's motivation level (facultative);
- $M_N$ = job's motivation needed (facultative);
- $f_K$ = percentage of influence of the technical competence on the job;
- $f_P$ = percentage of influence of the physical competence on the job.

In this context, the mean of the percentage of influence of the technical $f_K$ and physical $f_P$ competences depend on the different importance of "knowledge" and "physical skills." The sum of both factors is one. Based on this parameter, the influence of the personnel on the process time and process costs can be described as follows:

$$t^W_{process,k} = t_{process,k} * \left[ (1 - p_k) + \frac{p_k}{COMP_k} \right] \quad (5)$$

with

- $t^W_{process,k}$ is the process time of the *k-th* process influenced by the worker
- $t_{process,k}$ is the process time of the *k-th* process only influenced by the machine
- $p_k$ is the percentage of personnel influence on the process time of the *k-th* process
- $COMP_k$ is the coefficient of personnel for the *k-th process.*

The percentage of influence of the personnel on the process time is a value between 0 and 1: this value defines the percentage of the time of the process when the worker effectively works on the job (e.g. the percentage of the work in a programmable turning machine including the loading time and the programming time). Related to that, the formula of the process cost is

$$C^W_{worker,k} = C_{worker,k} * COMP_k * p_k \quad (6)$$

where

- $C^W_{worker,k}$ is the process cost of the *k-th* process influenced by the worker
- $C_{worker,k}$ is the process cost of the *k-th* process only influenced by the machine
- $p_k$ is the percentage of personnel influence on the process time of the *k-th* process
- $COMP_k$is the coefficient of personnel for the process *k-th.*

Thus, for integrated technological and competence-oriented planning, the costs of the finishing process are finally a function of several factors as follows:

$$C_{Finishing} = f\left(a_p, v_c, f, \Delta z, COMP_{pr}\right) \quad (7)$$

## 3 Software-Prototyope and Optimization Results

The presented process models and ranges for optimization are the basis for an integrated technological- and competence-oriented process chain planning. A software prototype has been developed in MATLAB R2010b using the GUI-Builder (GUIDE) and the Global optimization Toolbox for the Genetic Algorithm (Fig. 5).

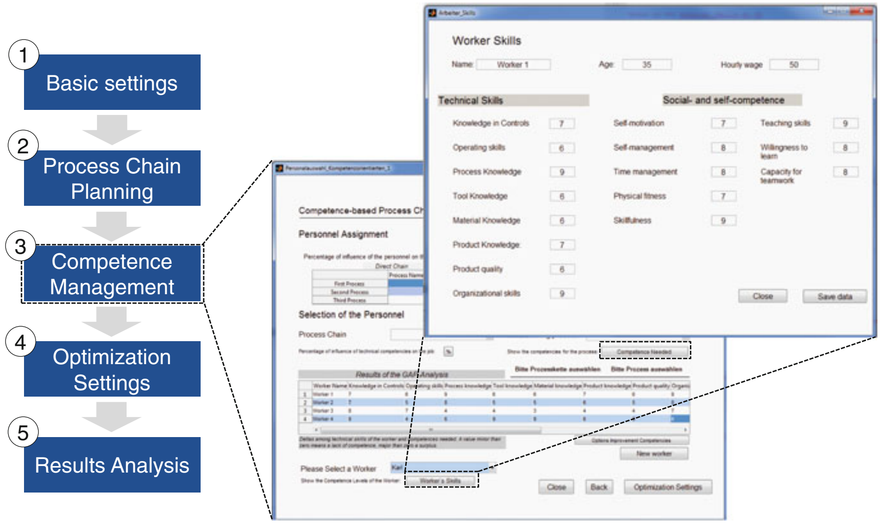


**Fig. 5** Step 1–5 for competence-based planning and screenshots of the prototype

The prototype is connected to an Access Database storing, e.g., the parameters for the process models, the variables to be optimized, the competence-criteria and relating competence values for the single workers, and optimization results. With the help of the prototype, the planner can define process chains for single customer orders and provide the parameters as well as the relating ranges for optimization. Furthermore, the assignment of the personnel is supported by the requirements and competence matrix, which are stored in a database. The parameters are connected to mathematical process models which have been generated regarding to the optimization targets as a fitness function (minimization of costs and production time, optimization of product quality).

An extract of the results of one exemplary optimization run is shown in the following. In the application scenario, 43 technological parameters of the coupled process chain (e.g., feed rate and cutting speed of the cutting parameters and heating temperature of the forging process) as well as the competence values for each process have been optimized simultaneously with the following genetic operators and parameters:

- Codification: Real
- Population Size: 20
- Elite-count: 2
- Generations: 100
- Stopping criterion: Change of fitness values $<10^{-2}$
- Selection-function: Tournament
- Crossover-function: two-point
- Crossover-fraction: 0.8

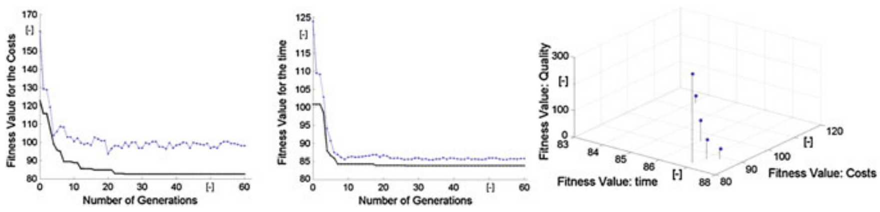


**Fig. 6** Fitness values for the whole process chain: costs (*left*), time (*middle*); dashed line: mean fitness values, *solid line*: best fitness values; projected Pareto-frontier of the last generation (*right*)

In the following, some results from the optimization are presented (Fig. 6, Table 2).

It is shown, that based on the set of pareto-efficient results, the planner can choose suitable technological process parameters for the process chain. Furthermore the calculated optimal competence value can be matched with the competence value of the single workers with regard to the gap-analysis for each competence criterion presented in A framework for optimising product performance through using field experience of in-service products to improve the design and manufacture stages of the product lifecycle. The results presented in Table 2 show that the ranges of the Fitness values as well as technological and competence parameters increasingly converge to optimum values. These can then be selected by the planner in terms of optimal process chain dimensioning based on his experience.

## 4 Conclusion and Outlook

A novel approach for planning coupled manufacturing process chains has been illustrated which enables the optimization regarding technological and competence-based criteria. The approach requires the application of software tools and adequate optimization algorithms in order to lead to an efficient optimization. The genetic algorithm has been selected from the class of heuristic approaches for optimizing. The algorithm has been implemented into a software prototype and discussed for a coupled forging process chain involving forging and machining processes. Because of the pareto-based approach, the planner can decide on the basis of his preferences and competence, which set of parameters is adequate for a given case. Thereby, several benefits can be observed: Considering coupled process chains, eliminates the drawback of single-process oriented optimization. Including the skills of the work planner adds flexibility to the process planning. The results from the case study already depict the possibility of integrating technical and competence-oriented criteria into optimization contributing to a sustainable continuous planning of process chains. Using this approach, the planner is supported by assigning suitable workers to the processes from the worker pool, as the corresponding influence on the production targets is considered.

**Table 2** Optimization results for selected parameters of the first and last generation

| Fitness values | | | | | Technological parameters | | | | Competence parameters | |
|---|---|---|---|---|---|---|---|---|---|---|
| Generation | Time | Cost | Quality | Σ | […] | cutting depth [mm] | feed rate [1/rev] | rotational speed [1/min] | […] | Competence for turning ($COMP_{pr}$) |
| 1 | [101–1,978] | [116–1,401] | [19–412] | [280–3,398] | […] | [0.4–0.085] | [0.05–0.09] | [2,000–2,240] | […] | [0.11–1.23] |
| … | … | … | … | … | … | … | … | … | … | … |
| 60 | 86 | 94 | 19 | 199 | […] | 0.085 | 0.09 | 2,005 | […] | 1.06 |
| | 87 | 83 | 257 | 427 | […] | 0.085 | 0.09 | 2,005 | […] | 1.06 |
| | 85 | 103 | 19 | 207 | […] | 0.085 | 0.09 | 2,170 | […] | 1.06 |
| | 84 | 116 | 89 | 289 | […] | 0.085 | 0.09 | 2,170 | […] | 1.06 |
| | 87 | 91 | 19 | 197 | […] | 0.085 | 0.09 | 2,005 | […] | 1.06 |

The depicted methodology is currently being enhanced referring to the scope of application and level of detail. The approach is further implemented for assembly processes of specialized industries in which the impact of the worker's competencies to the production targets is very significant as well. Thereby, the scope of optimization is further increased by developing detailed competence-models regarding individual learning-curves of the workers and learning effects by teamwork with experienced colleagues "on the job". Furthermore, an automated assignment of suitable workers by the algorithm is focused in order to perform a best possible allocation of the working personnel to the planning tasks for long-term competence-improvement. Due to the application of mathematical process models and an optimization algorithm, the method is as well suitable for these environments. In the future, this will contribute to a systematic process planning integrating the worker′s competencies and to a further increase of flexibility and transparency in long-term processes planning.

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## References

1. Denkena B, Henning H (2008) Dimensioning technological interfaces and process parameters in manufacturing process chains. In: Proceedings of the 6th CIRP international conference on intelligent computation in manufacturing engineering, pp 55–65
2. Tönshoff HK, Denkena B, Friemuth T, Zwick M, Brandes A (2002) Technological Interfaces of industrial process chains. Ann German Acad Soc Prod Eng (WGP) 41:43-46
3. Denkena B, Behrens B-A, Charlin F, Dannenberg M (2012) Integrative process chain optimization using a genetic algorithm. Prod Eng 6:29–37
4. AlGeddawy T, ElMaraghy H (2011) Manufacturing systems synthesis using knowledge discovery. CIRP Ann Manuf Technol 60:437–440
5. Mayrhofer W, März L, Sihn W (2011) Planning assistance for pearl chain forecasts and personnel assignment planning of sequenced assembly lines. CIRP Ann Manuf Technol 60:481–484
6. Warnecke G, Eichgrün K, Kluge R, Zitt U (1999) Improvement of process reliability within process chains by comprehensive control strategies. Prod Eng 6:1–6
7. Mansfield B, Mitchell L (1996) Towards a competent workforce. Gower Publishing Limited, Hampshire
8. Randall R, Ferguson E, Patterson F (2000) Self-assessment accuracy and assessment centre decisions. J Occup Organ Psychol 73:443–459
9. Witzgall E (2010) How does competence measurement with CM prowork relate to the European qualification framework? Considerations and practical experiences with regard to worker competencies. Professional Training Facts, Dortmund, pp 1–11
10. Witzgall E (2010) Kompetenzdarstellung mit dem CM prowork-tool. Möglichkeiten und Ergebnisse der Einordnung in den Europäischen Qualifikationsrahmen, Dortmund, pp 1–20
11. Westkämper E, Schmidt T (1998) Computer-assisted manufacturing process optimization using neural networks. J Intell Manuf 9:289–294

# Social Media in Manufacturing: Just Hype or Concrete Benefits?

**M. Lanz and S. Torvinen**

**Abstract** This paper aims to provide novel ideas for capturing tacit knowledge in order to enrich the product life-time information used in product design, process planning, and manufacturing. In this paper, a case from the factory floor is presented. For capturing the tacit knowledge, different social media applications and mobile tablets can be used effectively. The captured tacit knowledge, that hold both feedback and context in its creation time, can be connected to a semantically rich, formal, and machine-readable knowledge representation that combines product, process, and resource descriptions. The paper presents novel and innovative concept that can enhance design collaboration and co-creation by lowering the barriers between different design domains. One of the possible solutions is presented here and it is expected to lower costs of design in manufacturing industry as consumer needs, manufacturing realities, and rapidly developing media technology are holistically put together.

## 1 Introduction

Today's operation control and decision-making systems are based on traditional stand-alone concepts that are highly optimized for achieving their goals in a stable predictably behaving environment. Unfortunately, the real operating environment is not stable or predictably behaving. Systems in all fields have become parts of bigger systems via cooperation and communication within each other. It is recognized that today's systems do have characteristics of a Natural System, where it is expected that environment evolves and changes over the time and the system itself evolves during its life cycle in order to survive in its environment. In order to

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operate in such dynamic and complex environment best of the both worlds, human intelligence and computers' computing power needs to be utilized in right places. As the unpredictable changes occur, detailed simulations of large systems become unreliable. Traditional algorithms cannot solve the problems that arise, thus applying human intelligence to solve complex problems becomes highly important. Paradoxically, the current operation strategy has forced human to be the processing unit with his/her mighty 5 kbit/s information transfer speed, while computer attempts to make intelligent decision over relatively vague input information [1–4].

- *Challenge* 1: Today's operation control and decision-making systems are based on traditional stand-alone concepts that are highly optimized for achieving their goals in a static predictably behaving environment. The adaptation is not based on computer-processed information, but fully human processing. "Computer intelligence" is efficient in dealing with large data masses, but often fails to solve new problems as creatively as the human would.
- *Challenge* 2: Distribution of orders is not based on their individual characteristics or system capabilities. The system history is not used excessively, thus changes force the system to be remodeled in most cases completely. The changes do take time and cost, which cannot be estimated without history, content, and context information.
- *Challenge* 3: Utilization of algorithms has lead to the situation where computer intelligence is assumed to find the best solution. In static system this is possible, but we are no longer dealing with a static and predictable system. The utilization of computing power has lead to the situation where human is forced to follow the predescribed process determined by the computerized system whether or not it supports the needed action. The task is seen through a computerized system, while the system should only support the task not define it. This prevents humans from learning from their actions and from improving their actions. It also prevents the systems from adapting to the changes in operations.

As the operation and business environment in industry changes rapidly, also the human–machine interaction grows and keeps changing and thus adding pressure for finding the experts and capturing the tacit knowledge. When dealing in the lot-size-1 production scenario it is a widely approved fact that an experienced and competent operator can approach the problems, e.g., fault diagnostic or prevent jamming from appropriate point of view based on his/her experience. Sadly, the experienced operator might leave the workplace any time and by his/her leave, the knowledge and experience is lost from the company. Capture of tacit knowledge is one of the key factors of continuous and successful manufacturing in a turbulent production environment where the change is the norm for production.

The information management of product design and process planning in adaptive manufacturing systems using semantic information presentation and semantic modeling has been researched in several industrial projects [1, 2, 5] (Ribeiro et al. 2010). While the products and processes can be described with great detail and formally, the tacit knowledge of experienced operators remains unconnected to product knowledge. Internet communities are increasing in volume combining different people together. In the one hand, there is Social Media that is seen as new collaboration tools in work and off-work life. On the other hand, manufacturing industry would benefit these new types of collaboration and co-creation tools greatly. In the design and producing high-quality goods, the requirements for knowledge representation and accuracy are high.

In this scope, the research paper argues that this tacit knowledge can be gathered and distributed via modern Social Media (SoMe) applications, which are interlinked authentic context, events and performance chain based on the simulated and visualized scenarios of the virtual and real manufacturing systems. This connection gives context bound tacit knowledge reference so that planners and colleagues can understand the arguments, operations, and situations of decisions, approaches, and solutions. This tacit-information flow is managed by the issue tracking and systematic information management system. The commentating of solutions via other media than text is essential, because very often situation cannot be expressed only by words. "Let I show" is natural way for expressing ideas and solutions. Via virtual and web-based tools, the parameter adjustments, critical information annotation, and situation aware notations can be saved and comment in the simulated scenarios [6]. Semantically rich information flow and proper management of it allows better interoperability, reuse, and further processability. The formal information structure also structurizes the tacit knowledge contribution into such level that it can be found later on and into context where the tacit knowledge can be understood by others.

## 2 Background for the Dynamic Operation Environments

### *2.1 Complex Systems*

In complex systems, reconstruction is searching for a model that can be programmed as a computer simulation that reproduces the observed data 'well'. The ideal of predicting the multi-level dynamics of complex systems can only be done in terms of probability distributions, i.e., under non-deterministic formalisms. An important challenge is, contrary to classical systems studies, the great difficulty in predicting the future behavior from the initial instant as by their possible interactions between system components is shielding their specific individual features. In this sense, reconstruction is the inverse problem of simulation. This naturally indicates that the complex system cannot be understood as deterministic system, since the predictions from Complex Systems Science do not say what will happen, but what can happen [2, 7, 8]. In general, complex systems have many autonomous units (holons, agents, actors, individuals) with adaptive capabilities (evolution, learning, etc.), and show important emergent phenomena that cannot be derived in any simple way from knowledge of their components alone. Yet one of the greatest challenges in building a science of such systems is precisely to understand this link—how it is that micro level properties determine or at least influence those on the macro level. The current lack of understanding presents a huge obstacle in designing systems with specified behavior regarding interactions and adaptive features, so as to achieve a targeted behavior from the whole [7]. Due to the complexity of the system behavior and its possibilities, and the lack of tangible and implementable research results how the complex systems theory can bring revenue to the company; the implementations at the moment are scarce and acceptance varies.

### 2.2 Reconfiguration, Adaptation, and Autonomous Systems

Different manufacturing paradigms have been initiated in recent years to overcome the challenges relating to adaptivity requirements. Reconfigurable manufacturing systems (RMS) aim to meet these requirements by offering rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change in their structure as well as in hardware and software components [9, 10]. Agent-based and holonic systems take more dynamic approach to cope with the changeability requirements by providing self-organizing capabilities [11, 12] (Smale and Ratchev 2009). Whereas the reconfigurable system research focuses mainly on physical adaptation, in the latter approach the adaptation is performed also on logical and parametric levels.

As operations take place in more and more complex and dynamic environment, the need for adaptive control systems increases. Various scientific disciplines, like physics, biology, artificial intelligence, control theory, and the engineering sciences, use the term autonomous control [4]. In the context of logistic systems, Hülsmann and Windt define autonomous control as "processes of decentralized decision-making in heterarchical structures." Autonomous control method, Autonomous Logistics Engineering Methodology, by Scholz-Reiter et al. [4] provides tools and methods to develop models of autonomously controlled systems. Onori (Onori) introduced the concept for Evolvable Production Systems (EPS) already in 2002. Since then [13] have continued developing the concept within the area of complex systems. The main characteristics of the EPS is that the system is seen as evolving and adapting system thus having characteristics of an emerging system.

### 2.3 Cyber-Physical Systems and Intuitive Human–Machine Cooperation

In human–machine cooperation, automated assistance promises to simultaneously reduce operators' workload and human errors. In fact, "intelligent" machines frequently encounter difficulties in complex dynamic environments due to limited human-like adaptability. Chaotic and unreliable assistance to human operators usually leads to cognitive overload, emotional suffering, and other phenomena that have a negative impact on productivity. Such negative consequences significantly magnify the importance of effective management of human–machine cooperation [14]. The extent to which these media interactions can be optimized to be believable, realistic, productive, and satisfying has been the topic of research in recent years (Jsselsteijn et al 2003). Cyber-physical systems (CPS) for a start can be understood as a new system category that is simultaneously and intrinsically physical and computational. These new systems comprise computations and communications deeply embedded in and interacting with physical components providing potential for new capabilities. It is not possible, however, to determine whether these new capabilities are the result of computations, physical laws, or both working together [15]. Cyber-physical systems are expected to play a major role in the design and development of future engineering systems with new capabilities that far exceed today's levels of autonomy, functionality, usability, reliability, and cyber security [16].

## 2.4 Knowledge and Meaning of Things

Borgo and Leit [17] developed ADACOR ontology for distributed holon-based manufacturing focusing on processes and system interaction descriptions. ADACOR was later extended with an upper ontology (DOLCE). Research done in FP6 IP-PiSA project resulted Core Ontology (OWL DL), for connecting product, process and system domains under one reference model [2]. The main goals these approaches generally try to achieve are: improved overall access to domain knowledge and increased amount of additional information. However, none of these developed ontologies and approaches consider fully the needs above their narrow domain (Ray 2004) [1, 2]. EUPASS ontology described resources characteristics with basic and complex skills (Lohse et al. 2008). Emplacement concept was developed to give a standardized description of the EUPASS modules comprising an assembly system (Siltala et al. 2008). Barata et al. (2008) used skill information in a multiagent-based control architecture for shop floor system. Ameri and Dutta (2008) connected buyers and sellers of manufacturing services in web-based e-commerce environments based on semantic similarities of supply and demand in terms of manufacturing capabilities. Smale and Ratchev (2009) proposed a capability-based approach for multiple assembly system reconfiguration consisting of capability taxonomy, capability model, and reconfiguration methodology. However, these like others are highly domain constrained approaches and do not provide all the elements needed by the envisioned control approach.

### 2.5 Social Media

Social media can be defined as "a group of Internet-based applications that build on the ideological and technological foundations of Web 2.0, and that allow the creation and exchange of user generated content" [18]. Jussila et al. [19] divided social media based interactions into four different categories: one-way interaction, two-way interaction, community-based interaction, and user toolkit supported interaction, where as the interaction was via social media-related approaches, such as wikis, blogs, and virtual worlds. Majority of the studies in the field of Social Media focus on Business-2-Customer approaches in the field of sales and services. There are also studies considering the marketing aspect and marketing opportunities of social media in customer interaction, but the majority were found to concentrate decidedly on the one-sided company-to-customer aspect of marketing, instead of more interaction-related approaches. However, no studies were found on the opportunities of social media at large in customer interaction, and especially not from the innovation perspective [19].

## 3 Description of the Research

Humans are very visual creatures. Information processing happens through techniques that amplify human cognition by visual means. Text, tables, graphs, photographs, and videos are means of displaying information so that it can be perceived and acted upon. With the help of such tools humans can perceive information more quickly and process several orders of magnitude more information than without them. Interactive visualizations where the user changes the parameters of the visualization to focus on different aspects of the data further increase human processing power when the visualizations are well designed. There exist different methods for enhancing the instructions and feedback for the worker. In this research, the focus is set to the Social Media (SoMe), since the companies are looking forward the SoMe platforms to enhance and speed-up R&D and knowledge exchange among workers. However, the problem with knowledge management is not solved by new platforms, granted, it might help in short term, but in longer term the knowledge management challenges do require right place, right manner and right purpose. The aim of the future research is to systematically evaluate cases where SoMe platforms could be utilized to convey temporal instructions and feedback between designers and operators. This envisioned research, as carried out entirely, utilizes scientific results from various domains including the social sciences, bionic systems, and complex systems research, and adapts these to the field of manufacturing.

The full research has five steps outlined in the Table 1. This paper shows the research results of the step 1 and 2 in the case of dynamic operation environment (DOE).The main tasks of the full research plan are to:

**Table 1** The case of dynamic operation environment (DOE)

| Viewpoints | Font size and type |
|---|---|
| Step 1 | Systematically evaluate cases and temporal points in the detailed product design, process planning and in manufacturing execution process of a new production patch/unit where user instructions and feedback could be connected to the process model. This is partly done via interviews among Finnish companies |
| Step 2 | Analyze social media applications that would support each individual case different tools and methods are needed to different tasks over the life cycle of the product |
| Step 3 | Enhance the knowledge representation (Core Ontology by [1, 2]) in such way that it can represent feedback of human–machine system while keeping its formal computer readable structures, validity and consistency of representation |
| Step 4 | Form a concept for combining the essential tacit knowledge to formal information architectures |
| Step 5 | Test the suitability of the idea and final results against needs from the industry both in technical and economical aspect by (1) interviews among plant managers, designers and workers, and (2) time spend on social media versus gained benefits |

The hypothesis for the research project is formed as: There exist natural interfaces for formal and informal knowledge entities that can be connected in meaningful, effective and human-friendly manner.

## 4 Description of the Demonstration

### *4.1 Holonic Manufacturing System*

Agent-based and holonic systems take more dynamic approach to cope with the changeability requirements. The Holonic Manufacturing System (HMS) concept implemented here views the manufacturing system as one entity consisting of autonomous modules (holons) with distributed control. The holons act as autonomous entities able to fulfill their own goals, as well as communicate with other holons and form set of holons, holarchies, through common interfaces and negotiation process. The goal has been to attain the benefits that holonic organization provides to living organisms and societies, in manufacturing, i.e., stability in the face of disturbances, adaptivity and flexibility in the face of change, and efficient use of available resources through self-organization ability (Fig. 1).

The holonic system follows Service-oriented Architecture (SOA), where the resources provide services through their capabilities. The holons organize themselves in a hierarchical manner. This hierarchy is called holarchy. The upper owner holon is responsible for arranging the holons in such a way that the desired task can be accomplished. The system is robust in a way that new holons and holarchies can join and leave the system without disturbing the whole system. In this concept, the both hardware and software modules are service providers. When an order enters to the holonic framework, the system will search for those

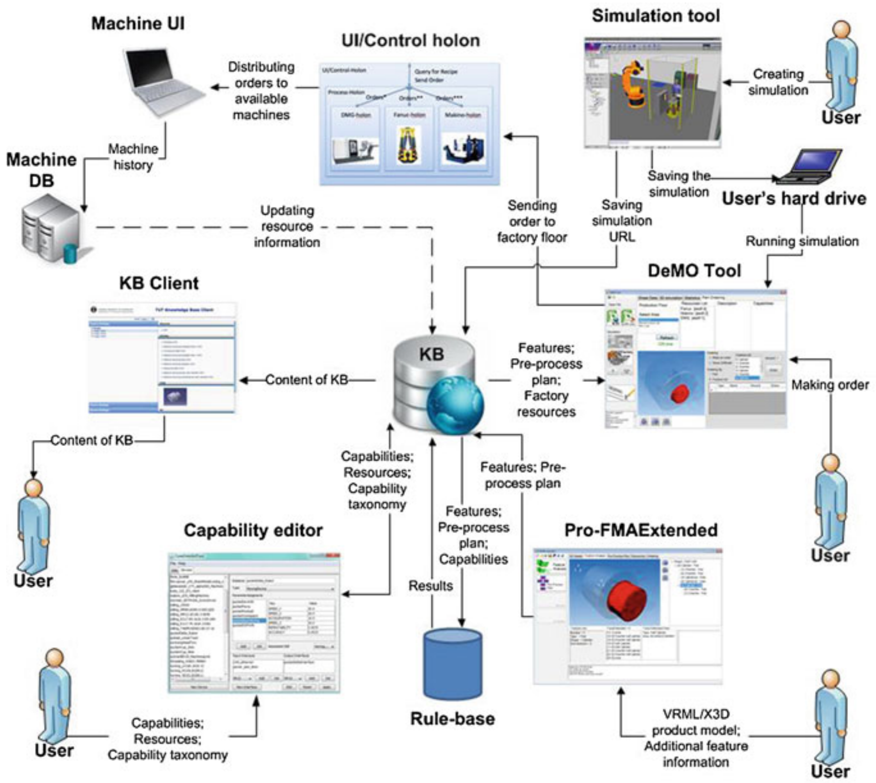


**Fig. 1** Tools for formal knowledge creation and management in dynamic operation environment [1] (Lanz 2011, 2012)

resources, which can alone, or with some other resource, satisfy the requested service. The holons will then negotiate to determine the best resource for the given situation or the part is directed to first available resource combination that has the capability to produce the part or specific feature (Lanz et al. 2012; Järvenpää et al. 2012) [20]. The reasoning is done based on mapping the geometrical and non-geometrical features of a part/product to the resource characteristics and determining possible matches.

## *4.2 Random Production Scenario*

The HMS paradigm addresses the agile reaction to disturbances at the shop floor level in volatile environments and it is built upon a set of autonomous and cooperative holons, each one being a representation of a manufacturing component, i.e., a physical resource such as a robot, CNC centre and conveyor, or a

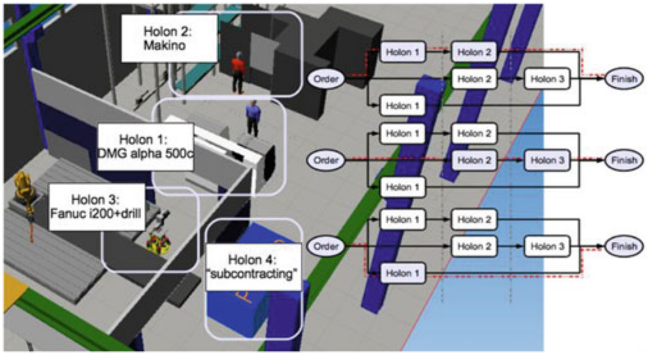


**Fig. 2** Product order can be routed to any suitable and free machine combination based on matching of product requirements and machine capabilities

logical entity, such as orders. The main character of the built holonic system is that the status of the production system and desired goal (defined as order connected to product model) are known, see Fig. 2, but the steps for reaching the goal, in this case the routing order of the parts in the factory floor, is not predefined (Lanz et al. 2012).

### *4.3 Connection of Formal Knowledge and Social Media*

The research utilized formal knowledge model namely the Core Ontology due to the fact that the traditional product data management (PDM) systems cannot represent their contents formally, i.e., in such level that the models would be in machine readable format and logic-based reasoning could be applied. For allowing the inclusion of old manual machines to the holonic system, the Social Media (SoMe) tools were utilized as human–machine interface, Fig. 3. The operator supervising the several manual stations received product order to each machines via Twitter account. In the product order the product model, its identifier and related code were listed. The operator had a possibility to comment about the product order and save comments as a tweet.

The tweets to the machines were as illustrated in Fig. 4. The product order information including part number was visible and operator could comment upon a tweet about its manufacturability.

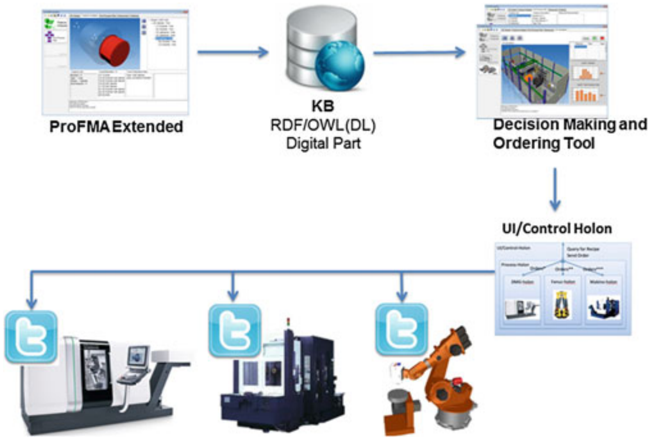


**Fig. 3** Utilization of SoMe tools as mobile human–machine interface for receiving production orders

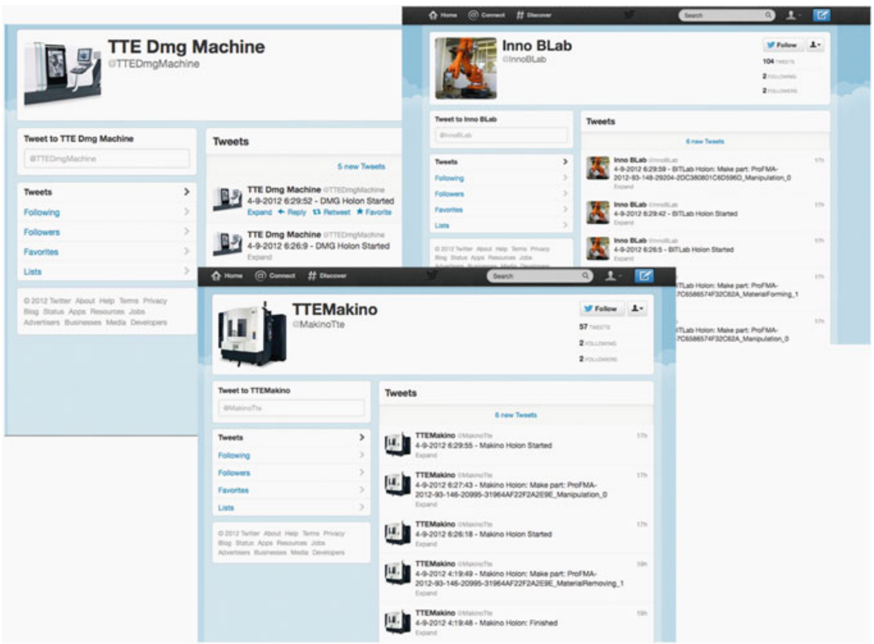


**Fig. 4** Twitter accounts of the machines

## 5 Conclusions

This paper introduced a novel idea for capturing tacit knowledge in order to enrich the product life-time information used in product design, process planning, and manufacturing. The case study showed one possible, feasible, and efficient solution for capturing feedback from the factory floor. For capturing the tacit knowledge, social media application and mobile tablets were used. By choosing the Twitter as a feedback collection tool the user was not constrained by any platform or operating system, any mobile device was acceptable. Twitter was chosen also because its user interface is light-weight and designed for mobile generation excluding large graphics or commercials. Twitter had also suitable interface, where the Holon Control was able to connect. The captured tacit knowledge, that hold both feedback and context in its creation time, is then connected to a semantically rich, formal, and machine-readable knowledge representation that combines product, process, and resource descriptions. The simple and slim solution represented here has gained growing interest among Finnish manufacturing industry. It has to be noted that security issues were not considered in this research. Partly this was because the twitter was only receiving end application and partly due to the time frame research was conducted. Nevertheless, this combination did arise interest among industrial partners and discussions where and how Social Media could be used in less critical interfaces. Thus, applied in right manner and right purpose Social Media can lower the costs related to knowledge management and transforming the non-value added time to the value adding services. As a conclusion, there are some benefits hidden inside the massive amount of Hype.

## 6 Future Work

Future work consists of identifying other suitable process steps where the Social Media tools could be integrated for tacit knowledge collecting. The aim is to follow a case product through out its life cycle and analyze the process where tacit knowledge should be collected and what kind of tool would provide the most feasible, efficient, and human-friendly solution.

## References

1. Järvenpää E, Luostarinen P, Garcia F, Lanz M, Tuokko R (2011) Dynamic operation, environment: towards intelligent adaptive production systems. International symposium of assembly and manufacturing (ISAM), 25–27 May 2011, IEEE Press, Tampere, Finland. ISBN: 978-1-61284-343-8
2. Lanz M (2010) Logical and semantic foundations of knowledge representation for assembly and manufacturing processes. PhD thesis, Tampere University of Technology

3. Lohtander M, Varis J (2012) Collecting manufacturing information in a global distributed manufacturing environment. Mechanics 18(1):84–88 ISSN (print): 1392–1207 ISSN (online): 2029–6983
4. Scholz-Reiter B, Rippel D, Sowade S (2010) Modeling and simulation of autonomous logistics processes, ECCE'10/ECCIE'10/ECME'10/ECC'10. In: Proceedings of the European conference of chemical engineering, and European conference of civil engineering, and European conference of mechanical engineering, and European conference on control. ISBN: 978-960-474-251-6
5. Onori M (2002) Evolvable assembly system—a new paradigm?. In: Proceedings of the 33rd international symposium on robotics 2002, Stockholm, Sweden
6. Nykänen O, Salonen J, Markkula M, Ranta P, Rokala M, Helminen M, Alarotu V, Nurmi J, Palonen T, Koskinen KT, Pohjolainen S (2011) What do information reuse and automated processing require in engineering design? Semantic process. J Ind Eng Manag 4(4):669–698 Universitat Politecnica de Catalunya
7. Chavalarias D, Cardelli L, Kasti J, et al. (2006) Complex systems: challenges and opportunities, an orientation paper for complex systems research in fp7. European Commission
8. Cotsaftis M (2009) A passage to complex systems. In: Bertelle C, Duchamp GHE, Kadri-Dahmani H (eds) Complex systems and self-organization modeling. Springer, Berlin
9. ElMaraghy HA (ed) (2009) Changeable and reconfigurable manufacturing systems. Springer, London. ISBN 978-1-84882-066-1
10. Koren Y (2006) General RMS characteristics, comparison with dedicated and flexible systems. In: Dashchenko AI (ed) Reconfigurable manufacturing systems and transformable factories. Springer, Berlin, pp 27–46. ISBN 3-540-29391-4
11. Monostori L, Váncza J, Kumara SRT (2006) Agent-based systems for manufacturing. CIRP Ann—Manufact Technol 55(2):697–720
12. Nylund H, Salminen K, Andersson P (2008) Digital virtual holons—an approach to digital manufacturing systems. In: Mitsuishi M, Ueda K, Kumura F (eds) Manufacturing systems and technologies for the new frontier. Springer, London, pp 103–106
13. Ribeiro L, Barata J, Pimentaõ J (2011) Where evolvable production systems meet complexity science. International symposium of assembly and manufacturing (ISAM), 25–27 May 2011, IEEE Press, Tampere, Finland. ISBN: 978-1-61284-343-8
14. Cai H (2011) Fine-tuning human-machine cooperation: cognitive processing oriented assistance coordination. PhD thesis, Northeastern University
15. Jones A (2012) Engineering cyber physical systems. NIST internal report (draft), p. 18
16. Rajhans A, Cheng SW, Schmerl B, Krogh BH, Aghi C, Bhave A (2009) An architectural approach to the design and analysis of cyber-physical systems. Third international workshop on multi-paradigm modeling, Oct 2009, Denver, CO
17. Borgo S, Leit P (2007) Foundations for a core ontology of manufacturing. Integr Ser Inf Syst 14:1–40
18. Kaplan AM, Haenlein M (2010) Users of the world, unite! the challenges and opportunities of social media. Bus Horiz 53(1):59–68
19. Jussila JJ, Kärkkäinen H, Leino M (2012) Social media's opportunities in business-to-business customer interaction in innovation process. Int J Technol Mark 7(2):191–208
20. Garcia F (2013) Dynamic selection of resources for incremental sheet metal forming based on feature analysis. In: Proceeding of FAIM 2013, Portugal
21. Lohse N (2006) Towards an ontology framework for the integrated design of modular assembly systems. PhD thesis, University of Nottingham

# RFID Implementation in the Footwear Supply Chain: From Production Line to Retail Store and Back

**Ana C. Barros, Rui Rebelo, Pedro França, João Sousa, José Rios, Ana Gomes, Paulo Monteiro and Guirish Vaguela**

**Abstract** Although Radio Frequency Identification (RFID) is one of the most promising technologies in recent years with the potential to radically improve the performance of supply chains, its adoption has been slower than anticipated in supply chain applications. This fact, led researchers to investigate the impediments and challenges of RFID implementations, as well as its critical success factors. Consequently, there is a need to understand how these challenges are being addressed during the implementation of RFID systems by organizations along the supply chain. This paper aims to fill this gap by investigating, by means of action research, and the solutions implemented in a footwear supply chain. The results of the study present the approaches developed to address six RFID implementation challenges, namely: forming the implementation team, selecting the RFID technology, and defining the RFID system infrastructure, overcoming technical problems, redesigning supply chain processes, integrating the RFID system with existent information systems, and measuring the RFID implementation performance.

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# 1 Introduction

The capability of creating agile supply chains has long been recognized as critical for companies' ability to respond quickly to sudden and unexpected market needs [1, 2]. Information technology developments have been playing a major role in supporting the creation of responsive supply chains [3]. In fact, technologies, such as electronic data interchange (EDI), web-based integration systems, and enterprise resource planning (ERP), permit sharing large amounts of information between supply chain partners, creating an integrated and coordinated supply chain, thus improving operational performance [4]. Radio Frequency Identification (RFID) has emerged as another promising technology that, by providing detailed information on the flow of products throughout the value chain [5], creates new opportunities to improve the efficiency of supply chain processes [6–8]. RFID is one type of auto-identification technology, such as barcodes, that uses radio waves to identify individual physical objects [6, 9].

After the impulse given by the retail sector with the mandatory RFID tagging requests by Wal-Mart, Target, Metro, and Tesco [5, 6, 8, 10], RFID has further been successfully implemented in other supply chain contexts, such as warehousing [9, 11], transportation [9], manufacturing [9, 12], and repair and maintenance centers [13]. Although several empirical studies about RFID implementation have been already published (see Table 1), to the best of our knowledge, none exists covering the forward flow from production line to retail store and reverse logistics from retail store to the warehouse. Aiming to fill this gap, this paper presents the insights of a RFID implementation along the supply chain investigated by means of action research on a footwear supply chain.

**Table 1** Evidence of RFID benefits from empirical research

| RFID benefits | Angeles [9] | Ngai et al. [13] | Delen et al. [10] | Virich et al. [25] | Zelbst et al. [24] |
|---|---|---|---|---|---|
| Lead time reduction | X | X | X | X | X |
| Customer service improvement | | X | | X | X |
| Productivity increase (through automation, better equipment usage, increased visibility, less workflow interruptions, production downtime reduction) | X | X | X | X | X |
| Human errors reduction | X | X | | X | |
| Inventory management improvement | X | X | X | X | X |
| Information accuracy improvement | X | X | X | X | X |

## 2 Literature Review

Radio Frequency Identification (RFID) is an e-tagging technology that can be used to provide electronic identity to any object [6]. This technology uses radio waves to capture data from tags embedded in the objects, such as products, containers, or pallets. An RFID system has two principal components: tags, with a microchip to store object information and an antenna to transmit it via radio waves; and readers, that send out a radio signal to communicate with tags and convert the radio waves returned from the tag into digital data forwarding it to a computer system [6, 9, 14]. Although RFID was first used in the Second World War to identify friendly aircraft [6], research on RFID since then has been mainly in the engineering field, dealing with technology design and performance issues, and research on its application in supply chain management has emerged only during the past decade [14–16]. Still, as the technical problems associated RFID usage are addressed and resolved, more research is needed to address managerial and organizational issues [7, 17].

The benefits of RFID systems in practice, as confirmed by empirical research, are listed in Table 1. The main driver for these benefits is the simplification and transparency of various processes, such as receiving, material handling, replenishment, picking, cross-docking, shipping, and returning [9, 10, 15].

Although RFID is one of the most promising technologies in recent years with the potential to radically improve the performance of supply chains, its adoption has been slower than anticipated in supply chain applications [14, 15]. This fact, led researchers to investigate the impediments and challenges of RFID implementations which may be of ethical, technical, organizational, and managerial nature [7, 15, 18, 19]. Consequently, there is now a need to understand how these challenges are being addressed during the implementation of RFID systems by organizations along the supply chain. This paper aims to fill this gap by investigating the solutions implemented in a case of a footwear supply chain. Therefore, we formulated our research questions as: "How to overcome the challenges of RFID implementation along the footwear supply chain?" The next section describes the research methods used to address this research question.

## 3 Research Methods

The research method used was action research, developed in the context of the R&D project *ShoeID*, co-financed by the Portuguese State, where researchers, technology developers, and operations managers collaboratively contributed to the development of solutions [20, 21]. Action research is appropriate to investigate the development of solutions for actual problems [22]. Data was gathered through active involvement of researchers in organizations and research materials include observations, meeting minutes, follow-up interviews, action experiments, and reports written at the various milestones of the project. Due to its applied and problem-solving nature, action research is often taken as a consulting project.

Therefore, there is a need to assure the validity of the research by clearly positioning it in relation to the research interests and the needs of the organizations [20, 22]. The R&D project in which this research is based involved two research institutions, one RFID technology company and two companies of the same shoe supply chain (producer and distributor). The two end-users aim with this project to improve efficiencies throughout the supply chain. The RFID technology developer is interested in developing new technologies for future commercialization. Researchers' goal is to build and test theory in action about how the RFID implementation challenges along the supply chain may be overcome. In the next section, we describe the context in which the research was carried out.

### 3.1 Research Context

The footwear supply chain of this study belongs to a major footwear group of companies based in the North of Portugal. The footwear group deals with a magnitude of players, both nationally and internationally, including: raw material and component suppliers, subcontracting network for production parts, warehouse center to store and distribute the finished product, suppliers of finished footwear, network of footwear stores, network of retail sales, network of collection designers and creators, and network of vendors and commercial agents. This vast array of players allowed us to obtain a more global and integrated study basis, which is fundamental to create the organisational and functional architecture needed for the introduction of RFID technology in the value chain.

Particularly, the R&D project *ShoeID*, in which this research is based, pursued the following objectives:

1. **RFID Factory**: Applying RFID technology to footwear manufacturing. The aim was to create more agile organisational models, with zero paper used, zero stock, automatic traceability, following a customized manufacturing logic.
2. **RFID Logistics Network**: Applying RFID technology in storage and distribution centers. The aim is to create new operational management concepts for these networks, providing solutions to receive, control, and monitor the entire supply chain until the retail networks.
3. **RFID Retail Store**: Applying RFID technology combined with technologies that promote interaction with the consumer in store environments.

## 4 Addressing RFID Implementation Challenges

This section presents the results of the research, namely the description of the solutions adopted by the studied footwear supply chain in order to overcome the various RFID implementation challenges identified in the literature [7, 15, 18, 19].

## 4.1 Forming the Implementation Team

Given the fact that the adoption of RFID technology in supply chain management is still in its infancy [14], companies often engage the expertise of consultants, researchers, and specialized companies in their implementation projects [9, 13]. Indeed, the partnership with competent technology providers has been pointed out as a critical success factor of RFID adoption [6]. Also, this approach is in line with the idea of using open innovation, i.e., inflow and outflow of knowledge, to accelerate innovation [23]. In the implementation studied the producer and distributor of shoes teamed up with two research institutions and one RFID technology company in order to develop and implement the RFID-system.

## 4.2 Selecting the RFID Technology and Defining the RFID System Infrastructure

In order to implement RFID technology in the footwear value chain, it was necessary to study the existing technology and to assess their potential and how they could be suitable to this industry. The study and selection were divided as follows:

1. **Verifying and characterizing which mature technologies based on RFID are available on the market:** Currently, technologies available on the market are grouped according to their signal frequency. There are two main groups: HF (High Frequency)—13.56 MHz and UHF (Ultra High Frequency)—868–870 MHz. The key decision is selecting which frequency—"Ultra High Frequency (UHF)" or "High Frequency (HF)", or both—will be implemented on all stages of the supply chain. Usually, the use of HF is for proximity readings (the reference value for the maximum reading distance is approximately 30 centimeters, depending on the type of material where the tag is applied, on the type of reader, etc.) and the use of UHF is for distance readings (the reference value for the maximum reading distance is approximately 6 meters, depending on the type of material where the tag is applied, on the type of reader, etc.). This means that lower frequencies (HF) would be more suitable to read items (the shoe), while higher frequencies (UHF) would be more suitable for shoe boxes and packs of shoe boxes at greater distances.
2. **Analyzing all typical stages of the value chain in the footwear industry:** Identifying the type of items, how the items are grouped and separated at different stages, types of materials of the items identified, operation mode and item manipulation, and existing points to control logistics flow.
3. **Defining the criteria to select the technology to be used:** Strategic factors (safety, operational speed and cost) and Physical factors (reading points, materials near the tag, shape and size of the tag, proximity, and orientation of the tag).

4. **Conducting laboratory tests to assess the performance of each technology considered:** several tests were conducted to select the frequency involving HF and UHF technology and several RFID tags, as well as the different positions that the tags may have in the shoe, and the several reading points throughout the supply chain.
5. **Selecting the technology:** Taken into consideration all the points above, the UHF option was chosen.
6. **Developing the concept of RFID architecture to be applied in the different stages of the value chain:** Table 2 presents the RFID infrastructure developed.

## *4.3 Overcoming Technical Problems*

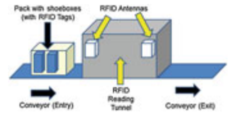
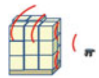
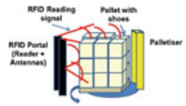
The main technical challenge of RFID implementation is related to the problem of missing reads and multiple reads [7, 10, 15, 19]. Here we present the solutions developed to address this problem.

**RFID coding:** A web platform was developed to perform the printing/coding order of the RFID tags throughout the entire manufacturing process, and each tag has a unique code. During the assembly operation, the RDIF tags are placed inside the shoe and stuck to the insole. After the assembly operation is completed, the different shoes go to the RFID kiosk for the final coding of the RFID tag (code for size and indication of right or left foot) and to be sent to the warehouse.

**RFID tunnel:** At this module, the shoe boxes are registered and received to enter the distribution warehouse. All shoes in each box are read automatically. When a pack (which can contain 8, 10, 12, or more shoes) goes through the RFID tunnel, the RFID tag is automatically read and all shoes in the box are identified. This information is synchronized with the ERP (obtaining the orders to receive, the type and contents of the packs, etc.) in order to compare the information of the ERP with the information read at the tunnel. A tag is printed for each pack containing information on whether the pack will remain in the warehouse as stock or if it will be shipped to a store. If this is the case, a specific shipping tag is printed and the order is immediately ready for shipping.

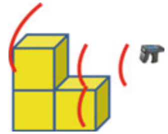
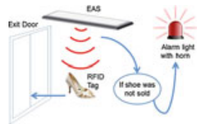
**Palletizer:** An RFID reading system was incorporated in the palletizer (system where the several packs are placed on a pallet and covered in plastic film) to facilitate the shipping of larger orders. The items are read as they are being covered by the plastic film. This way, it is possible to guarantee that all the boxes in the pallet are read and so there are no "shadow" areas for the RFID system. The system is set up by a gate (which contains one RFID reader and four RFID antennas) and safety areas. Using the palletizer with the RFID reading system is also relevant to register returned items from the stores. In this case, it is only necessary to place the returned packs on top of the pallet, select the return functionality in the software, and proceed to the reading process by making the palletizer spin (plastic film is not required). The software will provide the number of returned shoes.

**Table 2** Main stages of the target footwear processes

| Supply chain process | Stage of the process | Item to be read | Features of the process stage | RFID solution |
|---|---|---|---|---|
| Production | Footwear production | (1) Shoes | Only the tag is read at this station during the manufacturing stage (at the operation station) |  |
| | Movements to the Warehouse | (1) Shoes in boxes<br>(2) Pallets with packs of shoe boxes | At this stage the technology is able to read the entire group of packages/shoes associated to a specific entry point at the warehouse, disregarding other packages that may already be in the warehouse or being manufactured |  |
| Distribution (Warehouse) | Receiving pallets with packs of shoe boxes | (1) Packs of shoe boxes<br>(2) Pallets with packs of shoe boxes | Several packs of shoe boxes are manipulated during the receiving stage. The system only reads the box which is being received, and not the material that is already stored |  |
| | Warehouse inventory | (1) Packs of shoe boxes<br>(2) Pallets with packs of shoe boxes | The system reads all the tags associated to the material in the warehouse. All the material to be received or shipped is ignored |  |
| | Shipping | (1) Packs of shoe boxes<br>(2) Pallets with packs of shoe boxes | The read tags are associated to boxes related to a certain shipping operation |  |

(continued)

**Table 2** (continued)

| Supply chain process | Stage of the process | Item to be read | Features of the process stage | RFID solution |
|---|---|---|---|---|
| Store | Receiving stage | (1) Packs of shoe boxes | Packs of shoes boxes are manipulated during the receiving stage. The system only reads the box which is being received, and not the material that is already stored |  |
| | Movements warehouse-store/ store—warehouse | (1) Shoe boxes | In these operations, the tags are associated to the material to be transferred between the warehouse and the store, and vice versa. This allows the reverse flow from the store back to the warehouse |  |
| | Antitheft system (electronic article surveillance) | (1) Shoes<br>(2) Shoe boxes | This operation reads the tags (shoes) which leave the store and are not sold. The tags should be read before the shoes are put in the store and store window |   |

**RFID terminal:** An application for PDA was also developed to increase the flexibility of the RFID solution, which makes it possible to ship boxes to stores. Although the boxes are shipped not only by the RFID tunnel, but also by the palletizer with RFID reading, there are other situations when control needs to be made box by box, for instance, when smaller amounts of shoes are sent to each store. The portable terminal solution (PDA) responds precisely to this need. In this situation, the shoe boxes need to be placed in columns with a space in between. This way, it is possible to prevent boxes from other columns, that is, from different stores, to be read. The minimum space recommended between columns to prevent wrong readings is 25 centimeters. This portable terminal is similar to the one used on the factory solution and the reading is performed manually using the PDA.

### *4.4 Re-designing Supply Chain Processes*

RFID enables a re-engineering exercise intended to optimize and integrate supply chain processes [6]. Consequently, the different processes along the supply chain and the information systems involved were studied, namely at the store, central warehouse, and production. At the production level, the main processes analyzed for applying RFID were: receiving item orders and codes, preparing the documentation for manufacturing, and registering a manufacturing entry and exit at each manufacturing stage. At the central warehouse, the main processes analysed for applying RFID were receiving, inventory management, and shipping; whereas at the store the processes analyzed were receiving, inventory management and sales or devolutions. The processes analysis considered all the paper documentation involved in order to eliminate the largest number of documents possible using RFID. Moreover, this analysis also identified the information exchanges at the factory, warehouse, and store.

### *4.5 Integrating the RFID System with Existent Information Systems*

The integration of the RFID system with the existent information systems along the supply chain is one of the major challenges of the RFID implementation [5, 7]. The integration framework has both hardware and software modules. The hardware used is represented in Table 2 and the software modules are showed in Fig. 1.

The product coding system has also to be defined and this step is key for the RFID to be used by the entire logistics chain, allowing the products to be visible from the production lines to the stores. Applying RFID at each stage of manufacturing, distribution, and stores implies unique specificities and objectives. For

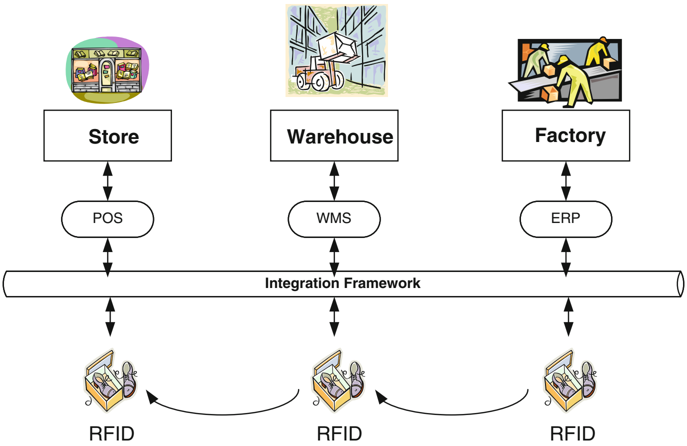



**Fig. 1** Integration of software modules

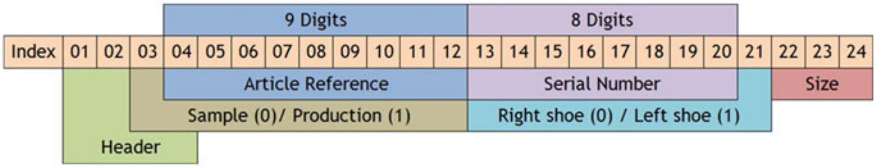



**Fig. 2** Coding of RFID tags

instance, the manufacturing focuses on following the orders and their progress, while the distribution focuses more on the state of orders and delivery in stores, and stores focus on stock levels.

By analyzing the entire chain, it was possible to find a "common denominator" focused on the item. Tag coding should focus on the items, which means that the identification of the shoe is transversal to the entire chain. One shoe identified with RFID moves along the entire value chain and is recognized by all information systems. After being given an RFID TAG, the shoe will undergo manufacturing operations at the manufacturer, logistics operations at the central warehouse, as well as operations at the store (Fig. 2).

## *4.6 Measuring the RFID Implementation Performance*

### 4.6.1 Production

At the beginning of the RFID system implementation some errors occurred, mainly caused by the exchange or absence of RFID tags in shoes during the

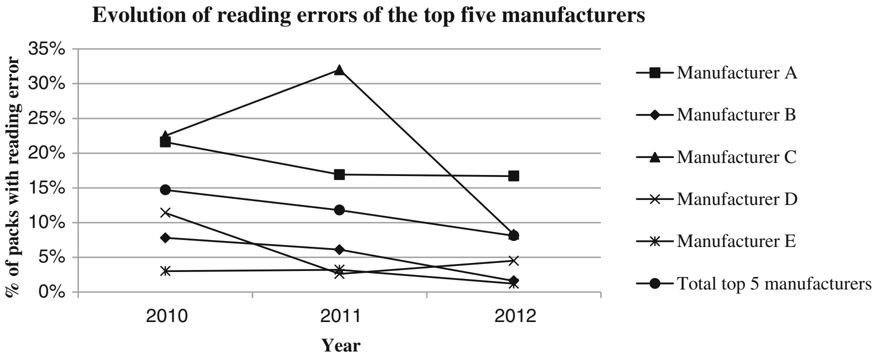



**Fig. 3** Evolution of RFID tag reading errors

assembly process. In the first implementation phase (production of the summer 2013 collection), 7,885 pair of shoes were encoded in the distribution chain. From these shoes with RFID, a total of 110 pairs were rejected (1.4 % rejection rate). 85.5 % of the errors were related to bad manipulation in the assembly process. Currently, the second phase is taking place and until now the distribution chain has already encoded 6,142 shoes, from which only 4 were rejected (0.07 % rejection rate).

### 4.6.2 Warehouse

After production, packs of shoe boxes are stored in a central warehouse before being distributed to customers or own stores. The warehouse receives customer orders and is responsible for the distribution of shoes delivered from 110 manufacturers around the world; all of them supplying shoes with RFID tags (though most of them still do not use RFID in the production process, adding the RFID tag only before shipping). In the beginning of the RFID implementation, most of the manufactures committed various errors placing the tag in the shoe box. The RFID software solution developed enabled the registration of reading errors by each manufacturer. Figure 3 shows the reading errors evolution of the top five manufactures, which represent 28 % of total packs received and 11.4 % of the total number of errors recorded. As Fig. 3 shows the total errors occurred have been decreasing significantly for the past 3 years.

## 5 Conclusion

RFID is a powerful technology that enables businesses to improve organizational and supply chain performance by simplifying processes and increasing supply chain visibility [15, 24]. Nevertheless, its adoption along the supply chain is still scarce. This research presents the solutions developed by the studied footwear supply chain in order to overcome the various RFID implementation challenges. The RFID implementation along the footwear supply chain covers the forward flow from production line to retail store and reverse logistics from retail store to the warehouse. The results of the study present the approaches developed to address six RFID implementation challenges, namely: forming the implementation team, selecting the RFID technology and defining the RFID system infrastructure, overcoming technical problems, re-designing supply chain processes, integrating the RFID system with existent information systems, and measuring the RFID implementation performance. Therefore, this study contributes to the literature on the RFID technology by advancing the knowledge on how this promising technology may be implemented along the supply chain.

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## References

1. Christopher M (2000) The agile supply chain competing in volatile markets. Ind Mark Manage 29(1):37–44
2. Lee HL (2004) The triple-a supply chain. Harvard Business Rev 82(10):102–112
3. Sanders NR (2008) Pattern of information technology use: the impact on buyer–suppler coordination and performance. J Oper Manag 26(3):349–367
4. Bardhan I, Mithas S, Lin S (2007) Performance impacts of strategy, information technology applications, and business process outsourcing in U.S. manufacturing plants. Prod Oper Manag 16(6):747–762
5. Whitaker J, Mithas S, Krishnan MS (2007) A field study of RFID deployment and return expectations. Prod Oper Manag 16(5):599–612
6. Attaran M (2007) RFID: an enabler of supply chain operations. Supply Chain Manag: Int J 12(4):249–257
7. Curtin J, Kauffman RJ, Riggins FJ (2007) Making the 'MOST' out of RFID technology: a research agenda for the study of the adoption, usage and impact of RFID. Inf Technol Manage 8(2):87–110
8. Ngai EWT, Moon KKL, Riggins FJ, Yi CY (2008) RFID research: an academic literature review (1995–2005) and future research directions. Int J Prod Econ 112(2):510–520
9. Angeles R (2005) RFIR technologies: supply-chain applications and implementation issues. Inf Syst Manag 22(1):51–65
10. Delen D, Hardgrave BC, Sharda R (2007) RFID for better supply-chain management through enhanced information visibility. Prod Oper Manag 16(5):613–624
11. Chow HKH, Choy KL, Lee WB, Lau KC (2006) Design of a RFID case-based resource management system for warehouse operations. Expert Syst Appl 30(4):561–576

12. Ngai EWT, Chau DCK, Poon JKL, Chan AYM, Chan BCM, Wu WWS (2012) Implementing an RFID-based manufacturing process management system: lessons learned and success factors. 29(1):112–130
13. Ngai EWT, Cheng TCE, Lai1 K-H, Chai1 PYF, Choi1 YS, Sin RKY (2007) Development of an RFID-based traceability system: experiences and lessons learned from an aircraft engineering company. Prod Oper Manag 16(5):554–568
14. Tajima M (2007) Strategic value of RFID in supply chain management. J Purchasing Supply Manag 13(4):261–273
15. Attaran M (2012) Critical success factors and challenges of implementing RFID in supply chain management. J Supply Chain Oper Manag 10(1):144–167
16. Sarac A, Absi N, Dauzère-Pérès S (2010) A literature review on the impact of RFID technologies on supply chain management. Int J Prod Econ 128(1):77–95
17. Liao W-P, Lin TMY, Liao S-H (2011) Contributions to radio frequency identification (RFID) research: an assessment of SCI-, SSCI-indexed papers from 2004 to 2008. Decis Support Syst 50(2):548–556
18. Barjis J, Wamba SF (2010) Organizational and business impacts of RFID technology. Bus Process Manag J 16(6):897–903
19. Li S, Visich JK, Khumawala BM, Zhang C (2006) Radio frequency identification technology: applications, technical challenges and strategies. Sens Rev 26(3):193–202
20. Coughlan P, Coghlan D (2009) Action research. In: Karlsson C (ed) Researching operations management. Taylor & Francis, Inc., New York, pp 236–264
21. Gummesson E (2000) Qualitative methods in management research. Sage
22. Eriksson P, Kovalainen A (2008) Qualitative methods in business research. Sage
23. Huizingh EKRE (2011) Open innovation: state of the art and future perspectives. Technovation 31(1):2–9
24. Zelbst PJ, Green KW, Sower VE, Reyes PM (2012) Impact of RFID on manufacturing effectiveness and efficiency. Int J Oper Prod Manag 32(3):329–350
25. Visich JK, Li S, Khumawala BM, Reyes PM (2009) Empirical evidence of RFID impacts on supply chain performance. Int J Oper Prod Manag 29(12):1290–1315

# Costs of Inbound Logistics: Towards a Decision Support Model for Production System Design

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**Abstract** Global competition forces companies to constantly increase the efficiency in their production systems. One important factor affecting the production performance is the inbound materials handling system. When designing or relocating a manufacturing system, the cost of the material handling system is one of many things to take into consideration. In connection with on-going research a comprehensive decision support for production location, both work procedures and model and tools for strategic and economic analyses are developed. A case study was conducted, at a supplier to the heavy vehicle industry, in order to develop cost models for inbound logistics. The results were two cost models of different accuracy giving the cost per part, where the comprehensive model is taking the process and equipment into consideration. In addition, the study also revealed the proportion between inbound logistics costs and assembly costs at the company studied. The result in this article is part of the development of making models for calculating the total production part cost.

## 1 Introduction and Research Design

In order to be competitive and increase profitability many manufacturing companies have to enter the global arena in both sales and manufacturing [1]. The need for internationalization results in board decisions on manufacturing relocation with regard to outsourcing and in-house manufacturing. For instance, a report done by OECD [2] revealed that intermediate value added inputs amounted to 56 % of the international goods trade in 2006, showing that a large amount of the products on the market were not consumed directly but instead used in manufacturing.

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Companies today constantly need to optimize their production systems, and one way to achieve this is to refine the material handling system.

Demands for cost reduction have forced many industries to establish manufacturing facilities in low-cost countries in order to get cost benefits. Although salary costs are not the only cost driver taken into consideration, decisions for relocation or outsourcing are often based on regional salary levels. This results in decisions made on a limited set of factors/parameters, which can cause the final costs to be higher than expected. Therefore, a comprehensive cost-based decision support framework, including information from a complete set of cost drivers in the production and logistics system, is beneficial.

This study is part of a larger research project, which aims to develop a comprehensive cost-based decision support tool for production location and production system design. One of the main goals within the research project is to develop an Excel-based support for calculating and estimating costs connected with the production system. To investigate different location scenarios, the decision support must contain and integrate all of the important cost drivers in order to provide the combined effects on the total cost.

One group of cost drivers, which is not often specified, associated with decision support for location is inbound logistics, or in other words material handling. According to some researchers these costs are negligible in comparison to costs of external logistics [3]. There are also reports on extensive logistics chain cost models and performance measurements in logistics chains, but they do not consider inbound logistics inside the manufacturing site as a variable factor, ultimately affecting the manufacturing and/or the total logistics costs [4, 5]. The inventory is commonly a major cost driving factor, involving inventory level and tied capital. The costs of plant operation or handling management are commonly seen as fixed costs or overhead costs not affected by changes in the supply chain [6]. Looking at inbound logistics costs and manufacturing costs there are many reports on cost models and optimization for each of the two different areas, but only a few making comparisons of them, including Thomas and Griffin [7].

The aim of the research presented here is twofold: (1) to develop a detailed cost model for determining manufacturing and inbound logistics costs; and (2) analyzing manufacturing costs and inbound logistics cost in order to develop a method for estimating inbound logistics costs when relocating production. The model presented in this article was developed in order to investigate the magnitude of the inbound logistics costs for each product produced in an assembly plant. The cost model is based on a concept presented in [8]. The inbound logistics model, together with the manufacturing cost model, makes it possible to analyse how the total production cost is affected by reconfigurations in the material handling process. One example is to investigate the cost outcome of employing one more personnel within the material handling in order to reduce the downtime rate at a manufacturing line.

To establish which cost parameters are important to include in the model, empirical studies at a supplier to the heavy vehicle industry were conducted. The purpose was to map the activities involved in inbound logistics and determine which cost factors these causes are dependent on. An analysis of data availability was also performed in order to investigate the accessibility of input data to the cost model. Given the context and motivation described, the following three questions were raised:

1. What parameters affect the cost of internal logistics and how can they be integrated in a cost model useful for supporting production location and production system design decisions?
2. What is the proportion of inbound logistics costs in relation to the total manufacturing costs?
3. What level of detail is required to conduct an analysis of internal logistics/ production for localization?

The purpose of this study is to develop a cost model for calculating the inbound logistics cost per part at a current location, making it possible to view the cost breakdown between different parameters and cost drivers. Another is to find a model for estimating costs in new facilities. There were two models developed in connection with the research work, one taking the current process of handling and storing products in consideration and one only calculating mean costs. The development of these two was dependent on a literature study, the observations at site, and connecting the new models to the previously developed manufacturing cost model [8].

The applicability of these two cost models were analyzed by conducting three case studies at the company. The aim of the applicability analysis was twofold: (1) investigate the effort of retrieving numerical values for each cost parameter; and (2) analyze the share of inbound logistics costs in relation to the total manufacturing cost. The purpose of having two different models was to investigate the importance of performing a detailed analysis of logistics cost to support production relocation decisions by comparing the two results.

In the following section, a theoretical framework is presented, followed by a presentation of the two models. Section 4 provides a description of the implementation of the two cost models in an Excel-based programmed interface to be used in the decision support model for location. Section 5 outlines the results from the case study, wherein the two models are compared, and the share of inbound logistics costs of the total manufacturing cost is analysed. Finally, the section of discussions and conclusions reflects on the results and the applicability of the two models.

## 2 Literature Review

As previously mentioned there are many articles dealing with material handling costs. The cost models found in the literature differ in use, aim and level of detail. In this section, a selection of different cost models for inbound logistics costs are presented. According to Johansson and Johansson [9], when analyzing material handling system the following function should be taken into consideration: materials feeding, storage, transportation, handling, packaging, and manufacturing planning and control. In Mannerheim and Petterssons [10] study at a Swedish truck manufacturer, the following cost factors are considered connected to the material handling process:

- Truck hours/truck cabin (personnel, depreciation (investment), electricity, maintenance).
- Delivery reliability.
- Warehouse space.
- Energy use for transport/truck cabin (e.g., forklifts).
- Material handling cost/truck cabin (e.g., truck) (staff, order processors, material (pallets, pallet racks), packaging (internally), and order cards).

The example above offers a good picture of important factors; however, these are quite specific for the facility for which was developed. In this case only material handling with forklifts is concerned.

Fang and Ng [11] presented a cost model based on activity-based costing. It consists of two main costs: loading and fixing cost, and storage cost. The cost of loading and fixing include pay rate of employees, rental rate of facility, and depreciation of equipment multiplied by total product quantity. The storage cost includes depreciation and cost of capital multiplied by unit cost and total quantity. The model results in the total cost of inbound logistics.

Manunen [12] presents a more in-depth activity-based cost model for logistics costs. The model presented involves seven different cost groups, where four are related to inbound logistics and warehousing. The result gives the cost of handling one order. The model takes the following in consideration:

- Time spent on orders (reserving, shelving, packing, picking).
- Labor costs.
- Costs of outsourced services.
- Holding costs of inventory, cost of capital.
- Investments in buildings, land, machines, storage and IT equipment, and software.
- Spaced used for inventory.
- Number of order lines in the order.

Hudgson and Lowe [13] present a cost minimizing model, taking both production lot size and storage space in warehouse into consideration. In their model, there are several factors affecting the total material handling and storage cost such as costs for crane transportation time for one unit. The material handling cost consisted of market demand, lot size, distance, speed, and inventory carrying costs.

McCann [14] presents a location decision support based on logistics costs using the principles of economic order quantity, where inbound logistics is one of the costs taken into consideration. The model includes product size and weight, along with labor and rental costs, and the work time needed to handle the products.

There are several cost factors common for the models reported in the literature study. Most of the factors mentioned above are represented in the model presented in this paper, except costs of outsourced services and tied capital of products. Although tied capital of products is an important cost to take into consideration, it should not be mixed with costs for running operations.

## 3 Inbound Logistics Cost Model

The inbound logistics cost model presented in this article is based on the principle of a generic manufacturing cost model presented in [8, 15]. The unique feature of this model is the integration of production performance. The manufacturing product cost model is presented in Eq. 1, where the cost factor for inbound logistics G is added to the model in [8, 15]. The main difference of the developed model compared to other cost models in material handling is that the costs are calculated per product and not as a mean value cost for all products. To handle the costs connected to the internal logistics, the manufacturing cost model has been refined and extended, and the additional terminology are presented in the next section. The generic manufacturing cost model provides the direct production cost, excluding the overhead cost, for a batch production with a nominal batch size $N_0$. The resulting value is the production cost for one part produced. The parameters of the model are compiled from the results from a Systematic Production Analysis (SPA), where the downtime rate, scrap rate, and production loss rate are measured. These are related to a factor in one of the following factor groups [8]: (A) Tool and tooling system; (B) Work piece material; (C) Manufacturing process and process data; (D) Personnel, organization, and outer logistics; (E) Maintenance and wear; (F) Special process behavior/factors tied to A, C, D, and G; (G) Surrounding equipment and inbound logistics; and (H) Unknown or unspecified factors. The G-factors (Surrounding equipment and inbound logistics) are connected to changes in the material handling system.

The cost model presented in this article is an extension of the manufacturing cost model and was developed within a case study at a supplier for the heavy vehicle industry. The model was developed by studying the material handling work performed at the company and by frequent discussions with relevant personnel. One important factor was that data used in the model should be able to be collected by using an existing economic system or easily measured.

The inbound logistics cost model is initially presented with a high degree of detail, introducing parameters associated with inbound logistics. A large range of the parameters is mentioned in the literature; however, the product specific distribution of the different cost factors is not commonly used. The calculations are based on the amount of pallet space all components of one product occupy, the amount of time they are placed in stock, the number of times and distance they are moved, the rental cost, and the cost of personnel and equipment. Based on the detailed cost model, a far less detailed cost estimation model is extracted, which can be used in the development of a decision support model for production relocation issues, where only the annual material handling cost and annual amount of manufactured products are considered. In both cases, the result gives the product part cost given in Eq. 1. All parameters used in the article are listed in Appendix 1.

$$
\begin{aligned}
k = {} & \frac{K_{sum}}{N_0} + \frac{1}{N_0}\left[\frac{k_B N_0}{(1 - q_Q)}\right]_B + \frac{k_{CP}}{N_0 60}\left[\frac{t_0 N_0}{(1 - q_Q)(1 - q_Q)}\right]_{CP} \\
& + \frac{k_{CS}}{N_0 60}\left[\frac{t_0 N_0}{(1 - q_Q)(1 - q_Q)} \times \frac{q_S}{(1 - q_S)} + T_{su} + \frac{1 - U_{RP}}{U_{RP}} \times T_{pb}\right]_{CS} \\
& + \frac{k_D}{N_0 60}\left[\frac{t_0 N_0}{(1 - q_Q)(1 - q_Q)(1 - q_S)} + T_{su} + \frac{1 - U_{RP}}{U_{RP}} \times T_{pb}\right]_D + [k_{GIL}]_G
\end{aligned} \tag{1}
$$

## 3.1 The Extended Cost Model for Inbound Logistics

A material handling system can be designed and configured in different ways with regard to, for example, equipment, personnel involved, storage system and working system such as kitting, where separate items are grouped and supplied together feeding the system making one unit. In order to make it possible to view how reorganizations affect the throughput of an assembly line or manufacturing system and the final cost, the model divides the costs between personnel, material handling equipment, storage, and maintenance. This is in line with the earlier presented factor groups for Systematic Production Analysis. The cost of inbound logistics will have its own expression with the index GIL (Factor G Inbound Logistics).

The cost model of the inbound logistics consists of four different groups of cost drivers: personnel costs $k_{G.DIL}$, equipment handling costs $k_{G.CIL}$, storage costs $k_{G.SIL}$, and maintenance costs $k_{G.EIL}$ (see Eq. 2).

$$k_{GIL} = k_{G.DIL} + k_{G.CIL} + k_{G.SIL} + k_{G.EIL} \tag{2}$$

The inbound logistics cost model is based on the pallet equivalent, $p_e$, giving the number of pallets needed to transport all components for one part. A pallet in this case is considered to be of European standard. The pallet equivalent is the factor used to allocate time and thereby cost to a part (see Eq. 3). The use of the pallet equivalent $p_e$ makes it possible to take into consideration that different components are of different number and have size, and need different numbers of pallets in order to supply a line where a certain number of products are produced. Below is the calculation of each of the different cost groups.

$$p_e = \sum_{i=1}^{n} \frac{\text{used number of article i in product}}{\text{number of articles i in one pallet}\left(1 - q_{Qi}\right)} \tag{3}$$

*Personnel costs*: time for handling the pallet at different pallet spaces, time for order processing, time for moving pallets, and time for kitting the articles are taken into consideration. Also a factor for utilization will affect the personnel costs.

$$k_{G.DIL} = \left(p_e\left(p_p \cdot t_{hpp} + t_{OP} + t_t\right) + t_{kit}\right)\frac{k_{GDL}}{60}\left(\frac{1 - U_{RPDL}}{U_{RPDL}}\right) \tag{4}$$

*Equipment handling costs*: the cost for handling pallets, for example from stock to the process, then to an assembly station and lastly to an inventory of finished goods. The equipment costs used are based on annuity on investments where the technical lifetime serves as the time factor.

$$k_{G.CIL} = \left(p_e\left(p_p \cdot t_{hpp} + t_t\right)\frac{(k_{GC} + k_e)}{60}\right) \tag{5}$$

where $k_e$ is the energy cost per hour used in order to transport material and $k_{GC}$ the cost per hour when handling products. The parameter includes both investments in equipment and rent/costs for assets used for handling and transportation. The parameter is calculated on the same basis as the equipment costs $k_{CP}$ in previous work [16, 17].

*Storage costs*: the cost of storage equipment and storage area used, but also the cost for the unused storage space.

$$k_{G.SIL} = p_e \cdot \frac{t_i}{1440}\left(k_{GCS} + K_{pp}\left(\frac{1 - U_{RPP}}{U_{RPP}}\right)\right) \tag{6}$$

where $k_{GCS}$ is the cost for investments in fix stock equipment, for example pallets racks and for rent/costs for an area connected to the space needed for storage, and $K_{pp}$ is the total cost for area needed to hold inventory.

*Maintenance costs*: the cost for maintaining equipment used in the material handling process. The yearly cost is divided between all products produced.

$$k_{G.EIL} = \frac{K_{EIL}}{N_{tot}} \tag{7}$$

Giving the detailed version of the total inbound logistics cost:

$$k_{GIL} = p_e\left(\left(p_p \cdot t_{hpp} + t_{OP} + t_t\right)\frac{k_{GDL}}{60}\left(\frac{1 - U_{RPDL}}{U_{RPDL}}\right) + \left(p_p \cdot t_{hpp}\right)\left(\frac{k_{GC} + k_e}{60}\right) + \frac{t_i}{1440}\left(k_{GCS} + K_{pp}\left(\frac{1 - U_{RPP}}{U_{RPP}}\right)\right)\right) + \frac{k_{EIL}}{N_{tot}} + t_{kit} \cdot \frac{k_{GDL}}{60} \tag{8}$$

### 3.2 The Simplified Cost Model for Inbound Logistics

For manufacturing products that are similar in configuration and consist of similar components, a more generalized model can serve to allocate resources in the material handling system. The simplified model is based on the total cost resulting from the use of all resources (e.g., personnel, equipment, space, and heat) divided by the number of total manufactured products, according to the equation below.

$$k_{GIL} = \frac{K_{GLtot/year}}{N_{tot}} \tag{9}$$

In the event that the products produced differ in volume, there is a need for a different distribution model, which takes into account the size and the handling involved. One way to do this is to make the assumption that the volume is proportional to the amount of handling and pallet places needed. It is possible to use the pallet equivalent to distribute the cost between products of different sizes, but it is also possible to use other distribution keys. Equation 10 offers an example of how to calculate cost when having large differences in product size.

$$k_{GIL} = K_{GLtot/year} \cdot \frac{p_{e_i}}{\sum_{i=1}^{n} N_i \cdot p_{e_i}} \tag{10}$$

where $N_i$ is the number of products produced of one product i.

## 4 Decision Support Tool

Since the decision support that this case study is a part of is implemented in an array of Excel tools, the result from this study is presented likewise. The extended cost equation is implemented in an Excel tool, where the result is the cost of inbound logistics related to handling one product. The user must outline different facts and costs, and the tool generates the personnel, handling, storage, and maintenance costs for inbound logistics. The tool is based on the comprehensive alternative and requires a set of input data with regard to the cost drivers; personnel involved in material handling, equipment, layout, and storage. The layout of the tool is in accordance with these cost driving categories, and the cost breakdown result is visualized accordingly. The input data requirement for the detailed analysis amounts to 25 input data items and are sorted in the following categories: product data, handling, personnel, areas, investments, and equipment maintenance. The tool can be used when estimating inbound logistics at a current location. By gathering necessary data, the user can obtain knowledgeable information about the material handling system, which is useful when estimating costs on new location. The analysis is especially useful when investigating the differences in costs between different products. Figure 1 shows the tool used for calculating inbound logistics using the extended cost model. In each of the white squares, the users must fill in information. In the top on the left side of the tool, the internal logistics part cost is shown for the investigated product. In the bottom on the right side of the tool, the generated costs depend on the four cost groups; however, the costs of personnel per minute are also stated, making it possible to compare and analyze the cost outcome depending on the different cost drivers.

## 5 Case Study

The material handling cost was compared with the cost of manufacturing in order to find out its proportion of the total product cost, thereby investigating the importance of conducting a detailed analysis. As mentioned above, the development of the models occurred in connection with a medium size supplier to the heavy vehicle industry, only performing assembly work with different levels of automation. The company provided time for interviews with employees from all levels in the company, for example the CEO, controller, employees responsible for logistics, assembly workers, and personnel working with material handling. Information and inputs were also acquired through observations at the working site. The models were developed with the support of observations of the work process in the material handling department together with the literature studies. Three different products were selected in order to investigate and compare cost incurred when assembling and handling them, and were selected because they were high volume products manufactured in three different assembly lines. In order to the necessary obtain data, time studies at the assembly stations were performed and information about order handling and product specification were gathered through the use of the economic system. All products are about the same size and contain the same type of components; therefore, the simpler model was

| Cost/part | 15,1 | Currency/part |
|---|---|---|
| Product data | | |
| Batch size | 250 | |
| Number of different articles | 25 | |
| Pallet equivalent | 0,04 | |
| Total annual number of products | 350000 | |
| Handling | | |
| Average transport distance | 100 | m |
| Average number of destinations | 2 | |
| Working time at pallet space | 0,5 | min |
| The average time in inventory | 12 | days |
| Time for order processing | 3 | min |
| Personnel | | |
| Average annual cost direct personnel | 470000 | Currency |
| Average number of persons (direct personnel)/shift | 4 | |
| Average hours/shift and year | 1725 | |
| Annual cost indirect personnel | 625000 | Currency |
| Total Number of people (direct personnel) | 18 | |
| Number of people (indirect personnel) | 1,14 | |
| Production time | 5300 | h |

| Areas | | |
|---|---|---|
| Area linked to personnel | 110 | sqm |
| Number of pallet spaces | 770 | |
| Area linked to inventory | 340 | sqm |
| Area linked to the handling processes | 900 | sqm |
| sqm price production | 1100 | Currency/sqm |
| sqm price offices | 1200 | Currency/sqm |
| Investments | | |
| Investments handling equipment | 34000 | Currency/year |
| Investments inventory | 5000 | Currency/year |
| Equipment maintenance | 5000 | Currency/year |
| Personnel cost/min | 4,7 | Currency |
| Personnel costs/part | 9,8 | Currency |
| Handling costs/part | 3,9 | Currency |
| Inventory costs/part | 0,8 | Currency |
| Maintenance costs/part | 0,01 | Currency |

**Fig. 1** Decision support tool for calculating inbound logistics costs. The figures are fictive and not related to the study

**Table 1** The results from the case study

| Model | Share of total cost (%) |
|---|---|
| Extended model | 10–16 |
| Simplified model | 13–14 |

used (see Eq. 9). The results from using the extended model and the more elementary one were compared and are presented in Table 1, giving the share for inbound logistics compared to the total cost of assembly and material handling for the range of selected products.

While making the calculations some assumptions and simplifications were made. The average speed of the forklift was set to 3 km/hour. The velocity was set throughout observations and recommendations from the industry. Together with the measured distances the time for transporting the pallets were calculated. When calculating the investments in handling equipment and storage equipment, the annuity based on technical lifetime were used. Added to the investment in handling equipment is the cost of leasing forklifts. In the square meter price, the cost of light and heat are included. Calculating the energy cost of operating the forklifts, the cost per part was insignificant and therefore excluded from this study. Further research will analyze whether it is a factor to take in consideration or exclude from the model.

## 6 Discussions and Conclusions

In this article, two new models for analyzing inbound logistics costs are presented and integrated into an existing manufacturing cost model. The models introduce the pallet equivalent, used to divide costs between products composed of many articles. Another factor separating the model from the literature is that the cost of capital tied to products in inventory is not included. The simpler one has some similarities to the model presented in [14], where size and weight are used to distribute cost between products. Figure 1 shows the different parameters needed in order to calculate the inbound logistics cost according to the extensive cost model.

The results of the case study show that the two different models generate a similar result, but the more detailed model gives a larger range than the simpler one. This is in line with what was expected. The reason for the result within the simpler model is because of differences in the manufacturing cost of the different products. This indicates that the two models together could give valuable information to companies. The simpler one outlines a mean cost for the material handling process, whereas the more detailed one gives the cost for each product being handled. The pallet equivalent $p_e$ can be used in the simpler model in order to have some dependence on what product is being handled. According to Table 1, the material handling cost is approximately 14 % of the total production cost at the case study company, which is not a negligible share.

The detailed model can be used when investigating how changes in the material handling system affect the production performance and thereby the total cost. A higher inbound logistics cost could lead to lower manufacturing cost and reverse. Some costs are hard to retrieve, for example energy cost could be very low in comparison to other costs and at the same time be hard to access. There could be a reason not to take these types of costs into consideration, or simply use mean costs. The models are meant to be generic and work on all types of material handling processes, but additional analysis is required to clarify if the model can be used on all types of material handling processes in all industries. Further research will test the model on different companies. These companies should be of different size and involve both different processes and assembly stations. It is reasonable to think that the share for inbound logistics of the total cost is lower in the cases where expensive equipment is used in the manufacturing processes.

The detailed model could be used on existing material handling processes, and the simpler one is more suitable for investigating future needs and configurations. Further research will aim to implement the presented models in decision support for relocation, where the detailed model is used in order to obtain the current cost situation and the simpler one for analyzing alternative locations. Other costs to add are external logistics, purchase, marketing, and quality assurance in order to receive the total production part cost.

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## Appendix 1: List of Symbols

| Parameter | Description | Value |
|---|---|---|
| $k$ | Cost per part | Currency/unit |
| $k_A$ | Equipment cost | Currency/unit |
| $k_B$ | Material cost per part | Currency/unit |
| $k_{CP}$ | Hourly machine cost during production | Currency/h |
| $k_{CS}$ | Hourly machine cost at downtimes and adjustments | Currency/h |
| $k_D$ | Salary cost | Currency/h |
| $k_e$ | Cost for electricity | Currency/min |
| $k_{GC}$ | Hourly cost for handling material | Currency/h |
| $k_{G.CIL}$ | Cost per part for inbound logistics equipment | Currency/unit |
| $k_{G.DIL}$ | Cost per part for inbound logistics personnel | Currency/unit |
| $k_{GDL}$ | Hourly cost for inbound logistics personnel | Currency/h |
| $k_{G.EIL}$ | Cost per part for inbound logistics maintenance | Currency/unit |

(continued)

(continued)

| Parameter | Description | Value |
|---|---|---|
| $k_{GIL}$ | Cost per part for inbound logistics | Currency/unit |
| $k_{G.SIL}$ | Cost per part for inbound logistics storage | Currency/unit |
| $K_{EIL}$ | Total cost for maintenance for inbound logistic equipment | Currency/year |
| $K_{pp}$ | Total cost for area connected to inventory | Currency/h |
| $K_{GLtot/year}$ | Total cost per year for inbound logistics | Currency/year |
| $N_i$ | Total number of parts of a product | unit |
| $N_0$ | Nominal batch size | unit |
| $p_e$ | Pallet equivalent | pallets/unit |
| $p_p$ | Pallet places | number |
| $q_P$ | Relative rate reduction | - |
| $q_Q$ | Rejections rate | - |
| $q_S$ | Downtime proportion | - |
| $t_0$ | Nominal cycle time per part | min |
| $t_{hpp}$ | Time for handling pallets at pallet places | min |
| $t_i$ | Time in inventory | days |
| $t_{kit}$ | Time for kitting | min |
| $t_{OP}$ | Time for order processing | min |
| $t_t$ | Time for transportation | min |
| $T_{pb}$ | Production time for one batch | h |
| $T_{su}$ | Time for adjustments | min |
| $U_{RPDL}$ | The utilization rate of inbound logistics personnel | - |
| $U_{RP}$ | The utilization rate at reduced occupancy | - |
| $U_{RPP}$ | The utilization rate of pallet places | - |

## References

1. Bell J, Crick D, Young S (2004) Small firm internationalization and business strategy an exploratory study of ‘knowledge-intensive’and ‘traditional’manufacturing firms in the UK. Int Small Bus J 22(1):23–56
2. OECD (2010) OECD economic globalisation indicators. Organisation for Economic Co-operation and Development, Paris
3. Vidalakis C, Tookey JE, Sommerville J (2011) The logistics of construction supply chains: the builders’ merchant perspective. Eng Construct Architectural Manage 18(1):66–81
4. Gupta A, Maranas CD (2003) Managing demand uncertainty in supply chain planning. Comput Chem Eng 27:1219–1227
5. Bertazzi L, Speranza MG (1999) Minimizing logistic costs in multistage supply chains. Naval Res Logistics 46:399–417
6. Syarif A, Yun YS, Gen M (2002) Study on multi-stage logistic chain network: a spanning tree-based genetic algorithm approach. Comput Ind Eng 43(1):299–314
7. Thomas DJ, Griffin PM (1996) Coordinated supply chain management. Eur J Oper Res 94:1–15
8. Ståhl J-E, Andersson C, Jönsson M (2007) A basic economic model for judging production development. SPS Gothenburg, Division of Production and Materials Engineering, Lund University

9. Johansson E, Johansson MI (2006) Materials supply systems design in product development projects. Int J Oper Prod Manage 26(4):371–393
10. Mannerheim K, Pettersson M (2007) Fokus på—utveckling av nyckeltal för effektiv internlogistik (Swedish), Linköping University
11. Fang Y, Ng ST (2011) Applying activity-based costing approach for construction logistics cost analysis. Construct Innovations 11(3):259–281
12. Manunen O (2000) An activity-based costing model for logistics operations of manufacturers and wholesalers. Int J Logistics Res Appl: Lead J Supply Chain Manage 3(1):53–65
13. Hodgson TJ, Lowe TJ (2007) Production lot sizing with material-handling cost considerations. AIIE Trans 14(1):44–51
14. McCann P (1996) Logistic costs and the location of the firm: a one-dimensional comparative static approach. Location Sci 4(l/2):101–116
15. Jönsson M, Andersson C, Ståhl J-E (2008) A general economic model for manufacturing cost simulation. In: The 41st CIRP conference on manufacturing systems
16. Ståhl J-E (2007) Industriella Tillverkningssystem (Textbook in Swedish), Division of Production and Materials Engineering, LTH, Lund University, Lund
17. Ståhl J-E, Gabrielson P, Stål C, Andersson C (2012) A cost model for determining an optimal automation level in discrete batch manufacturing. In: 45-th CIRP conference on manufacturing systems, Athens, Greece 16–18 May

# PCB Assembly in a Multi-Machine Flowshop with Dynamic Board Release Times

**M. T. Yazdani Sabouni and Rasaratnam Logendran**

**Abstract** This paper investigates solving a group-scheduling problem in the assembly of printed circuit boards (PCBs). The type of setup operation to assemble a group of boards exactly matches with the real application. The kitting operation in the assembly of PCBs which have always been ignored in previous research is paid attention to by introducing the term "integration of external (kitting) and internal (machine) setups," which eventually results in the development of a dynamic PCB assembly system incorporating the concepts of just-in-time manufacturing. The problem investigated is NP-hard implying the requirement of heuristic approaches for solving industry-size problems. A meta-heuristic algorithm called Tabu Search, which is known to be efficient in solving combinatorial optimization problems, is employed. However, apart from finding the best sequence of jobs, evaluation of the objective function associated with each sequence is still an issue and it cannot be guaranteed to be optimal without the help of a mathematical model. Thus, a decision tree-based approach enabling the search to evaluate each of the sequences is developed including several properties and a lower bound, all of which are demonstrated in this paper.

## 1 Introduction

In this research a common problem in the assembly of PCBs is investigated in which an enormous number of components must be located on several boards and on three machines. The objective function considered is to simultaneously minimize the weighted sum of total weighted flow time and total weighted tardiness. The assembly process takes place on several machines where each of them is

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capable of placing certain type of components. In order to make the machines ready to be able to assemble different components, a setup operation should be performed. However, because of the existence of a large number of components, this setup can take up a long time. Thus, to decrease the number of unnecessary operations, similar boards requiring similar components are grouped together demanding only one setup operation. However, the group formation is basically related to group technology as a research area, and is not within the scope of this research which is group scheduling. As a technical constraint, all boards should be prepared for the assembly operation during a process called kitting operation and by kitting staff. However, this process which is essentially very important in the assembly of PCBs has been traditionally ignored in the related literatures to simplify the overall study of assembly processes. For the first time, the kitting operation is captured at the same time the assembly operation is being performed by completely eliminating the role of kitting staff and by assigning their task to the machine operator, which is introduced in this paper as integration of internal and external setup operations. Since the machine operator only performs the setup operation, he can also be assigned to perform the kitting operation during the time he is idle or during the time the machine is automatically performing the assembly operation. The setup operation in this type of assembly system is very complicated to be efficiently or even correctly evaluated. Because of the natural complexity in this problem, the setup operation is assumed to be at most sequence-dependent (see [1–4]) which is very different from what it should be in the real manufacturing system. In a real assembly system, not only there is a dependency between any two consecutive board groups, but also this dependency starts immediately from the first group in the sequence and is continuously carried over throughout the entire sequence and changes each and every time a new group is assigned to the machine. Thus, different types of previously scheduled groups as well as their different combinations result in having a different setup time value for a group. This setup time is introduced as carryover sequence-dependent setup time and exactly matches with the real setup observed in industrial problems. The closest setup time yet very far from the carryover sequence-dependent setup time is group setup strategy. In this type of setup, the dependency is transferred from a group of boards to another, yet the dependency is only on the immediately previous scheduled group which makes this setup inappropriate in PCB manufacturing. Leon and Peters [5] considered a group setup strategy as well as some other setup forms. Yilmaz and Günther [6], and Leon and Jeong [7] considered group setup strategies for minimizing makespan on a single machine. The only study in PCB assembly and even in scheduling that studies the carryover sequence-dependent setup is the work of Gelogullari and Logendran [8]. However, our work is fundamentally different because of considering a multi-objective function, existence of a dynamic assembly system, and considering the kitting operation by integration of internal and external setups. The problem in this research is very complex or equivalently is NP-hard, which requires applying heuristics or meta-heuristic approaches. Thus, an algorithm based on Tabu Search (TS), which is known to be successful in solving combinatorial optimization problems is developed and applied in this research. In many scheduling problems, finding the optimal sequence of jobs is translated into solving the problem. However, in the problem investigated in this research even after the optimal sequence is available, the problem remains unsolved because of evaluation of the objective function of the given sequence. In other words, the objective function cannot be optimally evaluated unless a mathematical model is formulated and used. Thus, in order to be able to evaluate several solutions proposed by the TS, a very efficient algorithmic approach to evaluate the objective function for a given sequence is developed and is integrated with the TS algorithm. Several properties on the application of this approach are provided which is also supported by developing a lower bound enabling the approach to be faster and more efficient. In Sect. 2, the explanation on objective function evaluation is provided. Section 3 outlines the fundamentals of TS. Section 4 presents the computational experiments followed by conclusion in Sect. 5.

## 2 Objective Function Evaluation

Typically, in most of the scheduling problems, objective function can be easily evaluated for a given sequence of jobs. In other words, for any sequence of jobs, there is only one objective function value that needs to be evaluated by observing the start and finish times of any operation required by jobs. This can essentially be the case when jobs have static arrival times which substantiates the fact that the start, and correspondingly finish, time of any operation can be determined when the finish times of the previous operations are known. However, in the problem in this research, the boards have ready times implying that the flow times, which are evaluated as the difference between finish assembly times (run times) and finish kitting (ready) times, are minimized when all of the finish assembly times to be close to the finish kitting times as much as possible. Thus, the assembly/kitting operations should immediately follow the assembly/kitting of the previous board on any machine if the interest was only to minimize the sum of flow times. Should the attempt be merely on minimizing the sum of flow times, the sum of tardiness would substantially increase because of the incurred delays in finishing the boards. Accordingly, sum of tardiness is minimized when boards are assembled as soon as possible but no sooner than they are delivered from the previous machine. Based on this explanation, a board can start its assembly operation at any point in time on the current machine but after its finish assembly time on the previous machine to minimize the sum of tardiness, and it must be supported by a time in advance to perform its kitting operation, while simultaneously minimizing the sum of flow times. Consequently, the problem associated with objective function evaluation for a given sequence of boards and groups turns into finding the finish/start kitting/assembly times of boards on all of the machines to minimize the overall weighted sum of weighted flow times and weighted tardiness, which is denoted in this paper by "time-scheduling" for kitting/assembly operations.

The mathematical form of the objective function is $\sum_{g=1}^{m}\sum_{i=1}^{n_{[g]}}\sum_{k=1}^{3}\beta_1 w_{[g],[i]}f_{[g],[i],k}+\beta_2 w_{[g],[i]}\max(O_{[g],[i],m}-d_{[g],[i]},0)$ where $f_{[g],[i],k}$ implies the flow time of the $i$th ordered board ($b_{[g],[i]}$) in the $g$th ordered group ($G_{[g]}$ with $n_{[g]}$ number of boards) on the $k$th machine which is equal to the difference between its completion time and finish kitting time of $b_{[g],[i]}$ on this machine and $d_{[g],[i]}$ is the due date of $b_{[g],[i]}$ on the last machine. Since negative tardiness does not contribute, the maximum of zero and the deviation of completion time from due date is considered. $w_{[g],[i]}$, $\beta_1$, and $\beta_2$ are, respectively, the weights of $b_{[g],[i]}$, and the weights associated with the sum of flow times and sum of tardiness in the objective function. Throughout this paper $N$,$m$, $rt_{[g],[i],k}$, $kt_{[g],[i],k}$, and $S_{[g-1],[g],[k]}$, respectively, imply the number of groups, number of machines, assembly time (run time), kitting time, and the setup time to transfer from $G_{[g-1]}$ to $G_{[g]}$ on the $k$th machine. Also, $TK$ implies the total kitting times required to kit the boards of a group. Clearly, even if the optimal arrangements of groups and boards in each group are known, the problem would remain unsolved since finding the best time-schedule of the boards to minimize the objective function is still an issue. Thus, any algorithm developed for finding the best sequence of the groups and boards should be equipped with an approach which is capable of finding the optimal time-schedule. In the following, a decision tree-based approach is demonstrated to calculate the objective function value for an $m$-machine problem and a given sequence. This approach evaluates the objective function optimally on the first machine and heuristically on the machines following the first machine. To demonstrate this approach, first it is demonstrated that the application of this approach on the first machine is optimal. Then, the application of this approach on the remaining machines will be demonstrated which eventually leads to the development of an algorithm supported by a lower bound to evaluate the objective function on all of the machines.

### 2.1 First Machine

Assembly operation on the first machine is independent from the other machines. It implies that a board on the first machine can be assembled at any time after the previous board on this machine has been assembled. On the other hand, inserting idle times between any two consecutive boards' assembly operations increases both the flow times and the tardiness of the boards that will be assembled later. Thus, in order to minimize the objective function contributed by the first machine, all of the boards must be consecutively assembled without any idle time in between. Also, as mentioned before, the kitting operation is solely performed by the machine operator during the time he is idle. Since the machine operator performs the setup operation and not the assembly operation, the kitting operation required by the next group should be assigned to him after the time the setup operation of the current group has been performed or equivalently during the assembly time of the current group on the first machine (there are idle times between the setup and assembly operations on the other machines in which the kitting operation can be performed and this will be described in detail later in the next section). Thus, the kitting operation of the next group can begin at a time immediately after the assembly of the current group starts. On the other hand, since all of the boards must be kitted before the assembly operation starts, any idle time between any two consecutive kitting of boards is translated into increasing the flow times and tardiness of the boards and accordingly it implies that there should be no idle time between any two consecutive boards' kitting operations. In Yazdani Sabouni and Logendran [9], some properties to find the start kitting operation of the next group on the first machine are provided. Accordingly, if the kitting operation of the next group is shorter than the assembly of the current group, the kitting operation should start at a time in order to finish exactly when the assembly finishes.

## 2.2 Machines > 1

Assembly operation on a machine > 1 is dependent upon the previous machine. This implies that assembly of a board on a machine > 1 is initiated after it has been completed on the previous machine. This substantiates that there may be idle times between the assembly of a board on a machine > 1 and the assembly of the next board on the same machine. The reason is after finishing the assembly of a board on the current machine, the machine would remain idle until the next board from the previous machine arrives. Consequently, this idle time would provide the chance of performing the kitting operation of the next group before the setup operation is performed (see Fig. 1). This complies with the idea of performing the kitting operation by the machine operator because he remains idle after performing a setup operation until the next setup operation. As it was described for machine > 1 and unlike the first machine, there may still be idle times between the assembly of any two consecutive boards of a group. However, in order to minimize the flow times, these idle times should be reduced to a minimum value. On the other hand, since the assembly of a board cannot start no sooner than its completion time on the previous machine, idle times on the current machine can be minimized by moving the boards of a group toward the boards that are scheduled later in this group which results in some of the boards become close to each other

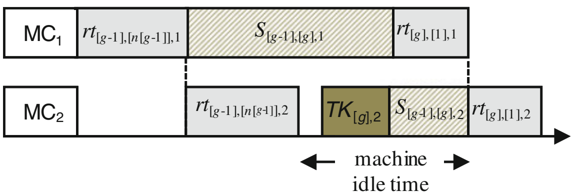


**Fig. 1** Performing the kitting and setup operations of $G_{[g]}$ during the idle time on the second machine

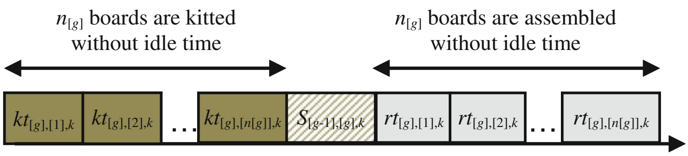


**Fig. 2** Kitting, setup, and assembly operations are performed without any idle time in between

without any idle time in between. In property 1 below it is shown that the minimum value of sum of flow times for a group on a machine is obtained when all of the boards are attached to each other and there is no idle time between any of them (see Fig. 2).

**Property 1** *The minimum value of* $\sum f_{[g],[i],k}$ *for the boards of* $G_{[g]}$ *on machine k is when all of the boards on this machine are assembled one after the other without any idle time in between preceded by setup operation, which in itself is preceded by the kitting operations of the boards immediately before the setup and without any idle time in between. In the interest of space, the proof for this property, as well as for Properties 2 and 3 below, are not included.*

While moving the boards may decrease the flow times, it may increase the tardiness similar to the reasoning given for the first machine. Thus, again finding the best time-schedule minimizing the objective function associated with a machine $> 1$ becomes an issue. However in this case, the possibility of existence of idle times between the assemblies of boards on a machine $> 1$ makes finding the best time-schedule more challenging. The optimal time-schedule including the start and finish times of different operations can be optimally determined using any mathematical model that captures all characteristics of the problem. However, in solution finding mechanisms in which the objective function is evaluated for a given sequence of groups and boards and eventually for a number of different solutions, an algorithmic approach should be developed to evaluate the objective function each and every time a different solution is identified. The approach in this paper to evaluate the objective function on the machines $> 1$ is an algorithm called OFDT (Objective Function-Decision Tree) that examines different cases for starting the assembly of a particular board such as $b_{[g],[cb]}$ $[1] \leq [cb] \leq [n_{[g]}]$ (called current board) in different positions on the current machine according to the board $b_{[g],[nb]}$ $[nb] \geq [cb]$ (called next board) on the previous machine. Then, all of the boards prior to $b_{[g],[cb]}$ on the current machine are immediately attached to it without any space in between preceded by setup operation which in itself is immediately preceded by the kitting operations of all of the boards without any space. The start assembly time of a board $b_{[g],[i]}$ $[i] > [cb]$ on the current machine is evaluated based on finding the maximum of its arrival time from the previous machine and the finish assembly time of $b_{[g],[i-1]}$ on the current machine and assigning $b_{[g],[i]}$ immediately after this maximum of times. Since the start assembly of $b_{[g],\ [i]}$ is set to be the soonest possible time, this results in minimizing its completion time which also minimizes its tardiness (inserting an idle time before the assembly of $b_{[g],[i]}$ increases its current tardiness). Since in this approach, a discrete time for start/finish assembly of $b_{[g],[cb]}$ is supposed, although it may be a continuous value in the optimal time-schedule, it is considered to be heuristic. In doing so, $b_{[g],[cb]}$ is assigned based on the following seven cases:

Case 1: $b_{[g],[cb]}$ starts its assembly immediately after the completion time of $b_{[g],[nb]}$ on the previous machine and $[nb] = [cb]$ (if $[nb] = [cb]$ and the current machine availability time is longer than the completion time of $b_{[g],[nb]}$ on the previous machine, then $b_{[g],[cb]}$ starts its assembly immediately after the current machine availability time).
Case 2: $b_{[g],[cb]}$ completes its assembly when the assembly of $b_{[g],[nb]}$ on the previous machine starts.
Case 3: $b_{[g],[cb]}$ starts its assembly when the assembly of $b_{[g],[nb]}$ on the previous machine starts.
Case 4: $b_{[g],[cb]}$ completes its assembly exactly at half the duration of time spent by the assembly of $b_{[g],[nb]}$ on the previous machine.
Case 5: $b_{[g],[cb]}$ starts its assembly immediately after half the duration of time spent by assembly of $b_{[g],[nb]}$ on the previous machine.
Case 6: $b_{[g],[cb]}$ completes its assembly when the assembly of $b_{[g],[nb]}$ on the previous machine completes.
Case 7: $b_{[g],[cb]}$ starts its assembly when the assembly of $b_{[g],[nb]}$ on the previous machine completes.

To simply, we refer to a time-schedule on each machine in which machine number, type of case and values of $b_{[g],[cb]}$ and $b_{[g],[nb]}$ are declared, and use the notation $P_{k,c,[cb],[nb]}$, where $k$ and $c$, respectively, imply the machine number and the type of case. Different time-schedules that result from different cases, with one current board and all next boards for an example problem of a group with three boards are displayed in Fig. 3. In this figure CB, NB, $rt_{[i],p}$, and $rt_{[i],c}$, respectively, imply current board, next board, assembly time of $b_{[i]}$ on the previous machine, and assembly time of $b_{[i]}$ on the current machine. The bold line between the assemblies implies the start or finish assembly time of current board with respect to the case assumed. Although the investigation in this example is performed when CB = 1, it could have continued by assuming CB = 2, 3, but in the interest of space they are not reported.

### 2.2.1 Objective Fuction-Decision Tree Algorithm

The Objective Fuction-Decision Tree (OFDT) algorithm is a branching decision tree algorithm with depth-first structure. Every node of this tree corresponds to a $P_{k,c,[cb],[nb]}$ made by assuming a different case, current board, or next board on the $k$th machine. If this is a feasible time-schedule (all of the boards on the current machine start after they have been completed on the previous machine), then the search goes to the next machine by updating the next machine as the current

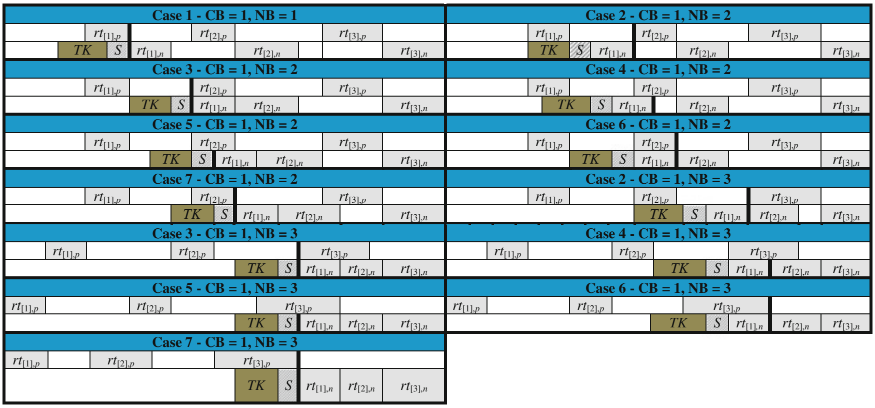


**Fig. 3** Display of different time-schedules obtained by different cases, current boards, and next boards

machine or $k = k + 1$. Then on this machine different nodes corresponding to different $P_{k,c,[cb],\ [nb]}$ are examined while each of them being the parent of a number of nodes on the next machine. The search examines the seven cases by assuming that the current and the next boards are fixed. Then it modifies $b_{[g],[cb]}$ by letting $cb = cb + 1$ and examines the seven cases again while keeping the $b_{[g],[nb]}$ as it was before. If there is no $b_{[g],[cb]}$ remaining for this $b_{[g],[nb]}$, then $b_{[g],[nb]}$ is updated by $nb = nb + 1$. So in this algorithm and on each of the machines, there are three loops, each of them inside the other one. The most inner loop counts the cases (from 1 to 7) and is in the loop that counts the current boards and this loop itself is in the most outer loop which counts the next boards. In the problem investigated in this research, a node on the $k$th machine ($P_{k,\ c,[cb],[nb]}$) has a contribution to the objective function because of the sum of flow times on the $k$th ($k \leq m$) machine. However, any node on the last machine has a contribution to the objective function because of the sum of weighted flow times and sum of weighted tardiness, as this demonstration is for a $m$-machine problem and the weighted tardiness comes into play only on the last ($m$th) machine. So the objective function for a given sequence of boards in a group is evaluated by finding the nodes that have child-parent relationship on the last $m - 1$ machines and adding up their contributions and adding the result to the contribution (sum of weighted flow times) obtained on the first machine. Since the time-schedule on the first machine can be optimally identified, only one-unique contribution on the first machine exists. Thus, essentially, the OFDT algorithm searches for the best nodes with child-parent relationships on the last $m - 1$ machines whose contribution has the minimum value. The best nodes obtained identify the best time-schedules on all of the machines for the group under investigation. These time-schedules on the machines are kept for this group and the search continues to find the next best time-schedules on the machines for the next group.

OFDT identifies all of the nodes and selects the best ones on the machines, while there may be some nodes on each machine that guarantee not to give a contribution better than the best contribution identified so far. Thus, in the following a lower bound will be developed in order to disregard the unnecessary nodes in the exploration on each machine. Before presenting the lower bound, two properties used in the lower bound are given. By assuming that $P_{k,c,[cb],\ [nb]}$ is a time-schedule already under investigation on the $k$th machine, we let $P_{k,cl,[cbl],\ [nbl]}$ be another time-schedule that will be investigated *later* (indicated by subscript $l$) after $P_{k,c,[cb],[nb]}$. Also $P_{k-1,cp,\ [cbp],\ [nbp]}$ and $P_{k-1,\ cpl,\ [cbpl],\ [nbpl]}$ are, respectively, the parent of $P_{k,c,\ [cb],\ [nb]}$ and another time-schedule on the *previous* machine (indicated by subscript $p$) that will be investigated after $P_{k-1,\ cp,\ [cbp],\ [nbp]}$.

**Property 2** *Given $n_{[g]}$ boards $b_{[g],\ [1]}, \ldots, b_{[g],\ [n[g]]}$ in group $G_{[g]}$, $P_{m,c,\ [cb],\ [nb]}$ on the last machine when $[cb] = [nb]$ has the least tardiness among all of the $P_{m,cl,\ [cbl],\ [nbl]}$ that will be obtained later on the same machine but from the same parent* (see Fig. 4).

**Property 3** *Given $n_{[g]}$ boards $b_{[g],\ [1]}, \ldots, b_{[g],\ [n[g]]}$* in *$G_{[g]}$, $P_{m,\ 1,[1],[1]}$ on the last machine has the least tardiness among all of the time-schedules $P_{m,cl,[cbl],[nbl]}$ on the last machine that will be generated later from $P_{m-1,\ cp,\ [cbp],\ [nbp]}$ or will be generated later from a $P_{m-1,cpl,[cbpl],[nbpl]}$, which will be investigated, after $P_{m-1,cp,[cbp],[nbp]}$ is investigated* (see Fig. 4).

**Corollary** By a similar reasoning it can be shown that if $P_{m,\ 1,[1],[1]}$, $P_{m-\ 1,1,[1],[1]}$, …, $P_{m-j,\ 1,[1],[1]}$, *and* $P_{m-j-1,\ c,\ [cb],\ [nb]}$ $2 \le j < m$ have child-parent relationships, their associated tardiness on the last machine is smaller than the tardiness of any other child-parent relationship time-schedule on the last $j+1$ machines which will be investigated later. In other words, other child-parent relationships that result later from $P_{m-j-1,\ c,[cb],\ [nb]}$ or $P_{m-j-1,cl,\ [cbl],[nbl]}$ will have a greater tardiness on the last machine.

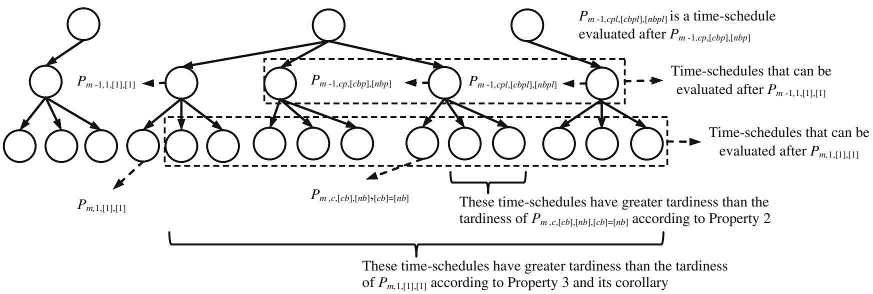


**Fig. 4** Application of Properties 2 and 3 in a decision tree display

### 2.2.2 Lower Bound

OFDT examines all of the $P_{k,\ c,\ [cb],\ [nb]}$ that can be identified from a parent on the previous machine. Although in order to obtain the best time-schedule for the boards of a group on each machine all of the possible time-schedules should be evaluated by the algorithm, there may be some time-schedules that will never produce a dominant time-schedule on the next machine and also any other time-schedule following them on the current machine would be dominated. So essentially to cut down on the unnecessary evaluations performed in identifying the dominant time-schedules on each machine, a lower bound based on Properties 1, 2, and 3 is developed. Suppose that the objective function is evaluated for $G_{[g]}$ for a given sequence of boards and groups. Also suppose the best child-parent relationship time-schedule identified so far on the machines 2 to $m$ has $SF_2, \ldots, SF_m$ as the associated sum of flow times on the machines 2 to $m$ and $ST$ as the associated tardiness on the last machine where $SF_2 + \ldots + SF_m + ST$ is the minimum value so far. Accordingly, $SF_2, \ldots, SF_m$, and $ST$ are updated whenever a smaller value is found. Also, $T_{[cb]=[nb]}$ implies the tardiness of the current time-schedule $P_{m,c,[cb],[nb]}$ under investigation in which $[cb] = [nb]$. Based on Property 1, the minimum values of flow times on each machine can be evaluated and, respectively, are shown by $MinSF_2, \ldots, MinSF_m$. To decide if a time-schedule $P_{m,cl,[cbl],[nbl]}$ on the last machine should be evaluated after $P_{m,\ c,[cb],[nb]}$ or not, consider the constraint $SF_2 + \cdots + SF_m + ST \leq MinSF_2 + \cdots + MinSF_m + T_{[cb]=[nb]}$. Based on Property 2, any $P_{m,\ cl,\ [cbl],\ [nbl]}$ from the same parent on the last machine will have a greater tardiness value than the tardiness of $P_{m,\ c,\ [cb],\ [nb]}$. On the other hand, the sum of flow times of the previous parents on the previous machines plus the flow time of $P_{m,\ c,\ [cb],\ [nb]}$ or the flow time of $P_{m,\ cl,\ [cbl],\ [nbl]}$ are greater than $MinSF_2 + \cdots + MinSF_m$. Accordingly, the associated contribution of $P_{m,\ cl,\ [cbl],\ [nbl]}$ together with those of its previous parents (on machines 2 to $m-1$) will not be better than $MinSF_2 + \cdots + MinSF_m + T_{[cb]=[nb]}$. Thus, if the condition is satisfied, the best child-parent relationship time-schedule identified so far would remain the best and it satisfies the need to *not* investigate $P_{m,\ cl,\ [cbl],\ [nbl]}$ from the same parent. A similar constraint can be developed to stop the investigation on the other machines $< m$. In doing so, let $T_{[cb]=[nb]=[1]}$ be the tardiness of the time-schedule $P_{m,\ 1,\ [1],\ [1]}$ on the last machine and $P_{k,\ 1,\ [1][1]}$, $k = j, \ldots, m-1$are all the previous parents of $P_{m,\ 1,\ [1],\ [1]}$ on the machines $j$ to $m-1$. Thus according to the corollary of Property 3, $T_{[cb]=[nb]=[1]}$ is the minimum among the tardiness of all of the child-parent relationship time-schedules identified later on the last $j+1$ machines. Accordingly, if the constraint $SF_2 + \ldots + SF_m + ST \leq MinSF_2 + \ldots + MinSF_m + T_{[cb]=[nb]=[1]}$ is satisfied, then any other time-schedule identified later on the last $j+1$ machines will be dominated.

### 2.2.3 OFDT Algorithm in Pseudo Code

The pseudocode of the OFDT algorithm to find the best time-schedule of the $n_{[g]}$ boards in group $G_{[g]}$ on 2,…, $m$ machines is provided in this section. *Flow* $T_k$ and *Tard* $T$ are, respectively, the sum of weighted flow times of the time-schedule under investigation on the $k$th machine and the weighted tardiness of the time-schedule under investigation on the last machine. $OBV_{\mathrm{OFDT}}$ is the contribution in the objective function found by OFDT on machines $k = 2, \ldots, m$. Initially, $k$ is supposed to be 2.

For $g = 1$ to $N$
1.1. For $nb = 1$ to $n_{[g]}$
For $cb = 1$ to $nb$
1.2. Select Case
If $nb = cb$ Then '*Case 1* Place $rt_{[g],[cb],k}$ immediately after $O_{[g],[nb],k\text{-}1}$.
Else
'*Case 2* Place $rt_{[g],[cb],k}$ to finish it exactly at the start of $rt_{[g],[nb],k\text{-}1}$.
'*Case 3* Place $rt_{[g],[cb],k}$ immediately after the start of $rt_{[g],[nb],k\text{-}1}$.
'*Case 4* Place $rt_{[g],[cb],k}$ to finish it exactly at the half of $rt_{[g],[nb],k\text{-}1}$.
'*Case 5* Place $rt_{[g],[cb],k}$ immediately after the half of $rt_{[g],[nb],k\text{-}1}$.
'*Case 6* Place $rt_{[g],[cb],k}$ to finish it exactly at $O_{[g],[nb],k\text{-}1}$.
'*Case 7* Place $rt_{[g],[cb],k}$ immediately after $O_{[g],[nb],k\text{-}1}$.
End If
2.1. Set $i = cb$. For $p = cb - 1$ to 1, place $rt_{[g],[p],k}$ before $rt_{[g],[i],k}$, Set $i = p$, Next $p$.
2.2. For $p = cb + 1$ to $n_{[g]}$, place $rt_{[g],[p],k}$ immediately after the maximum of $O_{[g],[p],k\text{-}1}$ and $O_{[g],[p\text{-}1],k}$, Next $p$.
2.3. Place setup time immediately before $rt_{[g],[1],k}$.
2.4. Place $kt_{[g],[n[g]],k}$ immediately before setup time. Set $i = n_{[g]}$.
For $p = n_{[g]} - 1$ to 1, place $kt_{[g],[p],k}$ immediately before $kt_{[g],[i],k}$, Set $i = p$, Next $p$.
3.1. If this is a feasible time-schedule Then
3.1.1. Set $FlowT_k = \beta_1 \sum_{i=1}^{n} f_{[g],[i],k} \times w_{[g],[i]}$.
3.1.2. If $k = m$ Then
Set $TardT = \beta_2 \sum_{i=1}^{n} \max\left(O_{[g],[i],m} - d_{[g],[i]}, 0\right) \times w_{[g],[i]}$.
If $\sum_{i=2}^{m} FlowT_i + TardT < \sum_{i=2}^{m} SF_i + ST$ Then
$SF_i = FlowT_i$, $ST = TardT$, $i = 1, \ldots, n_{[g]}$.
End If
If $[nb] = [cb]$ Then
If $\sum_{2=1}^{m} SF_i + ST < \sum_{2=1}^{m} MinSF_i + T_{[nb]=[cb]}$ Then
Stop time-schedule evaluation from the same parent on the $m$th machine. Set $cb$ and $nb$ on this machine to $n_{[g]} + 1$.
End If
End If
If $[nb] = [cb] = [1]$ in $P_{mc,1,[1],[1]}$, $mc = j, \ldots, m$ Then
If $\sum_{2=1}^{m} SF_i + ST < \sum_{2=1}^{m} MinSF_i + T_{[nb]=[cb]=[1]}$ Then
Stop time-schedule evaluation on machines $mc = j - 1, \ldots, m$. Set $cb$ and $nb$ on these machines to $n_{[g]} + 1$. Set $k = j - 1$ and go to step 5.1.
End If
End If
Else If $2 \le k < m$ Then start evaluation on the next machine by setting $k = k + 1$, go to step 1.1, End If.
End If
4. If there is still a case that has not been evaluated for the current $nb$ and $cb$ on machine $k$, Then go to step 1.2, End If.
Next $cb$
Next $nb$
5.1. If $2 < k \le m$ Then there is no time-schedule remained on machine $k$ from the current parent, set $k = k - 1$and continue the investigation from the most recent case, $nb$ and $cb$ on the previous machine, End If.
5.2. If $k = 2$ Then set $OBV_{OFDT} = OBV_{OFDT} + \sum_{i=2}^{m} SF_i + ST$, End If.
Next $g$
6. Terminate the algorithm.

## 3 Tabu Search Algorithm

Tabu Search (TS) algorithm has been known to be an efficient searching mechanism in solving combinatorial problems, especially scheduling problems in which the challenge is to find permutations. It starts with an initial solution and iteratively generates the neighbors surrounding the current solution. Generation process is performed by employing a set of exchanges in the sequence of a given number of elements (groups and boards in our problem). More information on the type of the tabu search implemented in this paper can be found in Yazdani Sabouni and Logendran [9].

## 4 Computational Experiment

Several problem instances were randomly generated and their associated mathematical models were formulated using Yazdani Sabouni and Logendran [9] and solved with CPLEX. These problems were also solved by TS and the obtained results were compared against CPLEX and are given in Table 1. Comprehensive explanation on data generation based on the information from a real PCB manufacturing can be found in Yazdani Sabouni and Logendran [9] and is not included here because of space limitations. Although, the TS and OFDT algorithms can be applied to solve any problem, number of machines is assumed to be 3 with number of groups (*N*) of 3, 4, and 5, and each of them having 1 or 2 boards. The setup time per feeder (*AST*) on the first machine is assumed to be 30 and 180, while it is 220 on the second and the third machine. By observing that that the OFDT algorithm is

**Table 1** CPLEX, $OBV_{OFDT+F}$, and TS comparison

| AST | N | Solution value | | | | | CPU time | | Solution number | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | CPLEX | $OBV_{OFDT+F}$ | Deviation C vs. O (%) | TS | Deviation C vs. T (%) | CPLEX | TS | CPLEX | TS |
| 180 | 3 | 18,546 | 18,546 | 0 | 18,546 | 0 | 0.34 | 0.01 | 70 | 16 |
| | | 53,027 | 53,027 | 0 | 53,027 | 0 | 0.13 | 0.81 | 226 | 86 |
| | 4 | 46,410 | 46,467 | 0.12 | 46,467 | 0.12 | 2.95 | 1.35 | 2,627 | 172 |
| | | 28,046 | 28,046 | 0 | 28,046 | 0 | 2.59 | 1.27 | 1,117 | 230 |
| | 5 | 37,435 | 37,435 | 0 | 37,435 | 0 | 3.46 | 2.42 | 7,886 | 201 |
| | | 99,186 | 99,203 | 0.02 | 100,091 | 0.91 | 2.81 | 2.57 | 21,223 | 352 |
| 30 | 3 | 9,297 | 9,297 | 0 | 9,297 | 0 | 0.36 | 0.01 | 75 | 19 |
| | | 6,953 | 6,953 | 0 | 6,953 | 0 | 0.08 | 0.01 | 72 | 15 |
| | 4 | 23,149 | 23,149 | 0 | 23,149 | 0 | 2.29 | 0.89 | 2,236 | 121 |
| | | 16,932 | 16,932 | 0 | 16,932 | 0 | 1.25 | 0.81 | 2,343 | 96 |
| | 5 | 70,680 | 70,764 | 0.12 | 70,764 | 0.12 | 3.04 | 2.13 | 18,792 | 1,026 |
| | | 55,672 | 55,672 | 0 | 55,672 | 0 | 1.37 | 2.69 | 25,561 | 1,034 |

applicable only to the second machine and after, $OBV_{OFDT+F}$ implies the best contribution found by OFDT on the second and the third machines plus the contribution on the first machine. In columns 5 and 7, the deviations of CPLEX, respectively, from $OBV_{OFDT+F}$ and TS are displayed. Computation time and number of enumerated solutions are shown in the last four columns. As it can be seen in the table, actually in all of the cases the optimal solution is targeted by TS, however, its deviation from the optimal solution is really small (a maximum of 0.91 % and an average of 0.96 %). In order to evaluate the efficiency of OFDT to observe how efficient it is in terms of evaluating the objective function for a given sequence, in each problem the optimal sequence of boards and groups found by CPLEX was given to OFDT and its final contribution found plus the value found on the first machine ($OBV_{OFDT+F}$) was compared against CPLEX. As it can be seen, $OBV_{OFDT+F}$ matches with the optimal objective function value in most of the problems. Yet the deviation recorded in some of the cases is because of the possibility of having continuous values for start/finish of assembly operations that can be only determined by the mathematical model. The number of solutions identified by TS compared to CPLEX is much smaller which implies its superiority over CPLEX. The computation effort of CPLEX (number of solutions identified) increases exponentially when problem size gets larger and this indicates that it is inapplicable in solving larger problems.

## 5 Conclusion

For the first time in the research undertaken in PCB scheduling, both the kitting operation and the assembly operation are integrated. Unlike most of the scheduling problems, the objective function calculation in this problem is a challenging task which results in the development of a decision tree algorithm together with lower bound. This approach can be integrated with any searching mechanism in which the objective function is evaluated for a given solution. In doing so, a solution finding mechanism based on TS is integrated with this approach and both the efficiency of the approach and TS are studied against the optimal solutions in solving several problem instances. Since optimally solving larger size problems is practically impossible, a lower bounding mechanism is proposed to be developed in the future to test the efficiency of the TS and other metaheuristics.

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## References


1. Strusevic VA (2000) Group technology approach to the open shop scheduling problem with batch setup times. Oper Res Lett 26:181–192
2. Eom DH, Shin HJ, Kwun IH, Shim JK, Kim SS (20002) Scheduling jobs on parallel machines with sequence-dependent family setup times. Int J Adv Manuf Technol 19:926–932
3. Schaller JE, Gupta JND, Vakharia AJ (2000) Scheduling a flowline manufacturing cell with sequence dependent family setup times. Eur J Oper Res 125:324–339
4. Kim YD, Lim HG, Park MW (1996) Search heuristics for a flowshop scheduling problem in a printed circuit board assembly process. Eur J Oper Res 91:124–143
5. Leon VJ, Peters BA (1996) Replanning and analysis of partial setup strategies in printed circuit board assembly systems. Int J Flexible Manuf Syst 8:389–412
6. Yilmaz O, Günther HO (2005) A group setup strategy for PCB assembly on a single automated placement machine. In: Operations research proceedings, Bremen, pp 143–148
7. Leon VJ, Jeong IJ (2005) An improved group setup strategy for PCB assembly. In: International conference on computational science and its applications, Singapore, 312-321
8. Gelogullari CA, Logendran R (2010) Group-scheduling problems in electronics manufacturing. J Sched 13:177–202
9. Yazdani Sabouni MT, Logendran R (2012) Carryover sequence-dependent group scheduling with the integration of internal and external setup times. Eur J Oper Res

# A Multi-Agent Architecture Framework to Improve Wine Supply Chain Coordination

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**Abstract** Over the last few decades, a rapid advancement in the arena of technology has escalated the competitive scenario across the globe. Several companies are now using intelligent systems to assist their supply chain management activities. This research, therefore, attempts to explore the advantage of using intelligent systems in managing supply chain activities. A review of the literature shows that with growing demand of food products, improved supply and storage facilities, and strong emphasis on cross boundary trade and policies have generated a lot of interest among researchers to look at the issues faced in the food supply chain. Researchers have attempted to study various types of food supply chains; however, little emphasis has been given to study the wine supply chain industry. One of the key challenges that exist in wine supply chain is the integration among the key members of the supply chain to accomplish a collective set of tasks. This paper, therefore, aims to address the supply chain coordination issue. To achieve better coordination among the wine supply chain members, this paper put forward the use of an intelligent agent based architecture framework. The paper suggests that the proposed intelligent multi-agent framework can reduce the complexity of

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decision making process, improve the supply chain coordination, and assist the SCM managers in smooth running of the wine supply chain.

## 1 Introduction

An increasing competition around the globe has forced companies to look out for effective ways to remain competitive. Companies are following various means to counter the threat imposed by their competitors by opting for different strategies such as entering new markets, improving their processes using continuous improvement techniques, and improving their work efficiencies. Efficient functioning of supply chain is core to many companies and thus they work hard to improve their supply chain efficiencies. Among the various factors that affect the efficient functioning of the supply chain, having a better coordination between supply chain members is very important [1]. Supply chain coordination is imperative to successful supply chain management (SCM). It plays a critical role in integrating different members along the supply chain to enhance the overall performance [2]. The issues regarding the integration of supply chains that need attention include type of supply chain relationships, supply chain mechanisms, information sharing, and information systems [1]. One of the supply chain coordination challenges that has been identified in the literature is the low level of coordination effort with supply chain members that firms carry out in defining and fulfilling customer needs [2]. Furthermore, little attention has been given to integrating and revealing the interactions of key design elements that drive the effectiveness of the chain members to realize better performance [3] despite the fact that coordinating between supply chain members can contribute positively to supply chain performance [2, 4]. Supply chain coordination is a key to success for both manufacturing and food supply chain. This study focuses on the coordination issues in food supply chain, particularly in the wine sector.

The issue of the food supply chain management has attracted much scholar attention and has been studied extensively for many years. The wine supply chain can be thought of as a subset of the food supply chain, however, the supply chain practices of these two industries can differ from one another [5]. The economic downturn has affected almost all types of industries in last few years and the wine industry is not an exception. Apart from the economic downturn there are several other factors that globally and consistently pose significant challenges to the wine industry such as droughts, bushfires, and increasing competitive pressure from other competitors. The wine supply chain is one of the longest supply chains in the world and managing these multiple supply chains across the globe can be an immense challenge. These factors often challenge the financial viability of many small and large wine producers. Furthermore, the competition has been intense with ‘new world wine producers’ who are known for their quality wines at competitive prices. In addition, changing geographies of wine production have been driven to a large extent by the rapid expansion of consumption demand in countries such as India and China. This has resulted in the development of wineries throughout the non-traditional wine production world [6] adding suppliers to the already competitive wine markets.

The wine industry relies on a constant flow of "raw material" inputs and any problem in raw material flow makes the matching of supply to demand very difficult. Some other factors such as winery location is also crucial, as unlike other manufacturing factors that do not depend on natural factors for their production, wine has certain restrictions as grapes can only be grown in certain locations [7]. Additionally, wine industry is one of the heavily regulated industries where regulations affect the whole wine supply chain process. Therefore, having a proper understanding of these regulations is crucial in designing a successful marketing and distribution system for the wine supply chain. Reference [7] points out that industry atomization across all the tiers of the wine supply chain has made the information sharing and overall collaboration very difficult. He further highlights that information sharing occurs in informal ways through personal bonds or relationship that organizations build with each other, which is true in case of wineries and grape growers. Reference [8] mentioned the fragmented nature of the wine industry where a plethora of parties participate in various activities at the winemaker or wine merchant level. Additionally, highly competitive environment contributes to unwillingness to share information between these parties. Reference [9] define three categories of operational coordination: Buyer-Vendor coordination, Production–Distribution coordination, and Inventory-Distribution coordination. Their research emphasized that with increasing competition firm's profit margin declines, so firms are forced to reduce their costs and simultaneously maintain their customer service excellence. One of the ways to achieve potential savings is to have a proper coordination among operational coordination categories, as these are crucial for firm's competitiveness. In wine supply chain, the complexity in information sharing poses problem in vendor-customer collaboration [7]. Therefore, wine firms are under intense pressure to make potential savings and at the same time look for ways to improve the coordination among the different supply chain players. Thus, these factors indicate that wine supply chain coordination is a challenging task.

A typical wine supply chain [8] is shown in Fig. 1 which consists of activities including grape growing, wine making, blending, bottling, packaging, distribution, retailing, and finally delivering to consumers. Furthermore, [10] describe the logistics of the wine supply chain to include six processes: Supply, Production and Bottling, Inventory Management, Warehousing, Transportation and Distribution, and Customer Response. Supply means all activities related to the purchase and management of suppliers; Production and Bottling involve all the activities related to the wine making process through to bottling and packaging; Inventory Management entails the activities of planning, inventory administration and moving; Warehousing activities start from product reception and picking to container loading; Transportation and Distribution involve activities of delivering the order to the customer; and Customer Response activities deal with the customer with

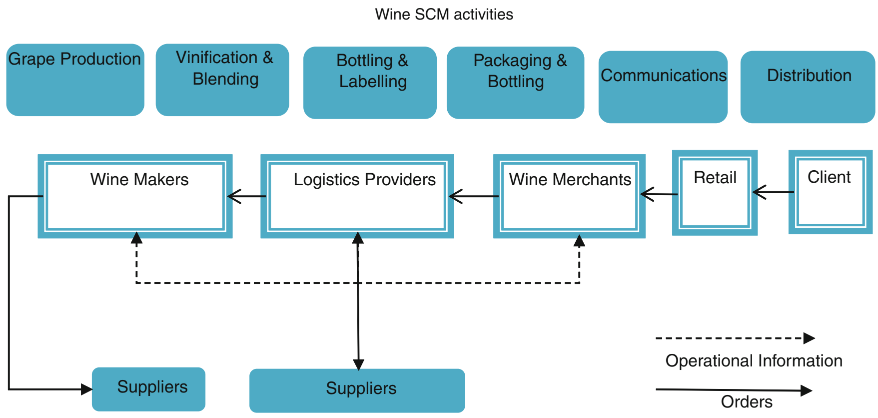


**Fig. 1** Wine supply chain

regard to customer services; order entry, order processing, follow up, etc. One of the challenges of the wine supply chain is that it inherits the characteristics of many agri supply chains [11]. The nature of the product forces the use of a mixed push and pull strategy and makes supply chain tasks even more challenging. For instance, to preserve the quality of products in the wine supply chain, expensive measures are needed such as cooling, controlling air conditions, or prevention of incidence of light even for the finished products. Successful SC integration is the key to keeping the costs down and achieving competitive advantage. Therefore, it is essential for wine companies to seek ways to establish good integration of the wine supply chain activities. This paper, therefore, proposes an intelligent multi-agent architecture framework for the wine supply chain coordination. The multi-agent architecture consists of a number of self-adaptive agents that cooperate among themselves to assist in various wine supply chain activities and thus improve the performance of the overall supply chain. The detailed tasks of these agents are discussed in the next section.

## 2 Intelligent Multi-Agent Framework

The agent based systems have gained popularity in recent years because of their capability to perform task independently and efficiently [12–14]. References [15] and [16] points out that these intelligent agents are programs that can perform a specific task on behalf of a user, reactively and/or pro-actively, independently or with little guidance. They also highlight that to accomplish these tasks agents should possess general characteristics like independent, learning, cooperation, reasoning and intelligence. Therefore, intelligent agent based system must be capable of working on its own, making decisions based on the past experiences and information available in the knowledge base; they must be able to continuously learn, i.e., must be self-adaptive; they must work together with other agents to improve the efficiency of the task; they must be able to take logical decisions to handle any task, and finally they must be also able to make smart decisions without any input from the external sources.

This research, therefore, proposes an intelligent reconfigurable multi-agent architecture framework for carrying out wine supply chain operations. The proposed framework has been adapted from the work of [17] that has been altered to suit the wine industry supply chain. A research on intelligent agent system architectures by [18] has proven that problems which are inherently distributed can be efficiently implemented in a multi-agent framework and thereby different distributed resources in the agile supply chain network are assumed to constitute a multi-agent architecture. Here the autonomous agents are able to self-organize or manipulate their activities and patterns, thereby obtain maximum benefit from abrupt and dynamic environment to achieve goals exceeding their individual skills. In order to convey self-organization properties in the system, the wine supply chain activities are considered to be performed whereby agents form a network of collaborative, yet autonomous, units modeled as interacting agents that proliferate, monitor, control, and organize all activities involved in a distributed, dynamic, and observable environment. In the upcoming sections, the multi-agent framework is explained in detailed.

## *2.1 Intelligent Multi-Agent Architecture Framework for Wine SCM*

The framework of the proposed architecture is shown in Fig. 2. This framework consists of ordering agent, planning agent, inventory agent, data mining agent, corporate memory agent, distribution agent, logistics service provider agent, winemaker assistant agent, merchant assistant agent, and learning agent. Every agent poses certain skills. These agents also have the ability to perceive their neighborhood. While perceiving their neighborhood they exchange their status among themselves. The status of the agent refers to whether agent is busy in some job or helping other agent. Based on this agents can make decision who will respond to a particular situation. The status of agent also decides the position of an agent to perform a task and forms the basis for achieving a cooperative task utilizing inter-agent communication. For example, when a task is found, only those agents are suited to perform the tasks that are in 'explore' state. As soon as a new task arrives, the centralized system (corporate memory agent) will contact the appropriate agents to know their status and then it will coordinate the activities according to the updated status of the agents.

The way these agents interact among themselves and their associated tasks are described in detail below:

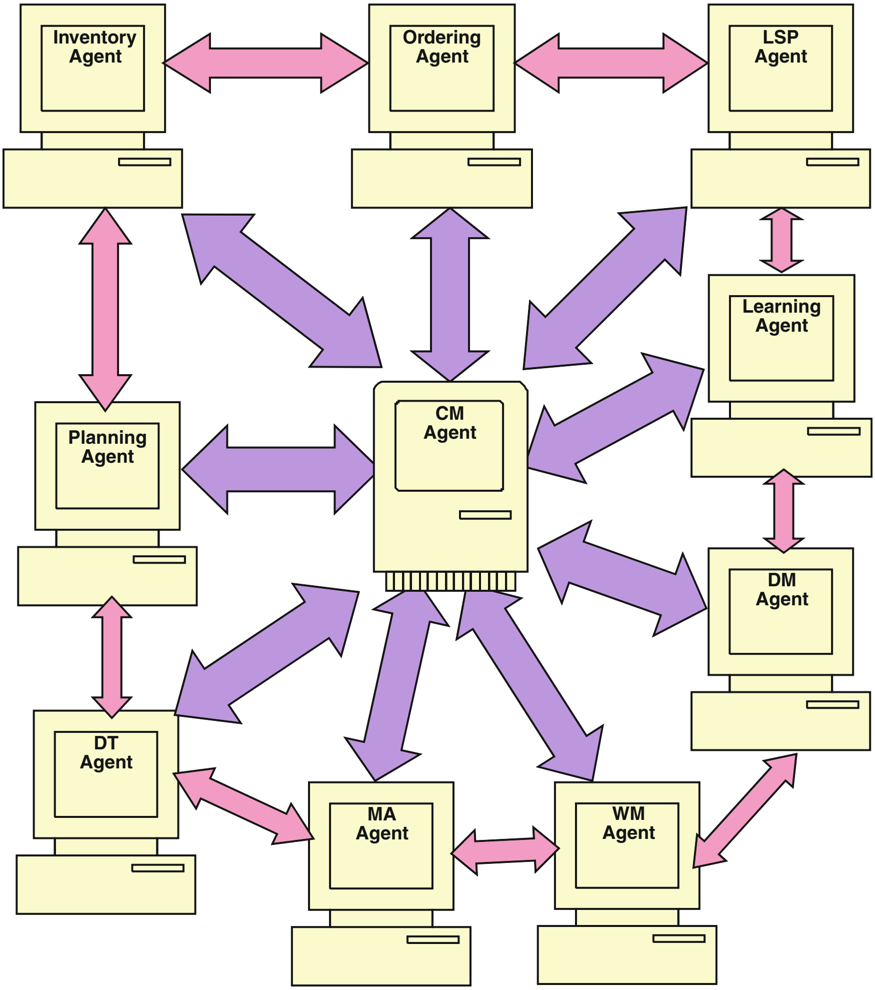


**Fig. 2** Multi-agent architecture framework

1. *Ordering Agent*:

This agent is responsible for taking orders from the customers or wine merchants. After receiving the orders, this agent gathers all the information related to completion of the order such as the quantity required, the wine types, delivery dates, logistics required, and packaging related information. According to the order, this agent then communicates with planning and the inventory agent to estimate the type and size of the order. Planning agent further provides information on the current batch of the order being processed at the vineyard and inventory agent provides estimate of the material available inside the vineyard. Once the order is finalized the ordering agent contacts the corporate memory agent to find possible available alternatives (in-plant or outsourced suppliers) where the order can be placed at the minimum cost. If more than one alternative is available then it checks the past records and accordingly assigns the order. This agent also takes into account the distance between the alternatives, logistics medium used, and the availability of the warehouse. If the outsourced unit/supplier is selected, then products are transferred by the logistics medium through the available warehouse. Therefore, every time the outsourced unit is selected, the agent evaluates not only the capacity and capability of the outsourced units but also takes into account the logistics medium and the warehouse availability. These considerations are also taken into account while transferring the products within the in-plant vinery. Also, whenever the ingredients are ordered, the logistics cost is considered by the ordering agent.

2. *Inventory Agent*:

The main task of the inventory agent is to check and keep the records of the available ingredients within the vinery. This agent also continuously exchange information with the planning and ordering agents. Furthermore, this agent also forecasts the required inventory level based on past experiences and by sharing information with suppliers thus following path of collaborative forecasting. After forecasting, this agent communicates with the ordering agent and selects appropriate suppliers to replace the orders. Additionally, the inventory agent also decides where and how much ingredients need to be stored while simultaneously minimizing the traveling and storage costs. Moreover, it also makes ingredients easily available to appropriate vinification and blending machines as per the requirement. This agent makes the use of either forecasting methods based on judgment such as, Delphi, Structured Analogies, Game Theory, and Expert Systems; or methods based on quantitative data such as Extrapolation, Quantitative analogies, Data mining, and Rule-Based Forecasting [19–22]. The decision regarding the use of best forecasting method is a tricky one as sometimes more than one method may be suitable. To overcome this problem the inventory agent chooses the best method by adopting a decision making methodology.

3. Planning *Agent*:

The main task of the planning agent is to decide where and how many bottles of the wine need to be produced. According to the capacity of the vinery, the available resources and the due dates, this agent decides whether the wine needs to be produced within the plant or in the outsourced units. The planning agent receives information regarding the availability of the resources as well as information on the status of the machines such as whether it is idle, in process, in breakdown condition or in maintenance state from the corporate memory agent. As soon as a new order arrives, this agent helps in re-planning. As soon as any problem is detected the agent communicates among themselves and seeks help. The help ontology used by the agents to communicate among themselves and the skill manipulation algorithm is described in detailed in the work of [19].

4. *Learning Agent*:

Intelligent agents are capable of self-learning from their daily operation. With the presence of continuous noise and variation in the system, it is almost impossible to detect and take preventive mechanism passively or without updating the knowledge base. Thus, the knowledge base is exposed to the dynamics of the stage discrepancy as well as the impact of the variation in market determiners over time. For this purpose, specific agent architecture is employed for symptom recognition of each stage as well as for the whole architecture. The learning agent learns through both online and offline learning mechanism. In online learning, data gathered through in-process stage is used. For example during the wine making process the data is gathered on the quality of the product, and tardiness and fault in the blending or bottling machines. This data will be used either in new adjacent planning or rescheduling. While in offline learning the information is collected from the data mining agent.

5. *Data Mining Agent*:

This agent analyzes the wine production process and order data. This agent further ranks the outsourcing partners, suppliers, and production machines according to their past performances. All the information collected by this agent is continuously shared with the corporate memory agent. The rankings assigned by this agent are also used to resolve the conflict of allocation in future if more than one alternative is available.

6. *Distribution Agent*:

This agent gathers information from the planning agent on the production units and accordingly assigns particular operation to appropriate machine, which can be either in-plant or outsourced partners. If the outsourced unit is selected then this agent passes all the information related to the order such as due date, type of wine, and quantity required to the outsourcing partner. This agent remains in continuous touch with the outsourced and in-plant vinery. If they fail to meet due dates then this agent instantly informs the planning agent. Planning agent then finds an alternative way to complete the order within the due date. This agent also remains in continuous contact with the learning agent.

7. *Corporate Memory Agent*:

This agent is the central hub of useful information. Therefore, it stores all the information related to the vinery such as available resources and outsourcing partners/suppliers. Further, this agent keeps information on the status of the products such as on which vinery they are being processed, their processing times, and the batch/order number. This agent also tracks information of the machines in vinery such as their maintenance condition, idle or in process stage, breakdown status etc. This agent also continuously communicates and learns with the learning agent. This agent coordinates with all the other agents such as planning, inventory, ordering agent, data mining agent, merchant, and winemaker assistant agent. This agent inherits the property of updating itself through both online and offline learning mechanisms. The offline and online learning of agents are discussed in detailed in the work of [19].

8. *Merchant Assistant Agent*:

Merchant assistant agent is mainly responsible for assisting the wine merchants in a number of operational tasks such as sales forecasts, blending specifications, bottling, labeling, packaging, and transfers these information's to the winemaker agent. This agent keeps data regarding the market trends and customer feedback. This agent caters the need of the merchants who have very strict specifications regarding the quality of the wine produced such as grape growing specification. The agent communicates these special requirements to the winemaker agents. Also this agent remains in continuous touch with the ordering, inventory, and planning agent.

9. *Winemaker Assistant Agent*:

This agent assists winemakers in handling a number of issues. This agent primarily assists the winemaker in keeping up to date information on the grape farming, vinification, and blending and bottling (sometimes) operations. It continuously exchanges information from the merchant assistant agent and processes any special request from the merchant. It remains in continuous touch with outsourcing partner agents, ordering agents, and planning agents.

10. *Logistics Service Provider Agent*:

Logistics service provider agent works closely with the distribution agent, merchant assistant, and winemaker assistant agent. This agent collects information from the distributor and passes this information to the supplier or winemaker. It is in constant touch with the inventory agent and checks every time if the order can be fulfilled from the existing stock before contacting the supplier or winemaker. This agent also handles the bottling, labeling, and packaging operations. The next section describes the workflow of multi-agent system.

## 3 Working Mechanism of the Proposed Intelligent Multi-Agent Framework

This section explains the execution process of the proposed intelligent multi-agent framework. The individual tasks of the various agents of the proposed framework have already been elaborated in the previous sections. After receiving orders, the ordering agent gathers all the information related to completion of the order such as the quantity required, the wine types, delivery dates, logistics required, and packaging related information. The agent then assigns the order to the best alternative based on a number of factors such as transportation time, costs involved, and delivery dates. The inventory agent checks and keeps the records of the available ingredients within the vinery. The planning agent then decides where and how many bottles of the wine are needed to be produced. Thus, according to the capacity of the vinery and other important considerations such as the due dates, this agent decides whether the wine needs to be produced within the plant or in the outsourced units. The distribution agent gathers information from the planning agent on the production units and accordingly assigns the appropriate operation either to in-plant or outsourced units. There is an agent dedicated to assist wine merchants, i.e., merchant assistant agent which assists the wine merchants in a number of operational tasks such as, sales forecasts, blending specifications, bottling, labeling, packaging, and transfers these information to the winemaker agent. Wine maker agent primarily assists the winemaker in keeping up to date information on the grape farming, vinification, and blending and bottling operations. Logistics service provider agent works closely with the distribution agent, merchant assistant, and winemaker assistant agent and collects information from the distributor and passes this information to the supplier or winemaker. These agents continuously exchange all the information with the corporate memory agent which acts as a knowledge hub and stores all relevant information that assists the agents in executing various tasks. There are also other agents that help these agents in successfully executing their tasks. Data mining agent analyzes the wine production process and order data and ranks the outsourcing partners, suppliers, and production machines according to their past performances thus assisting the ordering, planning, and distribution agents. Agents are capable of self-learning from their daily operation and learning agents help them through online and offline learning mechanism. All these agents extensively use the information from the knowledge base agent to execute their tasks. Thus, the use of multi-agent framework can facilitate better supply chain coordination and help the wine manufacturers to achieve supply chain efficiency.

## 4 Summary and Conclusions

The paper provides a brief overview of the wine supply chain and identifies some of the common problems that wine manufacturers are facing particularly highlighting the supply chain coordination problem. The emphasis of this research is to identify supply chain coordination as one of the major issues and propose a solution. Like any other manufacturing companies wine manufacturers and suppliers also struggle to establish proper coordination among the different supply chain members. To assist them, this paper proposes an intelligent multi-agent framework that consists of several independent decision making agents such as ordering agent, planning agent, distribution agents, wine merchant, and wine maker agent. All these agents continuously share information with each other and are able to independently execute their tasks. There is a central knowledge base termed as corporate memory agent that stores all the information of the agents and uses its past experience to assist agents in executing their tasks. The multi-agents can handle the supply chain coordination tasks more proficiently by working very closely with each other and executing their assigned tasks. Thus, using this multi-agent framework wine manufacturers and suppliers may handle their various supply chain related tasks more effectively. The corporate memory agent plays a crucial role in establishing this coordination among the agents. The paper, therefore, concludes by suggesting that the deployment of such an intelligent multi-agent framework can assist wine manufacturers to handle supply chain coordination issues more efficiently.

However, one of the limitations of this research is that the proposed framework is at a very early stage of development and needs thorough testing. Therefore, future research aims at testing this intelligent multi-agent framework using a simulated example. The research will also explore the use of evolutionary algorithms that can assist agents, particularly the ordering, planning, inventory, and distribution agents while making their respective decisions. Additionally, future research will aim at exploring the communication ontology that agents can use to communicate more efficiently.

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## References

1. Kanda AA, Deshmukh SG (2004) Supply chain coordination issues: an SAP-LAP framework. Asia Pacific J Mark Logistics 19(3):240–264
2. Simatupang TM, Sandroto IV, Hari Lubis HB (2004) Supply chain coordination in a fashion firm. Supply Chain Manag Int J 9(3):256–268
3. Simatupang TM, Sridharan R (2008) Design for supply chain collaboration. Bus Process Manag J 14(3):401–418
4. Soroor J, Tarokh MJ, Shemshadi A (2009) Theoretical and practical study of supply chain coordination. J Bus Ind Mark 24(2):131–142
5. Pullman ME, Maloni MJ, Dillard J (2012) Sustainability practices in food supply chains: how is wine different? J Wine Res 21(1):35–56
6. Banks G, Overton J (2010) Old world, new world, third world? Reconceptualising the worlds of wine. J Wine Res 21(1):57–75
7. Adamo C (1997) A global perspective of the wine supply chain—the case of argentinean wineries and the US market. M. Sc. Thesis, MIT, USA
8. Chandes J, Estampe D (2003) Logistics performance of actors in the wine supply chain. Supply Chain Forum Int J 4(1):12–27
9. Chandes J, Estampe D (2003) Logistics performance of actors in the wine supply chain. Supply Chain Forum Int J 4(1):12–27
10. Garcia FA, Marchetta MG, Camargo M, Morel L (2012) A framework for measuring logistics performance in the wine industry. Int J Prod Econ 135(1):284–298

11. Gigler JK, Hendrix EMT, Heesen RA, Hazelkamp VGW, Meerdink G (2002) On optimisation of agri chains by dynamic programming. Eur J Oper Res 139(3):613–625
12. Gjerdrum J, Shah N, Papageorgiou LG (2001) A combined optimization and agent-based approach to supply chain modelling and performance assessment. Prod Plann Control Manag Oper 12(1):81–88
13. Lee JH, Kim CO (2008) Multi-agent systems applications in manufacturing systems and supply chain management: a review paper. Int J Prod Res 46(1):233–265
14. Kumar V, Mishra N (2011) A multi-agent self correcting architecture for distributed manufacturing supply chain. IEEE Syst J 5(1):6–15
15. Kalakota R, Whinston AB The frontiers of electronic commerce, 1st edn. Addison-Wesley Publishing Company
16. Bui T, Lee J (1999) An agent-based framework for building decision support systems. Decis Support Syst 25(3):225–237
17. Mishra N, Kumar V, Chan FTS (2012) A multi-agent architecture for reverse logistics in a green supply chain. Int J Prod Res 50(9):2396–2406
18. Ferber J (1999) Multi-agent system: an introduction to distributed artificial intelligence. Harlow: Addison Wesley Longman, Boston
19. Mishra N, Kumar V, Chan FTS (2010) A multi-agent framework for agile outsourced supply chai, Enterprise networks and logistics for agile manufacturing. Springer, London, pp 207–223
20. Green KC, Armstrong JS (2007) Structured analogies for forecasting. Int J Forecast 23(3):365–376
21. Makridakis S, Wheelwright SC, Hyndman RJ (1998) Forecasting: methods and applications, 3rd edn. Wiley, New York
22. Rowe G, Wright G (2001) Expert opinions in forecasting: the role of the delphi technique. In: Armstrong JS (ed) Principles of forecasting. Kluwer, Norwell, pp 125–144

# Green Procurement in Trading Sector of Hong Kong

**Janiz H. Y. Heung, T. N. Wong and L. H. Lee**

**Abstract** Hong Kong is a strategic procurement center and logistics center in Asia. Majority of Hong Kong's trading companies' involvement in the supply chain is to bid orders from global distributors and retailers, and then search for appropriate contract manufacturers to produce the goods. In recent years, there has been an increasing concern for sustainability of products, processes, and services. To increase its competitiveness, it is an important issue for trading companies to take green supply chain management (GSCM) initiatives to improve its long-term development capabilities. This paper is on the establishment of a green procurement model for trading companies. The model integrates environmental and sustainability concerns into the procurement process. In trading firms, purchasing is the main SCM activity. It is therefore the focus of this paper to take environmental and corporate social responsibility (CSR) requirements into account for product and supplier evaluation and selection. The procurement model developed by Analytical Hierarchy Process (AHP) comprises an approach to rank and select products and suppliers with the incorporation of sustainability requirements. The proposed system aims to support long-term supplier continuous assessment for further performance monitoring and evaluation, and also help on reviewing supplier management strategies and green supply management.

**Keywords** Green procurement · Trading industry · Corporate social responsibility · Environmental responsibility

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## 1 Introduction

Hong Kong is a major strategic procurement center and logistics center in Asia. According to the data provided by the Hong Kong Trade Development Council (HKTDC) [1], as at December 2011, there were 102,273 import and export trading firms. Majority of these trading companies are small in size, with only around 6 employees on average. Majority of Hong Kong's trading companies' involvement in the supply chain is to bid orders from global distributors and retailers, and then search for appropriate contract manufacturers to produce the goods. That is, their main business model involves sourcing products from manufacturers and suppliers in Mainland China and South East Asia, for shipping to distributors and retailers in North America, Europe, and Japan. Typically, Hong Kong's trading firms can be categorized into three groups: (1) "Left hand-right hand traders" involving straightforward sourcing and reselling operations without any significant added value; (2) Traders with some value added services; and (3) traders with sophisticated value-added services [1]. Amid today's globalized business scenario, there is a growing trend for overseas buyers to deal directly with manufacturers and supplies in Mainland China, without the intermediation of Hong Kong traders. Facing this challenge, Hong Kong traders have to enhance their sourcing and selection of supplies and services, and to provide more value-added services.

Supplier selection is an important activity in the procurement function. In supply chain management (SCM), any purchasing decision made will ultimately affect many other aspects in the company and the supply chain. The topic of supplier selection and evaluation has attracted much research effort due to the increasing complexity of the global supply chain and large variations of supplier selection criteria. As revealed in the survey article by Ware et al. [2], more than 150 refereed articles on supplier selection have been published in leading and reputed journals in the last two decades. In general, price, lead time, quality, etc. are major criteria for supplier selection and evaluation. In recent years, there has been an increasing concern for sustainability of products, processes, and services. Governments and international organizations have issued guidelines and laws, with attempt to reduce and control greenhouse emissions, energy consumption, and environmental pollutions, etc. Besides, enterprises are under tremendous pressure to comply with corporate social responsibility (CSR) requirements and to integrate environmental and social concerns in their products, services, and operations. In consideration of the environmental concerns, companies worldwide have begun to adopt green supply chain management (GSCM) practices. Many global organizations have released their own environmental reports or sustainability reports regularly, highlighting their green strategy in different aspects including manufacturing and procurement. They also educate and urge their suppliers and trading partners from different tiers to implement green strategy to ensure their sustainable business runs. To maintain the business edge, Hong Kong traders have to take green supply chain management (GSCM) initiatives to fulfill the demand of sustainability responsibilities in today's globalized business environment.

This paper is on the establishment of a green procurement model for trading companies. The model integrates environmental and sustainability concerns into the procurement process. The focus of this paper is to take environmental and corporate social responsibility (CSR) requirements into account for product and supplier evaluation and selection. The procurement model developed by Analytical Hierarchy Process (AHP) comprises an approach to rank and select products and suppliers with the incorporation of sustainability requirements.

## 2 Literature Review

### *2.1 General Criteria*

Dickson [3] was the first to carry out systematic study on supplier selection criteria. In his pioneering work, a survey on important factors for vendor selection was taken by purchasing agents and managers of 273 of US companies. In the survey report [3] published in 1966, 23 vendor selection criteria were identified. Among these 23 criteria, price was only ranked at the 6th place. Product quality was considered to be the most important factor, and it was followed by on-time delivery, performance history of supplier, warranties and claimed policies, and so on. In their follow-up study, Weber et al. [4] reviewed 74 articles published from 1966 to 1990. Just-In-Time (JIT) components such as quality, delivery, net price, geographical location, and production facilities and capacity were found to be the most reviewed criteria. Rankings of Dickson's 23 criteria had changed. Price, ranked at the 6th place in Dickson's 1966 study, was ranked as the most important factor. The ranks for delivery and quality were the 2nd and 3rd places, respectively. Zhang et al. [5] attempted to study the changes of supplier selection criteria from 1991 to 2003. The results in Dickson [3] and Weber et al. [4] were compared to 49 relevant publications from 1991 to 2003. It identified that net price, quality, and delivery were recognized as the most important supplier selection criteria.

It can be seen that price, quality, and service are always the key purchasing factors, for most industry, even though the criteria of supplier evaluation vary greatly across different periods of time and environments. Indeed, in current market, broader consideration and demand from suppliers should be taken place.

Typically, the selection of suppliers is usually viewed as a multi-criteria decision making (MCDM) problem as so many criteria have been identified. Tremendous MCDM solution approaches have been proposed and attempted in supplier selection and evaluation [6–8]. For instance, analytic hierarchy process (AHP) based methods, TOPSIS, fuzzy set theory, etc.

## 2.2 Environmental and Corporate Social Responsibility Factors (Green Criteria)

Past studies of supplier selection criteria mostly included evaluation criteria focusing on both product performance and suppliers behaviors. It has later started to include in environmental concern and social concern under the introduction of sustainability, yet it is still rather limited even though many research studies over the years have shown the significant and positive relationship between corporate social performance and profitability [9–11]. When viewing the situation globally, green procurement has been widely adopted in European countries, UK, and USA, across various industries and different company sizes. Many International regulations have also been set up like WEEE, EuP, RoHS, ELV, REACH, and SA8000 which confine companies to follow.

Noci [12] proposed three stages of green supplier evaluation: (1) acknowledge related stipulations of environmental protection regulations; (2) acknowledge expected contributions of varied suppliers in terms of each objective; (3) formulate a final supplier evaluation process. The studied also suggested four major evaluation criteria for proactive green strategy: green competence, current environmental efficiency, suppliers' green images, and net life cycle cost.

As mentioned in Goffin et al. [13], manufacturers usually emphasized on price, quality, and delivery in supplier section. However, in the global competitive environment, the requirements of supplier evaluation have become more extensive, technical expertise, financial capability, after-sale service, and strategic consideration should also be considered. They also highlighted that manufacturers would inevitably take account of environment protection related regulation in supplier evaluation to meet international market demand under execution of some international environment protection decrees.

A number of publications have been devoted to the inclusion of environmental and social CSR criteria for supplier selection. For instance, Humphreys et al. [14] identified seven environmental categories; Lee et al. [15] identified six major criteria for selecting green supplier in high-tech industry; Awasthi et al. [16] proposed twelve environmental criteria; Bai and Sarkis [17] included all three categories of economic, environmental, and social issues in their study; Kuo et al. [18] identified six major criteria as quality, cost, delivery, service, environment, and corporate social responsibility (CSR); Tseng et al. [19] proposed 16 criteria, comprising environmental as well as conventional supplier selection considerations; Baskaran et al. [20] proposed criteria for social responsibility; Shaw et al. [21] proposed an integrated model to select supplier by criteria of cost, quality rejection percentage, late delivery percentage and demand, with addition environmental constraint of greenhouse gas emission.

When looking into nowadays business market, many international enterprises have taken a leading role to incorporate green policies into their procurement strategy, and engaged their supply chain partners, especially suppliers in different tiers to take the green policies into practice. So it can be seen that taking green

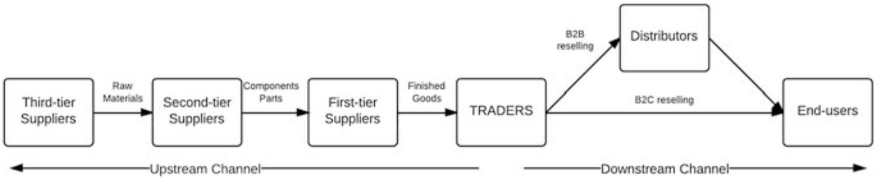


**Fig. 1** Supply chain model involving traders

strategy of both environmental and social consideration in supplier section is a way to sustain the business and market competiveness.

## 3 Supplier Selection for Local Trading Industry

Figure 1 depicts the supply chain model involving a trading company. Traders actually work like a middleman with strategic role to map appropriate suppliers with potential customers. Purchasing activities are the major operations in the trading industry, trading firms have to pay more attention to strategic purchasing and supplier selection to facilitate business runs. However, due to resources constraints and low bargaining and market power, strategic planning and purchasing are not practised in majority of the local traders. When selecting suppliers, they tend to rely on a few suppliers and adopt the “direct appointment” approach. To avoid uncertainty and extra workload, these small local procurement offices tend to buy from a small pool of suppliers. Supplier selection is usually based on lower price bidding to gain the price advantages and maximize the profit per unit item, due to a short-sighted and non-strategic behavior under resources constraint [22, 23].

In consideration of the establishment of a sustainable supply chain, the concept of triple bottom line (TBL) of business sustainability [24] is adopted in the establishment of supplier selection criteria for trading companies. Based on the TBL concept of sustainability, the supplier selection criteria for a sustainable supply chain should comprise issues with regard to corporate social responsibility (CSR) and environment responsibility (ER), in addition to the economic value.

A preliminary of supplier selection criteria with the incorporation of CSR and ER were suggested in a previous study [25]. The list was constructed through two elements. First, a literature review was carried out to collect supplier selection criteria from academic publications. Subsequently, interviews were conducted with purchasing professionals to consolidate the relevant set of selection criteria. In the literature review part, relevant articles from 1990 to 2011 were reviewed to compare with the criteria list first defined by Dickson [3]. The second part involved interviews with purchasing managers and representatives to identify the relevance of the various selection criteria.

In this paper, the preliminary set of selection criteria from our previous study [25] is used as a reference basis, literature review, and a questionnaire survey are being conducted to identify the unique and special requirements of the local trading industry. The set of decision criteria and indicators comprises qualitative and quantitative issues.

Quantitative variables are measured in numerical values and qualitative criteria have to be expressed in linguistic descriptions.

## *3.1 General Criteria*

Regarding supplier selection requirements, the case for traders is different from other buying companies such as manufacturers, due to its unique role and market position. Researchers have categorized the selection criteria in view of traders' perspective of their expected benefits from suppliers in two aspects, that is, the monetary or financial and the nonmonetary or differentiation benefits [26–28].

To establish the set of supplier selection criteria for traders, it should be first to understand the different approaches and considerations from other purchasers like manufacturing and consumers. The criteria should reflect their unique role of their role and market positions. In general, these supplier selection criteria have to be used to distinguish suppliers in terms of performance. So apart from the general self-benefits, it is more important for traders to have an overall review on suppliers' performance in the evaluation list.

In addition, for better understanding of the appropriate factors of supplier evaluation, local traders have to identify the external business environment to explore their market situation. The analysis can be represented by Michael Porter's five competitive factors [29, 30] as illustrated in the Fig. 2. The approach helps to understand the market details and firm performance, relationship with its related parties in the industry, as well as key factors affecting performance in vertical trading relationships and horizontal competitive relationships. The tool is effective in assisting the development of a set of supplier evaluation requirements and selection criteria. Throughout the analysis, traders can have deeper view on their needs and how they can collaborate with suppliers to increase market competiveness and strengthen their standpoint. Besides, it also provides a useful strategic framework for inclusion of the other two goals in a triple bottom line, that is, to increase social services and improving global resilience or ecology, by understanding others parties' wills or action plans. An individual company's performance represents the effectiveness of its business strategy, while the performance measure is directly related and supported by the supplier selection criteria.

It can be clearly seen that local traders are facing severe competition from worldwide distributions and also suppliers. Also, they face strong pressure from their buyers and sellers as an intermediate. By understanding on market influence, responsive strategy should be derived to strive for survival in market, and hence

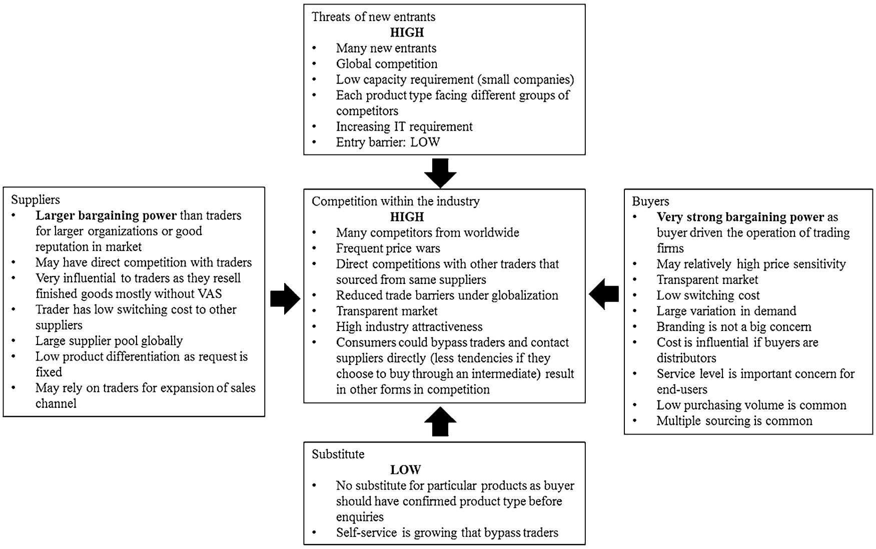


**Fig. 2** Michael porter's five force of trading industry in Hong Kong

the key factors on selecting appreciate suppliers, which can be viewed as criteria group. Detailed analysis is shown in Table 1.

## 3.2 *Green Criteria*

Usually manufactures will develop environmental checklist on green production and green process like waste management, pollution management, greenhouse gas emission, Ozone depleting substances, and hazardous material. Such approach may not be applicable for traders as each product type has variations, and it is difficult to collect appropriate data and measurements from all upstream suppliers within different tiers of the supply chain. Instead, they should focus on general green management practices like monitoring the overall management and practice and thus to filter non-green components to protect and strengthen their sales to customers. Traders should focus on "environmental management of competencies" and "green images of suppliers" with the aim to collaborate with green partners on evaluating the environment issue.

For the environment aspect, criteria should be focused on maintaining its competencies while building a position reputation. Certificate, information disclosure of environmental record, and different tier supplier environmental evaluation are declared as the easiest access and the most important environmental criteria by Handfield et al. [31]. These three items are also important for traders to evaluate their suppliers, especially the ability to fulfill consumers' needs and

**Table 1** Establishment of criteria categories from external market analysis

| Market influence | Responsive strategy | Factors/criteria group |
|---|---|---|
| Keen competition | Relationship development with suppliers and seek for protection scheme | Relationship |
| Worldwide market | Delivery is an important concern on cost and time | Suppliers' service commitment |
| Price competition | Cost concern and discount offered by suppliers | Profitability |
| Large market potential | Building positive reputation (brand building) in the market | Quality of both product and service (i.e., suppliers' service commitment; suppliers reputation on market and capabilities); green strategy |
| Higher request on customer service | Focus heavily on competitive differential benefit and seek for more supports from suppliers | Suppliers' service commitment |
| Reactive role that driven by customers' request, especially on new technology products | Co-operate with suppliers who have strong market sense and more updated technology or well R&D facilities | Review suppliers overall capability; information sharing and receive technical support from suppliers |
| Varies government laws and import regulations | Purchase from reliable and certificated suppliers and ensure related documentation and supports | Suppliers' management and organization |

ensure each component part on the final product satisfies international green requirements. Other important concerns are environmental management system, packaging, and reverse logistics programme. These criteria reinforce suppliers implementing complete environmental scheme in its management policies throughout the complete life cycle. More importantly, they should have assessed their suppliers in environment aspects. The approach of taking this concern is to ensure that the green strategies adopted by suppliers are in compliance with international approved standard. This helps to minimize the risk when doing the external exporting, and also the risk for complaints on non-green products. Besides, it serves to proactively monitor the continuous improvement on environmental conscious by the suppliers, as well as to provide consumers a positive image for brand building.

For the social aspect, Lindgreen et al. [32] suggested that under CSR policies, enterprises may require suppliers to document their raw materials, components, or services meet environmental and ethical standards. With instruction of Global Compact Principle, supplier code of conduct should include two categories of CSR factors, first is human rights and labor, and second anti-corruptions. So for identifying appropriate evaluation criteria, a general list of CSR criteria should evaluate the certificate and information disclosure by suppliers, to ensure adoption of the appropriate policies, as well as their external anti-corruption strategy and action, and internal working environment and employee treatment.

In addition, it is important for both traders and suppliers to have a complete picture of green practice in each supply chain activity, and reinforce their partners to take the green initiative in both environment and asocial aspects, to ensure that green supply chain management have practically performed in different tiers along the whole upstream of the supply chain, so as to reach the ultimate goal of sustainability.

### *3.3 Compiling Criteria List*

A preliminary set of criteria and key performance index (KPI) can be set up according to the above analysis. It is initiated by the traders' perspective in four areas, profitability, suppliers' service, relationship development, and (suppliers itself) management and organization, as shown in Table 2. Traditionally, profitability and suppliers' service are the important criteria as they directly influence the traders' sales performance and the success of a sales order. They are then followed by relationship or co-operation, in consideration of the long-term strategy that strengthens the future business run and business partnership to sustain a supply chain. The relationship development is also closely related to reputation building [33]. Finally, evaluation takes place on suppliers' management and organization—the overall capability, including the ER and CSR criteria, will be considered. Overall capability of suppliers have to be evaluated for future sales planning like technology advancement and expansion of product range, also the ability for the potential growth of business. Green strategy is also included for an all-rounder consideration, as well as risk avoidance strategy.

For different product categories, the KPIs will be different, as some criteria are product-specific or industry-specific. For example, for high-end products with small supplier pools, price may not be a concern but the customization, product specification, and performance will be more significant requirements. But for standard and popular products, price may be a much higher concern and outweighs other performance indices. So the criteria framework is actually similar for most the items, yet the detailed elaboration and indicators have to be varied.

## 4 Analytical Hierarchy Process

In the preliminary study, AHP is adopted for establishing the supplier selection model. AHP is a simple and powerful tool that with proven practicability and effectiveness in MCDM problem. It shows a common usage in supplier selection problem over the decades, since its development by Saaty in 1980 [34]. It provides

**Table 2** Criteria list for trading industry in Hong Kong

| Category (factor) | Criteria | Key performance index (KPI) |
|---|---|---|
| Profitability | Cost (direct and indirect) | Direct cost, that is, product cost that measured in unit price and different form of discount on product price; indirect cost are those logistics cost including shipping cost and transaction cost, as well as treatment on payment like credit terms |
| Suppliers' service commitment | Delivery | Speedy and on-time delivery; shipping time (duration) and variation |
| | Quality of product | Specification conformance; specification flexibility for customization; quality advantages and value added; certification (e.g., ISO 9000); warranty and claim policies; packaging |
| | Service | Pre-purchase stage: attitude, supportiveness and responsiveness, communication system; |
| | | Purchasing stage: problem solving/conflict ability; Post-purchase stage: after-sales services |
| | Performance history | Previous record/experience; reputation |
| Relationship/Co-operation | Distribution strategy | Protection scheme; numbers and location of resellers and fair treatment to resellers; direct competition |
| | Reciprocal arrangement | Attitude and desire for business; contract agreement |
| Management and organization | Overall capability | Financial status; R&D; technology; facility; range of product |
| | ER | Certifications (e.g., ISO 14000, WEEE, EuP, RoHS, ELV, REACH); different tier suppliers evaluation; information disclosure; environmental management system (EMS); packaging/reverse logistics |
| | CSR | Certifications (e.g., ISO 18000 & ISO 26000); information disclosure; (internal) work environment and employee treatment; (external) anti-corruption |

a framework to formulate the evaluation of tradeoffs between the conflicting selections criteria and helps to rank suppliers based on the relative importance of the criteria and the suitability of the suppliers. It is popular that it provides a practical and useful solution methodology for solving the supplier selection problem, which involves both qualitative and quantitative factors, but still requires a logical and rational control of decisions. To develop the AHP model, criteria for supplier selection should be first to define as well as the sub-criteria at each level of the hierarchy. Criteria can then be evaluated with pairwise comparison and evaluated based on goal. Since the list of criteria comprises qualitative and quantitative issues. The fuzzy set approach is to be applied to convert linguistic-based qualitative variables into numerals. That is, the qualitative variables will first be fuzzified as triangular fuzzy numbers. The decision model for local traders by the criteria developed in previous part is illustrated in Fig. 3.

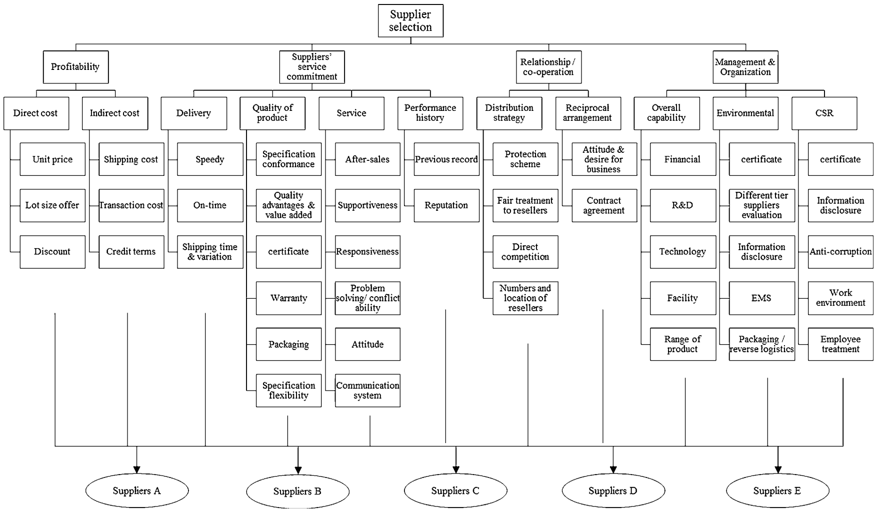


**Fig. 3** Decision hierarchy

After building the model, solution will be generated with the following procedures: (1) determine the priority weight of each criterion in each level, and prioritize the order of criteria or sub criteria; (2) determine the priority weight for alternatives for measuring supplier performance; (3) based on the global priority, weights of each alternative can be evaluated and summarized; and (4) finally suppliers will be prioritized by giving a ranking. Hence a final supplier can be chosen with alternatives can be recorded for further considerations like product allocation and multiple sourcing.

## 5 Concluding Remark

This paper has identified the requirements of green procurement strategy in trading industry. Taking environmental and corporate social responsibility (CSR) requirements into account for product and supplier evaluation and selection, a preliminary list of supplier selection criteria has been established for trading companies. An AHP-based MCDM model can then be used to rank and select products and suppliers with the incorporation of sustainability requirements. The proposed system aims to support long-term supplier continuous assessment for further performance monitoring and evaluation, and also help on reviewing supplier management strategies and green supply management.

## References


1. http://hong-kong-economy-research.hktdc.com/business-news/article/Hong-Kong-Industry-Profiles/Import-and-Export-Trade-Industry-in-Hong-Kong/hkip/en/1/1X000000/1X006NJK.htm. Accessed 9 May 2012
2. Ware NR, Singh SP, Banwet DK (2012) Supplier selection problem: a state-of-the-art review. Manag Sci Lett 2(5):1465–1490
3. Dickson GW (1966) An analysis of vendor selection systems and decisions. J Purchasing 2(1):5–17
4. Weber CA, Current JR, Benton WC (1991) Vendor selection criteria and methods. Eur J Oper Res 50(1):2–18
5. Zhang Z, Lei J, Cao N, To K, Ng K (2003) Evolution of supplier selection criteria and methods. Eur J Oper Res 4(1):335–342
6. Aissaoui N, Haouari M, Hassini E (2007) Supplier selection and order lot sizing modeling: a review. Comput Oper Res 34(12):3516–3540
7. Wallenius J, Dyer JS, Fishburn PC, Steuer RE, Zionts S, Deb K (2008) Multiple criteria decision making, multiattribute utility theory: Recent accomplishments and what lies ahead. Manag Sci 54(7):1336–1349
8. Ho W, Xu X, Dey PK (2010) Multi-criteria decision making approaches for supplier evaluation and selection: a literature review. Eur J Oper Res 202(1):16–24
9. Waddock SE, Graves SB (1997) The corporate social performance-financial performance link. Strateg Manag J 18(4):303–319
10. Margolis J, Walsh J (2001) People and profits? The search for a link between a company's social and financial performance. Lawrence Erlbaum Associates, London
11. Ciliberti F, Pontrandolfo P, Scozzi B (2008) Investigating corporate social responsibility in supply chains: a SME perspective. J Cleaner Prod 16(15):1579–1588
12. Noci G (1997) Designing green vendor rating systems for the assessment of a supplier's environmental performance. Eur J Purchasing Supply Manag 3(2):103–114
13. Goffin K, Szwejczewski M, New C (1997) Managing suppliers: when fewer can mean more. Int J Phys Distrib Logistics Manag 27(7):422–436
14. Humphreys PK, Wong YK, Chan FTS (2003) Integrating environmental criteria into the supplier selection process. J Mater Process Technol 138(1):349–356
15. Lee AHI, Kang HY, Hsu CF, Hung HC (2009) A green supplier selection model for high-tech industry. Expert Syst Appl 36:7917–7927
16. Awasthi A, Chauhan SS, Goyal S (2010) A fuzzy multicriteria approach for evaluating environmental performance of suppliers. Int J Prod Econ 126(2):370–378
17. Bai C, Sarkis J (2010) Green supplier development: analytical evaluation using rough set theory. J Cleaner Prod 18:1200–1210
18. Kuo RJ, Wang YC, Tien FC (2010) Integration of artificial neural network and MADA methods for green supplier selection. J Cleaner Prod 18(12):1161–1170
19. Tseng M-L, Lin R-J, Chiu ASF (2011) Green supply chain management with linguistic preferences and incomplete information. Appl Soft Comput 11(8):4894–4903
20. Baskaran V, Nachiappan S, Rahman S (2012) Indian textile suppliers' sustainability evaluation using the grey approach. Int J Prod Econ 135(2):647–658
21. Shaw K, Shankar R, Yadav SS, Thakur LS (2012) Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain. Expert Syst Appl 39(9):8182–8192
22. Pressey AD, Winklhofer HM, Tzokas NX (2009) Purchasing practices in small- to medium-sized enterprises: an examination of strategic purchasing adoption, supplier evaluation and supplier capabilities. J Purchasing Supply Manag 15(4):214–226
23. Morrissey Bill, Pittaway Luke (2004) A study of procurement behaviour in small firms. J Small Bus Enterp Dev 11(2):254–262
24. Sustainability—From Principle To Practice (2008) Goethe-Institut, March 2008

25. Wong TN, Lee LH, Sun Z (2012) CSR and environmental criteria in supplier selection. In: Proceedings of the conference of IFPR-APR 2012 and the APIEMS conference 2012, Phuket, Thailand, 2–5 Dec 2012, pp 74–84
26. Ghosh AK, Joseph WB, Gardner JT, Thach SV (2004) Understanding industrial distributors' expectations of benefits from relationships with suppliers. J Bus Ind Mark 19(7):433–443
27. Bolton RN, Myers MB (2003) Price-based global market segmentation for services. J Mark 67(3):108–128
28. Curry DJ, Riesz PC (1988) Prices and price/quality relationships: a longitudinal analysis. J Mark 52(1):36–51
29. Porter ME (1980) Competitive strategy: techniques for analyzing industries and competitors. Free Press, New York
30. http://www.markintell.com/porters-five-forces-analysis. Accessed 6 Jan 2013
31. Handfield R, Walton SV, Sroufe R, Melnyk SA (2002) Applying environmental criteria to supplier assessment: a study in the application of the analytical hierarchy process. Eur J Oper Res 41(1):70–87
32. Lindgreen A, Swaen V, Johnston WJ (2008) Corporate social responsibility: an empirical investigation of U.S. organizations. J Bus Ethics 99(1):73–91 Springer
33. Mudambi S, Aggarwal R (2003) Industrial distributors: can they survive in the new economy? Ind Mark Manag 32(4):317–325
34. Saaty T (1980) The analytic hierarchy process. McGraw-Hill, New York

# Resource Allocation in the Paced Assembly of Customer Specific Goods

**Kirsten Tracht and Lars Funke**

**Abstract** The production of large-dimensioned, customer specific goods like machinery, investment goods, and special vehicles is a demanding challenge because of the integration of numerous customer specific features and the need for short delivery times. In addition, complex assembly operations require highly skilled workers to ensure the flexibility of production, which is needed to cope with varying workloads and assembly procedures. The presented paper introduces a concept for planning and controlling the production of those products, with a focus on personal allocation and assembly order development. After giving a brief problem statement, which highlights the major aspects to be considered, an overview of the literature, which copes with comparable problems, is given. The following sections introduce three means of control used in the concept and present a computational investigation of these under varying settings concerning hindering effects in assembly operations. The paper is closed by a discussion of the achieved results and a brief summary.

## 1 Introduction

### *1.1 Problem Statement*

Manufacturers of large-dimensioned, customer specific products as machinery, investment goods, and special vehicles, as used in mining or forestry for example, must ensure the integration of numerous customer specific features to achieve competitiveness on present and future markets. This makes assembly process

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control and process planning a challenging task. Because products have to be manufactured as demanded by customers to fit the requirements of their future usage, multiple variants of products and varying workloads in the assembly line occur. This causes overstraining of capacities at assembly stations. While these drawbacks of a production of customer specific goods are overcome in other industries by arranging different variants with unequal workload in a favorable order, these techniques are not suitable for the production of customer specific large-dimensioned products, which has to cope with low production rates, small lot sizes and long, stochastically varying processing times. Task duration times of several minutes to hours are common and influenced by the skill of workers assigned to the task, the intensity of resource usage and resource availability among others. In addition, time restrictions are strict to avoid capital lockup by the produced goods and delivery dates are contractually committed setting narrow limits for the production. Under these circumstances, flexibility of processes is needed to cope with the complexity of assembly operations and to ensure an efficient production. Therefore, manpower is still a major production factor in companies, which have to deal with these issues. Predefined production plans are not very detailed and set the surrounding factors under which production control is executed. Production control is commonly done by experienced workers in these production areas, but being faced with a rising variety of products and features it becomes more difficult to stay on top of things and to give advice to production workers.

To enhance efficiency of production there is a trend to reorganize assembly areas in order to establish assembly lines for final assembly. While the usage of assembly lines is widely applied in manufacturing of consumer goods, the production of complex and bulky products in assembly lines was uncommon in past decades. The reorganization conducted now offers new perspectives in terms of synchronized material supply and shortening of cycle times, whereas new requirements for methods and procedures of production planning and control arise. In the following a concept of such a procedure is introduced.

## *1.2 Course of Investigation*

In the following a brief overview of methods and concepts dealing with comparable problems is given. The methods are described and compared to the special demands in assembly processes of bulky, customer specific goods with low production rates. The succeeding section gives an introduction to the developed approach for planning and control in production of those goods. The stimuli generation concepts mentioned in the previous are introduced and discussed finally. To allow the investigation of concepts and discussion of achieved results, evaluation criteria for a separate order investigation and the simulation model settings are defined. The section is closed by the discussion of stimuli generation concepts and a comparison of these. The conclusion summarizes the results and shows prospects of future research.

## 2 Literature Review

Concepts for allocation of workforce concern mainly applications besides manufacturing areas as scheduling in transportation, healthcare, and emergency systems [1]. Workforce in manufacturing areas is thought of as part of the production unit in form of the production unit's capacity. To avoid overstraining of this capacity at assembly line stations several concepts have been developed in automobile industry. These concepts can be sorted into three classes [2].

The concept of level scheduling was invented as part of the Toyota production system and is one of the basic requirements for the usage of a canton system in production. The objective of the concept is to achieve an equal distribution of material demand of production processes by bringing the goods to be produced into a favorable order at the final production unit. By doing so an overstraining of capacity of production units, which deliver to the last one, can be avoided [3]. Basing on Toyota's concept of level scheduling, several further concepts have been developed. Reference [4] gives an overview above existing procedures.

While the level scheduling focuses on an equal demand of material of the production units, car sequencing concepts aim for an arrangement of production orders of a sequence that minimizes production time variations at the assembly stations of a line. For this purpose production rules are used, which are based on technical product characteristics to avoid unfavorable production orders in terms of capacity restrictions. Orders, which include several comparable variants with time intensive tasks in a row, lead to an overstraining of capacity at assembly stations and need to be avoided therefore. Taking several rules into account, a production sequence is chosen, which contravenes as few rules as possible [5].

Comparable to the car sequencing, the objective of the mixed-model sequencing is the definition of a production order, which is favorable with respect to the minimization of time capacity overstress. The sequencing problem is related to the assembly line balancing, which addresses the allocation of assembly tasks to a given or to be defined number of stations considering restrictions, given by the process environment or the product itself [6, 7]. Product internal restrictions include restrictions based on predecessor and successor relationships of the tasks. Process related restrictions include the location of production equipment at predefined stations and drying time of paintwork for instance. The challenge of producing several variants of a standardized product on one assembly line is declared as the mixed-model assembly line balancing problem as a subcategory of the generalized assembly line balancing problem. The balancing of the assembly line is done as a part of planning activities in factory planning or when production program as important input information for the line balancing changes. The sequencing of the assembly line is based on the balancing and is used in time intervals of several days [6].

While these approaches were invented in automobile industry and are used in comparable industries like consumer goods manufacturing, only few concepts are dealing with the production of large volume products. In this case the cycle time is a multiple of those in classical application fields of assembly lines. Task times of several minutes up to several hours are common and require more than one worker to be assigned to each assembly station [8]. The two sided assembly line is one solution for this problem and enables two workers to be assigned to tasks on both sides of the line at opposite stations. Depending on the resource constraints of products, the number of stations is not necessarily rising, but the line can be shortened. Further advantages in comparison to a one sided assembly line are a reduction of the throughput time, sharing of tools and fixtures at stations, and the reduction of material handling, worker movement, and setup times at the stations [9–11]. These advantages are of help to overcome some of the problems linked with the assembly of large-dimensioned products, but do not consider cooperation of workers in teams at each station. Cooperation of workers allocated to a station is mentioned by [12]. In this case several workers fulfill tasks at one station, each of them performing one task. Comparable to this research, approaches are described by [8, 13]. The first one uses a heuristic of five steps to identify the optimal number of stations and operators with respect to the minimization of idle time at the assembly line. The first three steps are subsumed as code generation including the generation of a combined precedence graph, the creation of precedence matrices and the generation of codes for every task to express its relations in the precedence graph. The created mathematical model of tasks is solved in an optimization tool and results are analyzed. Reference [8] presents a five step heuristic as well, including two steps for line balancing followed by the phase of creating physical station. The following two steps include model sequencing and a worker transfer system, which is not discussed in detail. The results of the approach are compared to the results achieved by [12]. While these centralized approaches are focused on planning and scheduling of workforce, a reaction to unforeseen production changes or failures is not addressed. A decentralized approach for task and workforce allocation is the bucket brigade [14]. This approach uses the self-organization of workers at an assembly line, introducing two rules to be observed by the employees. Following the first rule, every employee stays devoted to an item and processes it on successive stations till the product is taken over by the succeeding worker at the line or the devoted worker reaches the end of the production line. Observing the second rule, the worker walks back along the assembly line and takes over the item of his predecessor. Under the assumption of a sequencing of the workers from slowest to fastest a self-balancing of the line is achieved, ensuring an optimal production rate. Reference [15], concerning learning in bucket brigades, showed that easy to learn tasks are more suited for the concept than complicated ones.

These approaches take the organization of workers in small groups into account, but do not refer to the cooperation of workers on the same task. Reference [16] describes a simulation based approach for resource allocation in paced assembly processes, considering allocation of more than one worker to a task in assembly of customer specific large-dimensioned goods. The allocation is done by allocation of resources in discrete steps based on the emitting of values by tasks. Reference [17] presents the usage of the concept in workforce planning with the aim to determine the number of shifts and workers for a production sequence, taking the workload of products into account. Reference [18] presents the identification of the optimal operating point for the usage of the approach in production control taking varying workloads in a given production program into account. The approach presented in the following is based on theses earlier concepts.

## 3 Method for Resource Allocation and Assembly Control

### 3.1 Basic Concept

The production of customer specific large-dimensioned goods, as machinery for mining and forestry for an example, is characterized on a low level of automation. To enable production units to manufacture the multiple variants and types of products, most assembly tasks are processed by skilled workers assembling the products. This leads to high flexibility, but causes high labor costs as well. As described in Sect. 1.1 production control and solving of occurring problems is done by experienced workers as foremen, knowing the process and the qualification of the workers of their production unit. The increasing number of variants makes it difficult to be informed about the current status of processes and giving helpful advice to workers. Therefore, objective situation evaluation and advice is needed to be combined with worker participation to allow production control that fits the requirements of the current situation. This unburdens the foremen of the task of planning and controlling production activities in detail and enables to spend further attention to process optimization tasks. Therefore, a method is developed that integrates workers as part of the production control comparable to the concept of bucket brigades. Compared to the concept of bucket brigades, the approach presented is intended to cope with complex assembly operations.

Reference [16] presented the simulation based approach for the first time. The concept is grounded on foraging behavior of insects and hummingbirds in mutualistic networks. In these networks plants emit stimuli to attract insects with the aim to achieve pollination. Insects react to the stimuli received and choose the plant, which is suggested to offer the highest value to its pollinator. This suggestion is based on characteristics of the stimulus, which is linked to flowers blossom size, color or the emitted scent, but it is also influenced by other factors as the qualification of the pollinator and the appearance of competing insects. The qualification of pollinators is often defined by evolution in form of the physical ability of the insect to reach the nectar restricted by the shape of the blossom. Therefore, some insects can be referred as specialists, being focused on pollination of a special plant species, while others are generalists, which are not focused on one species, due to their beneficial physical abilities. Research showed that the appearance of competitors discourages other species to use certain plants [19]. The mechanisms in these networks are used for workforce allocation in the production control process. One of the mechanisms is the generation and emitting of a stimuli. Tasks are considered as the emitters of the stimuli, while workforce as a resource is the receiver of it. The stimulus is a mean to express the importance of the task in terms of product completion and production program fulfillment and give an objective representation of this issue. Tasks are characterized by information concerning predecessors and successors, work content, and number of workers applicable for instance. While these task and product related characteristics are used to express the task's position in the product's assembly structure and its role for the completion of the task, current data of surrounding factors is integrated in task value determination. Latter factors include the remaining cycle time, the slack time, and the number of assigned workers to the station a task is located at. Emitting of stimuli is constant even during the processing of a task and rises as long as no resources are assigned to it. Being in process, it depends on the amount of resources, which are assigned to the task if the stimulus is further rising or decreasing. Based on the emitted stimuli, resource units assign to tasks as shown in Fig. 1. The assignment is limited by surrounding factors as station restrictions as maximum of workers at one of the assembly stations.

Former papers of the author considered issues of production planning and control assuming that more than one worker can be allocated to a single task as long as the number of assignable workers at task $i$ is not exceeded and no restrictions at the station, where task $i$ is located at, are violated. By assigning several workers to a task the duration of the task is shortened. The expected duration time $t_{Di}$ for task $i$ is given by the ratio of the work content of task $i$ $c_i$ and the number of workers assigned to task $i$ $m_i$. In this case it is ignored that cooperation of workers may lead to hindering effects in task processing. The duration time of a task may remain on a higher level due to unfavorable tool and equipment

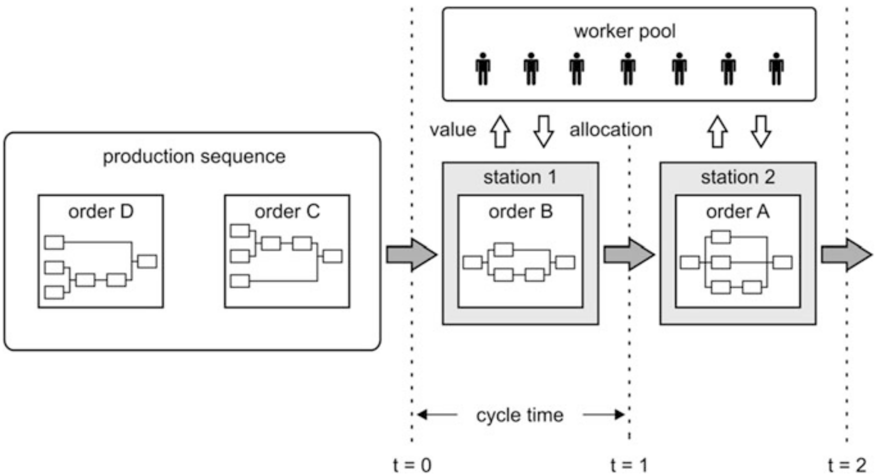


**Fig. 1** Stimuli based workforce allocation [16]

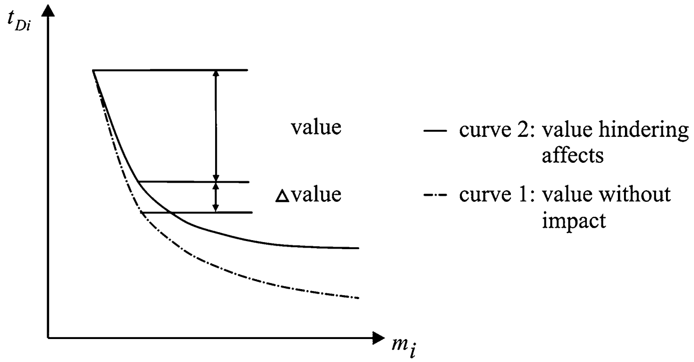


**Fig. 2** Duration time of tasks taking hindering effects in task processing into account

storage or the need of centralized material staging for example. The effect is shown in Fig. 2.

Curve 1 shows the duration time of a task in relation to the workers assigned to it, without any hindering of the progress by worker allocation. Curve 2 takes hindering effects into account and shows a much smaller decreasing than curve 1. The effect of a decreasing value of further workforce assignment is increasing with the number of workers assigned to the task. The more workers are assigned, the wider the gap between both curves and the smaller the value of further workforce assignment becomes. Therefore, the duration time of a given task $i$ must be calculated including a coefficient $f_{hind}$ for inclusion of hindering effects in task processing as shown in Eq. 1.

$$t_{Di\,hind} = \frac{c_i}{m_i} \cdot (1 + (m_i - 1) \cdot f_{hind}) \qquad (1)$$

Due to the effect of a decreasing value of workforce intensification on duration times of tasks, production control must take this relation into account. In the context of using stimuli for resource allocation, the stimuli generation must be able to react to duration time variations, caused by hindering effects. In the following, a simulation model is used for evaluation of three stimuli generation concepts for production control.

## 3.2 Concepts for Stimuli Generation

All concepts must include the $n$ successors of task $i$ to give an expression of the location of a task in the assembly structure of a product. Furthermore, it is necessary to include the remaining production time $tr_{pi}$ at the line for the considered product. While these components express the urgency of further processing of a task, the number of assignable workers to each successor $m_{max\,j}$ is used to express the processing time flexibility of the successor, given by different processing modes. Tasks with few processing modes are considered to be processed earlier than those with several ones. Thus, all the following stimuli generation concepts include the component $b_i$ given by Eq. 2, representing the influence of the task's successors for stimuli generation.

$$b_i = \sum_{j=1}^{n} \frac{c_j}{m_{\mathrm{max}j}} \cdot \frac{1}{tr_{pi}} \tag{2}$$

### 3.2.1 Centralizing Stimulus

The concept of a centralizing stimulus $v_{cen}$ includes the work content of task $i$ and its assigned or assignable workers, depending on its processing status given by the coefficient $a$, having a value of one when task $i$ is processed and zero when it is waiting for processing. Due to the assumption that no task splitting is allowed, it has to be ensured that a task is completed in one cycle without overstraining the available capacity. Thus, the remaining cycle time $tr_{cycle}$ is integrated to rate tasks in process higher than others and to ensure sufficient resource allocation. The concept of a centralizing value tries to gather as much resources as possible for the considered task. The concept is illustrated in Fig. 3 and was used in earlier investigations.

$$v_{cen} = (1 - a) \cdot \frac{c_i}{m_{\mathrm{max}\ i}} \cdot \frac{1}{tr_{pi}} + a \cdot \frac{c_i}{m_i} \cdot \frac{1}{tr_{cycle\ i}} + b_i \tag{3}$$

### 3.2.2 Decentralizing Stimulus

Intensifying of resource assignment may be an unfavorable choice, when the chance of hindering of workers is given and alternatives in form of other tasks are

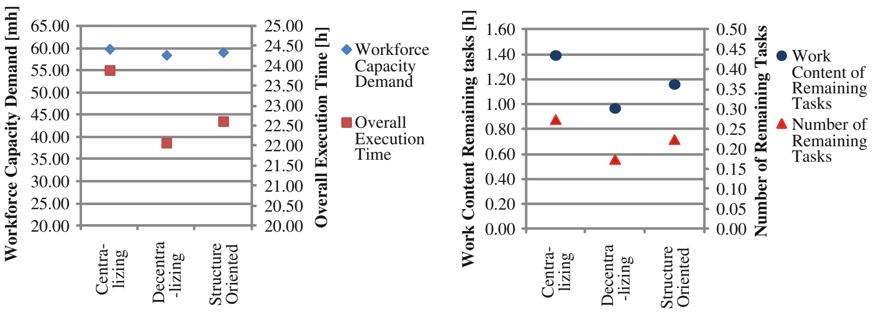


**Fig. 3** Performance of stimuli generation concepts ($f_{hind} = 0.05$)

offered. To avoid such negative effects the second, decentralizing stimulus generation concept $v_{decen}$ uses the value of further workforce concentration on task $i$, which is expected to be achieved. Resources are allocated to those tasks, which offer the greatest benefit with respect to the overall assembly efficiency of the considered product. In case of hindering effects, this causes an allocation of workers to several tasks, which can be processed in parallel.

$$v_{decen} = (1 - a) \cdot \frac{c_i}{tr_{pi}} + a \cdot \frac{(1 - f_{hind}) \cdot c_i}{(m_i^2 - m_i) \cdot tr_{pi}} + b_i \tag{4}$$

### 3.2.3 Structure Oriented Stimulus

While the centralizing and decentralizing generation concepts are concentrating on special scenarios it might be beneficial to include situation related decision making in stimulus generation. A beneficial strategy is expected to depend on the current situation, which is characterized by the available assembly tasks. Thus, the structure oriented assembly value includes the number of task, which can be processed alternatively to the considered one. To enable the consideration of alternatives, the sections of Eq. 6 are weighted by the factors $x_i$ and $y_i$, where $n_{ca\ i}$ is the number of current tasks which can be processed alternatively and sharing the same direct successor with task $i$, and $n_{ai}$ the number of potential alternatives.

$$v_{str} = (1 - a) \cdot \frac{c_i}{tr_{pi}} + a \cdot \left( x_i \cdot \frac{c_i}{tr_{pi}} + y_i \cdot \frac{(1 - f_{hind}) \cdot c_i}{(m_i^2 - m_i) \cdot tr_{pi}} \right) + b_i \tag{5}$$

$$x_i = \frac{n_{ca\ i}}{n_{a\ i}} \tag{6}$$

$$y_i = 1 - x \tag{7}$$

# 4 Computational Investigation

## *4.1 Evaluation Criteria*

For the computational investigation of the communication concepts, products are manufactured separately on the assembly line for investigation of effects occurring due to the different concepts. To evaluate the performance of the generation concepts the following criteria are chosen.

#### 4.1.1 Workforce Capacity Demand

Due to a high percentage of labor intensive tasks and high worker qualification levels in assembly areas under investigation, the demand for workforce capacity is of major interest. Therefore, the workforce capacity demand is an important criterion to evaluate the performance of a control method. Especially when execution time is expendable, the workforce capacity demand is a suitable performance measurement in separate order investigation.

#### 4.1.2 Overall Execution Time

Although, the production time of products is predefined by the cycle time and the number of stations, the overall execution time is an important hind for production efficiency. The less time is needed to process an order, the earlier workers can be allocated to tasks at other stations of the line. The influence of hindering factors may lead to higher overall execution times of orders and must be integrated in production control procedures to enable the reduction of hindering effects.

#### 4.1.3 Number of Remaining Tasks

Tasks, which remain unprocessed at the end of the assembly line, cause interruptions of the production processes. To enable the processing of the remaining tasks and to complete the assembly, the product must be transported to an alternative assembly station apart the line. For the duration of the handling operations for this purpose, activities at other stations cannot be started. Furthermore, extra workforce, material, and facilities are necessary, incurring additional costs. Thus, the number of remaining tasks is of interest in performance evaluation.

#### 4.1.4 Work Content of Remaining Tasks

In addition to the number of remaining tasks, the work content of these is considered to evaluate the performance of the concepts. While several remaining tasks may contain a small amount of work content, one single task may need a bigger amount of resources to be processed. Therefore, the number of remaining tasks and the work content of these have to be considered simultaneously.

### *4.2 Simulation Model*

The simulation model contains a paced assembly line of three assembly stations and uses a cycle time of 8 h. In each cycle, three assembly workers are available.

There are no buffers installed between the stations. In simulation runs each stimuli generation concept is tested using 200 generated products. Each product contains 10–16 tasks, the average workload of orders adds up to 55.4 man hours. Each task is characterized by a given number of assignable workers, which is between two and three workers in general. During the investigation the hindering factor $f_{hind}$ varies from zero to 0.10 using steps of 0.05. The products used in investigation are generated randomly with respect to the given work content of tasks and are not verified with respect to their ability to be processed in cycle time. The capacity and number of workers at the line is not enhanced during simulation runs. Thus, capacity can be overstrained. Comparing identical products, overstraining is measured by the number of remaining tasks and the amount of remaining work content. Thus, the adequacy of different concepts coping with maximum capacity demand can be evaluated. Under these restrictions, it is assumed that remaining tasks are processed by an extra worker. Therefore, the remaining work content is added to the overall execution time and to the workforce capacity demand of the product measured in production at the assembly line.

## 4.3 Simulation Results

The computational investigation is based on 100 simulation runs per stimuli generation concept, each including the assembly of 200 randomly generated products. Stimuli are generated as presented in Sect. 3.2, using Eqs. 3–7. The performance of resource allocation using the centralizing, the decentralizing and the structure oriented stimulus are presented in the following.

Stimuli generation concepts show differing abilities to cope with a variation of the hindering factor. In all scenarios the increase of the hindering factor results in the increase of execution times, but results differ with respect to the necessary amount of extra execution time. The decentralizing concept provided the best results and limited the effects of an increase of the hindering factor to an expansion of the execution time of 11 % when $f_{hind}$ is increased to 0.10. The second best concept is the structure oriented concept, providing similar results as the decentralizing one. The most significant increase of execution time is realized by the centralizing concept, achieving an execution time, which is 18 % longer than in the scenario without any hindering effects. Comparing the best and the worst concept under investigation the difference in execution time is 3.11 h on average.

In order to discuss the results of the investigation with respect to the other criteria, further considerations focus on the scenario including $f_{hind}$ 0.05, which are presented in Fig. 3. The average number of remaining tasks is 0.28 for the centralizing and 0.18 for the decentralizing concept, in maximum two tasks remained after the last cycle. The structure oriented value generation concept yields an average number of remaining tasks of 0.23. The work content related to those tasks is 1.39 and 1.16 man hours for the centralizing and the structure oriented stimuli generation concept. This corresponds to 2.5 and 2.1 % of the workload of considered products. In maximum a work content of 3.16 man hours is not processed. The best results are achieved using the decentralizing stimuli generation concept by leading to 0.97 h in average and a maximum of 3.14 man hours, which are not processed at the end of the assembly line. For measuring the efficiency of resource usage in the assembly processes, the execution time for complete assembly of products and the demand for workforce capacity is included. The centralizing and decentralizing approaches managed to complete the assembly processes in 23.89 and 22.07 h. Avoiding hindering effects, the decentralizing concept on average is faster in completing the assembly than the other concepts. The structure oriented approach lowers the overall execution time compared to the centralizing approach, but does not yield the result achieved by the decentralizing concept. An average execution time of 22.61 h is achieved. This means a reduction of the overall execution time per product of 1.27 h compared to the centralizing approach, but a plus of 0.53 h in comparison to the decentralizing generation concept. Comparable results are achieved with respect to the demanded workforce capacity. By using the structure oriented approach, it takes 0.63 man hours longer to accomplish all tasks compared to the decentralizing concept and 0.75 man hours less compared to the centralizing concept. Comparing the minimum workforce capacity used, it varies only slightly to the decentralizing and structure oriented concepts between 17.25 and 17.30 man hours, while the centralizing needed 21.81 man hours in minimum. This offers the opportunity to reduce the cycle time, when similar products are manufactured, but it gives the chance to produce various products as well, by processing of alternative tasks of other orders, when tasks are blocked by any circumstances, and enhance workforce utilization further. In general the decentralizing concept achieved the best results and managed to use resources more efficient than the other considered concepts. The structure oriented concept is second best under investigation and yields similar results of the decentralizing approach. While the investigation here focuses the usage of concepts when products are assembled separately, competition of tasks and orders for resources in production environment may have further influence on the performance of concepts.

## 5 Summary

The paper presents an approach for workforce planning and control in production of customer specific large-dimensioned goods with low production rate. The usage of the concept is demonstrated using a simulation model of a paced assembly line under consideration of hindering effects. Three concepts for generation of the control stimuli are discussed using a broad variety of products. The comparison of results showed the ability of the concept to cope with differing products. The decentralizing concept achieved the best results compared to a centralizing and a product structure oriented generation concept. Varying the hindering factor is not changing the result, but leads to an increasing of effects and a reinforcing of the

ranking. The gaps between the results of the stimuli generation concepts become wider with increasing hindering factor. The investigation presented here focuses on the application of concepts to the separate assembly of products to enable the comparison of concept related effects on assembly processes. For application in paced assembly lines, concepts are going to be evaluated in production of a production program as mentioned in former articles. Especially the influence of limiting, station dependent restrictions, and taking advantage of station related worker flexibility have to be evaluated.

## References


1. Ernst AT, Jiang H, Krishnamoorthy M, Sier D (2004) Staff scheduling and rostering: a review of applications, methods and models. Eur J Oper Res 153(1):3–27
2. Boysen N (2006) Production planning in mixed-model assembly lines (Produktionsplanung bei Variantenfließfertigung). In: Waldmann K-H, Stocker UM (eds) Operations research proceedings 2006, Springer, Berlin-Heidelberg, pp 11–15
3. Taiichi O (1988) Toyota production system: beyond large-scale production. Productivity Press, Cambridge (Mass)
4. Boysen N, Fliedner M, Scholl A (2006) Level-scheduling in mixed-model assembly lines (Level-Scheduling bei Variantenfließfertigung: Klassifikation, Literaturüberblick und Modellkritik), Jenaer Schriften zur Wirtschaftswissenschaft, Vol 26/2006
5. Solnon C, Cung VD, Nguyen A, Artigues C (2008) The car sequencing problem: overview of state-of-the-art methods and industrial case-study of the ROADEF'2005 challenge problem. Eur J Oper Res 191(3):912–927
6. Scholl A (1999) Balancing and sequencing of assembly lines, 2nd edn. Physica, Heidelberg
7. Boysen N, Fliedner M, Scholl A (2007) A classification of assembly line balancing problems. Eur J Oper Res 183(2):674–693
8. Cevikan E, Durmusoglu MB, Unal ME (2009) A team-oriented design methodology for mixed model assembly systems. Comput Ind Eng 56(2):576–599
9. Özcan U, Toklu B (2009) Balancing of mixed-model two-sided assembly lines. Comput Ind Eng 57(1):217–227
10. Lee TO, Kim Y, Kim YK (2001) Two-sided assembly line balancing to maximize work relatedness and slackness. Comput Ind Eng 40(3):273–292
11. Håkansson J, Skoog E, Eriksson KM (2008) A review of assembly line balancing and sequencing including line layouts. In: Proceeding of PLANs forsknings- och tillämpningskonferens, pp 69–84
12. Dimitriadis SG (2006) Assembly line balancing and group working: a heuristic procedure for workers' groups operating on the same product and workstation. Comput Oper Res 22(9):2757–2774
13. Chang H-J, Chan T-M (2010) Simultaneous perspective-based mixed-model assembly line balancing problem. Tamkang J Sci Eng 13(3):327–336
14. Bartholdi JJ, Eisenstein DD (1996) A production line that balances itself. Oper Res 44:21–34
15. Armbruster D, Gel ES, Murakami J (2007) Bucket brigades with worker learning. Eur J Oper Res 176:264–274
16. Tracht K, Funke L, Joppien T (2011) Decentralised resource allocation in paced assembly processes. In: 21st International conference on production research (ICPR 21), 31 July–4 Aug, Stuttgart
17. Tracht K, Funke L (2011) Order-related Shift Planning in Assembly (Auftragsorientierte Schichtplanung in der Montage), wt-online, 101(9):591–594

18. Tracht K, Funke L (2012) Resource allocation in manual assembly (Ressourcenallokation in der manuellen Montage), wt-online, 102(9):564–567
19. Fontaine C, Dajoz I, Meriguet J, Loreau M (2006) Functional diversity of plant-pollinator interaction webs enhances the persistence of plant communities. PLoS Biol 4(1):129–135

# Injection Mold Maintenance Scheduling with Mold-Lifting Crane Consideration

**C. S. Wong, F. T. S. Chan and S. H. Chung**

**Abstract** Injection mold maintenance scheduling is a challenging problem in plastics production systems. On one hand, it harmonizes the production activities on machines and molds. On the other hand, it decides when maintenance activities should be performed in order to improve the reliability of production systems. In the previous studies [1, 2], a Joint Scheduling (JS) approach was proposed to deal with some mold maintenance scheduling problems. It was shown that the JS approach outperforms the traditional Maximum Age (MA) approach. However, the models had not considered the capacity of mold-lifting crane which is likely to be the bottleneck of mold maintenance activities. Therefore, in this paper, a new problem is modeled with the consideration of the capacity of mold-lifting crane. A genetic algorithm approach is applied to deal with this new problem. The numerical examples show that considering the mold-lifting crane, the JS approach can still outperform the MA approach and obtain the shortest makespan.

## 1 Introduction

In the last decades, the availability of machines in production scheduling problem attracts researchers' attention [3]. Traditionally, machines are assumed to be in good condition and ready for use during scheduling. This assumption is not realistic since machines are usually subject to break down and require maintenance, replacement or repair [4–9]. Batun and Azizoglu [4] proposed a branch-and-bound algorithm to solve a single machine total flow time problem. In the problem, all jobs were not allowed to be interrupted during operation. The machine was subject to maintenance in which the start times and durations of maintenance tasks were

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assumed to be known in advance. They proposed to firstly plan the maintenance tasks to the schedule and then allocate the jobs to different machine availability periods. They indicated that for future research, it is very important to study the scheduling problem that the allocating production and maintenance tasks simultaneously. To schedule production and maintenance tasks simultaneously. Ben Ali et al. [3] proposed an elitist multi-objective genetic algorithm approach for a job shop scheduling problem to minimize the makespan and the total maintenance cost. With the computational experiments, they identified some lower bounds and Pareto optimal solutions of the problem sets. Mokhtari et al. [5] identified the research gap on production-maintenance scheduling problem. There are very few studies about the concurrent decision making on maintenance plan and job sequence. They developed a joint production and maintenance scheduling (JPMS) model. In the model, not only the job sequence on machines but also both the maintenance intervals and the number of maintenance tasks were determined at the same time. They adopted a reliability approach to model the availability of the machines in the problem. A mixed integer nonlinear programming model for JPMS was developed and the problem was solved by a population-based variable neighbourhood search (PVNS) algorithm. Moradi et al. [6] also applied the reliability approach for maintenance modeling in a flexible job shop environment. They aimed to minimize two objectives, the makespan for the all jobs and the system unavailability. Similar to the approach presented by Moradi and Zandieh [7], the maintenance task numbers and maintenance intervals were decided by four proposed algorithms. However, to our best knowledge, the majority of published works for production-maintenance scheduling, were mainly focused on machine availability. The availability of other critical resources such as injection molds has usually been ignored.

Injection molds are essential components of injection molding machines. In many manufacturing firms, each injection mold is designed for a particular plastic item and is unique due to the high cost of mold making. Therefore, any mold breakdown during production usually leads to shortage of at least one plastic item. To ensure stable and reliable production processes, a well-organized mold maintenance schedule plays a critical role in a plastics production system. Traditionally, maintenance departments generate maintenance schedules independently. It leads to a mismatch between production schedule and maintenance schedule. When a maintenance staff member arrives to the machine that is required to perform mold maintenance, the machine operator is not willing to stop operation since the operator has to achieve the productivity written on the production schedule. The delay of mold maintenance may result in costly emergency repair because the mold may be in even worse condition. Productivity will also be affected due to the unplanned emergency repair.

In the previous study [1], a Joint Scheduling (JS) approach was proposed to integrate production and mold maintenance scheduling. A Production Scheduling with Mold Scheduling (PS-MS) problem was identified to demonstrate the performance of the JS approach in a plastics production system. It is shown that jointly (but not sequentially) schedule production and mold maintenance activities can improve productivity with shorten makespan. However, in the model, it was assumed that setup time of each job was sequence-independently included in its processing time.

In the real situation, setup time is induced when the next job is required to produce another item with a different mold. The mold on the machine has to be removed with a mold-lifting crane. Mold-lifting crane is a significant capital investment that costs around 20,000 US dollar. Many small-and-medium-sized manufacturers only equip one or two cranes in their factories. As a result, if the molds on the injection machines are changed frequently, it is likely that the mold-lifting crane will be the bottleneck. The performance of the JS approach will also be affected seriously since the JS approach breaks down a comprehensive maintenance task into several small-sized maintenance tasks. The molds are changing more frequently when the JS approach is applied. Further investigation on the JS approach should be considered. In this paper, therefore, the capacity of the mold-lifting crane is considered to extend the PS-MS model. A genetic algorithm approach is applied to deal with this new problem. The numerical examples show that considering the mold-lifting crane, the JS approach can still harmonize the maintenance and production activities and obtain the shortest makespan.

## 2 Problem Description

The notations used in this paper are summarized as the followings:

| Index | Descriptions |
|---|---|
| $i$ | Index for jobs, $i = 1, \ldots, I$, where $I$ is total number of jobs |
| $m$ | Index for machines, $m = 1, \ldots, M$, where $M$ is total number of machines |
| $n$ | Index for injection molds, $n = 1, \ldots, N$, where $N$ is total number of injection molds |
| $L_t$ | Time slot $t$ of mold-lifting crane |
| $P_i$ | Process time of job $i$ |
| $A$ | Maximum age for injection molds |
| $t$ | Index of time slots, $t = 1, \ldots, T$, where $T$ is the maximum time horizon |
| $S_i$ | Starting time of job $i$ |
| $C_i$ | Completion time of job $i$ |
| $C_{\max}$ | Makespan of jobs |

*Decision Variables*

| | |
|---|---|
| $\delta_{imnt}$ | $= 1$, if job $i$ occupies time slot $t$ on machine $m$ with mold $n$<br>$= 0$, otherwise |
| $Z_{im}$ | $= 1$, if job $i$ is allocated on machine $m$<br>$= 0$, otherwise |
| $X_{in}$ | $= 1$, if mold maintenance is performed on mold $n$ after the completion of job $i$<br>$= 0$, otherwise |

## 2.1 Plastics Production Scheduling Problem Modeling

$$Objective: \text{MIN}\{C_{\max}\} \tag{1}$$

The problem is subjected to the following constraints:

$$C_i - S_i = \sum_m Z_{im} P_i \ \forall im \tag{2}$$

$$\sum_{mt} \delta_{imnt} = \sum_m Z_{im} P_i \ \forall imnt \tag{3}$$

$$\sum_m Z_{im} = 1 \ \forall im \tag{4}$$

$$\sum_{in} \delta_{imnt} \leq 1 \ \forall imnt \tag{5}$$

$$\sum_{im} \delta_{imnt} \leq 1 \ \forall imnt \tag{6}$$

In the plastics production model, there are $I$ jobs, $M$ injection machines and $N$ injection molds. Each job requires using a specific mold $n$ to produce required items with process time $P_i$. Equation (1) is the objective function of the problem. The aim is to minimize the makespan of the jobs. Equation (2) ensures that there is no interruption when a job is operating. Equation (3) is a process time constraint ensuring the time slot allocated to a job equals to its process time. Equation (4) defines that each job must be allocated to a machine once only. Equation (5) is a machine capacity constraint that a machine is only allowed to perform one job at the same time. Equation (6) is a mold capacity constraint that a mold is only allowed to perform one job at the same time.

## 2.2 Mold Maintenance Scheduling Problem Modeling

The maintenance scheme of the plastics production model is that an injection mold ($n$) is subject to damage with its maximum age ($A$). When the cumulated operating time of Mold $n$ reaches $A$, mold maintenance will be performed on Mold $n$. Besides, if the decision variable $X_{in}$ equals to one, Mold $n$ will be maintained after the completion of Job $i$. Assuming all molds will be in perfect condition after maintenance, the cumulated operating time of Mold $n$ will become zero after Mold $n$ is maintained.

### 2.3 Mold-Lifting Crane Scheduling Problem Modeling

There are two functions for a mold-lifting crane, mold installation, and mold removal. Both actions will occupy the time slot of the crane ($L_t$) during production. When Job $i$ is performed with Mold $n$ on Machine $m$, mold $n$ must be installed on Machine $m$ before Job $i$ starts. If there is another mold on Machine $m$, that mold must be removed before the installation of Mold $n$. Besides, if Mold $n$ requires maintenance, Mold $n$ must be removed before maintenance.

## 3 Methodology of Genetic Optimization

### 3.1 Encoding

Each gene consists of four parameters. The first parameter represents a machine number which indicates a specific machine to perform a job. The second parameter represents a job number that should be performed. The third parameter is a binary variable for mold maintenance. If its value is equal to one, mold maintenance will be performed after the completion of current job. If its value is equal to zero, no maintenance will be performed. This mechanism is regarded as Joint Scheduling (JS). The start time of a mold maintenance task will be determined during scheduling. The last parameter is also a binary variable. It records the good genes in a generation and brings it to the next generation under the evolution procedure. This idea was introduced by Chan et al. [10]. If the value of that parameter is equal to one, the gene will be classified as a Dominant Gene (DG). For example, there are 3 jobs and 2 machines. A chromosome, 1201-2110-1311, means Machine 1 firstly performs Job 2 and Machine 2 performs Job 1. After the completion of Job 1, mold maintenance will be performed. After the completion of Job 2, Machine 1 will perform Job 3. Lastly, mold maintenance will be performed after the completion of Job 3. Besides, the genes “1201” and “1311” are identified as DG. They will undergo crossover procedure later.

### 3.2 Initialization

At the beginning, chromosomes are randomly generated to form an initial population. Each chromosome represents one solution of the scheduling problem. The problem size and the population size of solution are predefined in advance. In this paper, the problem includes 30 jobs, 3 machines, 5 injection molds and 1 mold-lifting crane. The population size is 10. In other words, 10 solutions are randomly generated in the initial population.

## 3.3 Fitness Function

The objective function in this paper is to minimize the makespan of all jobs, which provides mechanism for evaluating all solutions in the population pool. However, the range of the objective value is varying from problem to problem. Thus, a fitness function is applied to normalize the objective value into a convenient range of 0–1. In this paper, the fitness value of a chromosome is one minus the objective value of the chromosome that is divided by the sum of the objective values of all solutions in the population.

## 3.4 Selection

The selection procedure in Genetic Algorithm (GA) models the survival-of-the-fittest mechanism. After the calculation of all fitness values in the population, the fitter chromosomes with higher value will have higher chance to survive and the weaker chromosomes with lower value are likely to perish. In this paper, a roulette wheel selection mechanism is adopted. The idea is similar to a roulette wheel in a casino. All chromosomes are allocated in different sectors of the roulette wheel. The proportion is based on their fitness value so that the chromosome with higher fitness value has larger sector on the roulette wheel and vice versa. A random number is generated to select a chromosome which is similar to the rotation of the roulette wheel. The roulette wheel selection procedure will continue until a new population pool is formed.

## 3.5 Evolution

The evolution procedure is to generate a next generation of solutions according to crossover and mutation operation. In crossover operation, the DGs in each pair of chromosomes will be exchanged to generate offspring. If the fitness values of the offspring are better than their parents, the DGs in the offspring will be reserved for next generation. However, if the fitness values of the offspring are poor than their parents, the DGs will be transformed as normal genes. The benefit of this mechanism is that no crossover rate is predefined in advance. In other words, there is no need to think about what the optimal crossover rate is. In mutation operation, with the objective of diversifying the potential solutions in the population, some genes of a chromosome will be randomly selected and changed with some random parameters. When a new generation population is formed, the procedures of fitness value calculation and roulette wheel selection will also perform. The entire evolution procedure will stop until the predefined number of evolution is reached. In this paper, the number of evolution is 6,000, which is enough to obtain steady solutions from the problem sets.

## 4 Numerical Example

In this section, five hypothetical problem sets are introduced to test the performance of the Joint Scheduling (JS) approach in the new scheduling model. Tables 1 and 2 show the parameters of the new model as an example. Table 1 is the job data in Problem Set 1. It indicates which type of products should be produced in each job and the number of units should be produced. It is assumed that there is only one specific mold for one type of products. Thus, the identification number of the product type is equal to the identification number of the mold. Table 2 is the machine parameters in Problem Set 1. It identifies which mold can be installed on the machines and the machine hours for each type of products. In each problem set, there are 30 jobs, 3 machines, and 5 injection molds. In the

**Table 1** Job data in problem set 1

| Job | Product/mold | Unit ('000) |
|---|---|---|
| 1 | 4 | 3 |
| 2 | 5 | 4 |
| 3 | 4 | 4 |
| 4 | 2 | 3 |
| 5 | 4 | 4 |
| 6 | 2 | 5 |
| 7 | 4 | 2 |
| 8 | 3 | 4 |
| 9 | 4 | 4 |
| 10 | 5 | 3 |
| 11 | 1 | 4 |
| 12 | 5 | 4 |
| 13 | 2 | 4 |
| 14 | 4 | 3 |
| 15 | 5 | 4 |
| 16 | 2 | 5 |
| 17 | 4 | 5 |
| 18 | 4 | 2 |
| 19 | 2 | 4 |
| 20 | 1 | 3 |
| 21 | 1 | 2 |
| 22 | 5 | 5 |
| 23 | 2 | 3 |
| 24 | 4 | 5 |
| 25 | 4 | 3 |
| 26 | 1 | 3 |
| 27 | 5 | 2 |
| 28 | 2 | 4 |
| 29 | 4 | 2 |
| 30 | 1 | 2 |

**Table 2** Machine parameters in problem set 1

| | | Machine hour per 1,000 unit | | |
|---|---|---|---|---|
| | | M1 | M2 | M3 |
| Mold | 1 | – | 4 | – |
| Mold | 2 | 5 | – | 5 |
| Mold | 3 | – | 3 | 3 |
| Mold | 4 | – | 2 | 2 |
| Mold | 5 | 4 | 4 | – |

**Table 3** Comparing the makespan in the new model between the MA and JS approach

| Problem | MA approach | JS approach | Improvement (%) |
|---|---|---|---|
| Set 1 | 177 | 171 | 3 |
| Set 2 | 145 | 137 | 6 |
| Set 3 | 126 | 124 | 2 |
| Set 4 | 181 | 173 | 4 |
| Set 5 | 192 | 188 | 2 |

problem sets, each injection mold is subject to its predefined maximum age, which is 48 h in this paper. If the operation time of a mold reaches the maximum age, mold maintenance will be performed which takes 10 h during production. In the JS approach, the start time of a mold maintenance task is decided by the Genetic Algorithm (GA), the maintenance task can be performed at any time between the completion time of the first job and the maximum age. In this case, the maintenance time will be calculated linearly. For instance, if a maintenance task starts at 24 h of current mold age, the maintenance time will be 5 h.

For the sake of comparison, a traditional maintenance scheduling approach called Maximum Age (MA) approach is introduced. In the MA approach, the start time of a mold maintenance task is only based on the predefined maximum age of each mold. If operating current job will lead to an excess of the maximum age, maintenance will be carried out before the operation of the current job. In the experiments, the GA procedure is implemented in Visual Basic for Applications (VBA) environment. The program is executed on a personal computer with Intel Core 2 Duo 2.13 GHz CPU. For each problem set, the GA procedure runs for 10 times and the best solution will be considered as the result of each approach.

Table 3 summarizes the results of the JS and MA approaches from all problem sets. Obviously, the JS approach outperforms the MA approach with 2–6 % improvement of the makespan for the new scheduling problem. Figure 1 is an optimized schedule of the MA approach in Problem Set 1. The letter "i" refers to the installation of a mold, whereas the letter "r" refers to the removal of a mold. The following digit refers to the mold number. For example, "i2" means the installation of Mold 2; "r5" means the removal of Mold 5. The minimum makespan and the total operation hour of the mold-lifting crane under the MA

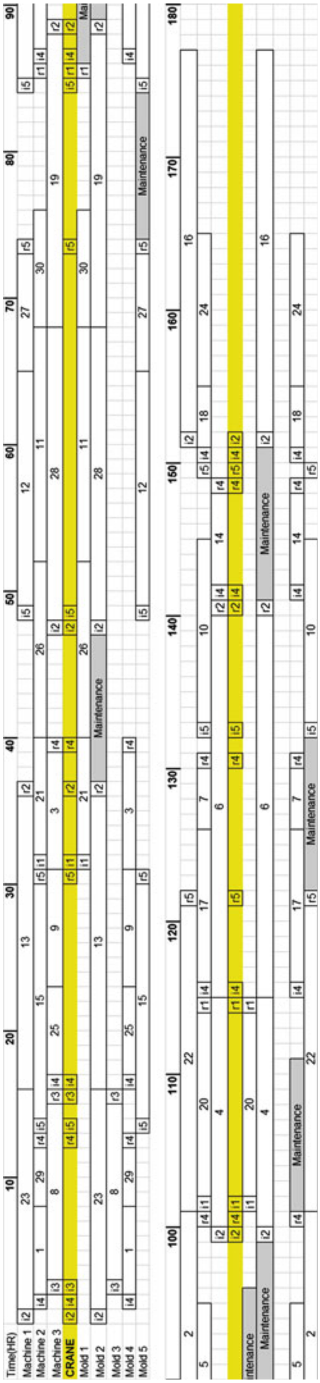


**Fig. 1** The optimized schedule of the MA approach in problem set 1

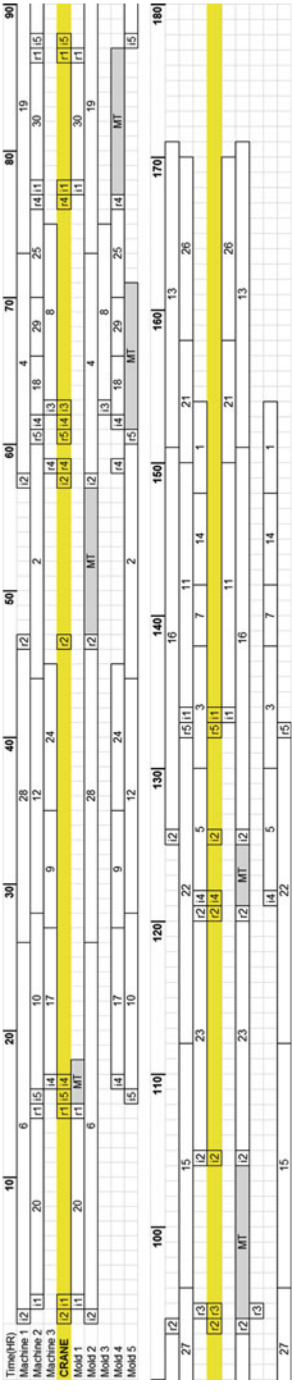

**Fig. 2** The optimized schedule of the JS approach in problem set 1. *MT* the maintenance activity decided by the JS approach

approach are 177 and 32 h respectively. In the schedule, Machine 1 usually has to wait a long time for an available mold with the idle time of 50 h. Figure 2 is an optimized schedule of the JS approach in Problem Set 1. The minimum makespan and the total operation hour of the mold-lifting crane under the JS approach are 171 and 23 h, respectively. The idle time of Machine 1 is 41 h. As a result, with the JS approach, production activities, maintenance tasks, and the workload of the mold-lifting crane can be harmonized. The JS approach allows more flexibility in the overall schedule of the new scheduling problem and improves the makepan.

## 5 Conclusions

In this paper, a new maintenance scheduling problem considering the capacity of mold-lifting crane has been modeled and introduced. A Joint Scheduling (JS) approach is proposed to improve the makepan in the new problem. In the numerical example, it is shown that the JS approach can achieve shorter makespan than the traditional Maximum Age (MA) approach. With the JS approach, the activities of production, maintenance, and mold-lifting crane can be harmonized.

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## References

1. Wong CS, Chan FTS, Chung SH (2012) A genetic algorithm approach for production scheduling with mold maintenance consideration. Int J Prod Res 50(2):5683–5697
2. Wong CS, Chan FTS, Chung SH (2013) A joint production scheduling approach considering multiple resources and preventive maintenance tasks. Int J Prod Res 51(3):883–896
3. Ben Ali M, Sassi M, Gossa M, Harrath Y (2011) Simultaneous scheduling of production and maintenance tasks in the job shop. Int J Prod Res 49(13):3891–3918
4. Batun S, Azizolu M (2009) Single machine scheduling with preventive maintenances. Int J Prod Res 47(7):1753–1771
5. Mokhtari H, Mozdgir A, Abadi INK (2012) A reliability/availability approach to joint production and maintenance scheduling with multiple preventive maintenance services. Int J Prod Res 50(20):5906–5925
6. Moradi E, Fatemi Ghomi SMT, Zandieh M (2011) Bi-objective optimization research on integrated fixed time interval preventive maintenance and production for scheduling flexible job-shop problem. Expert Syst Appl 38(6):7169–7178
7. Moradi E, Zandieh M (2010) Minimizing the makespan and the system unavailability in parallel machine scheduling problem: a similarity-based genetic algorithm. Int J Adv Manuf Technol 51(5–8):829–840
8. Ruiz R, Garcia-Diaz JC, Maroto C (2007) Considering scheduling and preventive maintenance in the flowshop sequencing problem. Comput Oper Res 34(11):3314–3330

9. Berrichi A, Yalaoui F, Amodeo L, Mezghiche M (2010) Bi-objective ant colony optimization approach to optimize production and maintenance scheduling. Comput Oper Res 37(9):1584–1596
10. Chan TS, Chung SH, Chan LY, Finke G, Tiwari MK (2006) Solving distributed FMS scheduling problems subject to maintenance: genetic algorithms approach. Robot Comput Integr Manuf 22(5–6):493–504

# A Multi-Agent System to Solve a New Formulation of Machine Layout Problem

**Ghaith Manita and Ouajdi Korbaa**

**Abstract** This paper focuses on the machine arrangement problem on common loop network. The machines are arranged in a cycle and materials transported in only one direction around the cycle using a conveyor belt. The goal of this problem is to minimize the maximum number of loops required for the manufacture of any of the products. The problem is known to be NP-hard. Thus, the right way to proceed is through the use of heuristics techniques. However, the industrial managers complain about an issue which is the mishandling of large variables and constraints that led to a lack of realism. In this work, we introduce a new formulation for the machine layout problem by adding new constraints which are the machine dimensions and the proximity constraints between the machines. This new formulation led us to propose two-stage approach to solve this problem. The first step consists on positioning the machines on a grid while respecting the proximity constraints and machines dimensions. The second step aim to optimize the path between these machines already positioned in order to minimize number of the loops traveled by parts. In this paper, we are interested in the first step by using multi-agent system. This choice can be explained by the well-known cooperation of the multi-agent system. The effectiveness of our approaches is demonstrated through numerical examples.

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# 1 Introduction

Flexible manufacturing systems (FMS) are a class of manufacturing system that can be quickly configured to produce multiple types of products (jobs). One of critical steps for the design of an FMS is drawing an efficient layout that can reduce material handling costs. Previous studies have demonstrated that 30–70 % of the total manufacturing costs are due to material handling [1]. And it has been reported that efficient layout design will reduce these costs by at least 10–30 % [2].

In practice many types of machine layouts are used, single-row layout, double-row layout, cluster layout, circular layout, and unidirectional loop layout. This last type is preferred to the other configurations since it requires relatively lower initial investment costs. Afentakis [3] have proved that unidirectional loop layout contain a minimal number of required material links to connect all workstations which provide a high degree of material handling flexibility. A unidirectional loop layout problem, as illustrated in Fig. 1, can be defined as a machines arrangement in loop path while keeping a one way direction.

We study in this work the unidirectional loop layout. Our aim is to place machines around an oval shape. This problem was already tackled and different approaches are described in the literature such as in [4–6].We choose one of the approaches based on genetic algorithms and we modify it by taking into account constraints, as far as we know, rarely considered in theory but very claimed by industrials. These constraints are called proximity constraints.

According to Drira et al. [7] existing solutions can be grouped, regarding to their resolution approaches, into three classes: exact methods, heuristics methods, and intelligence approaches. Figure 2 illustrates this classification.

In the literature, the machine layout problem is regarded as a quadratic assignment problem (QAP) by some authors and simplified to mixed integer programming (MIP) by others. Cheng et al. [8] proposed a hybrid approach of genetic algorithms and neighbourhood search for solving this problem whose

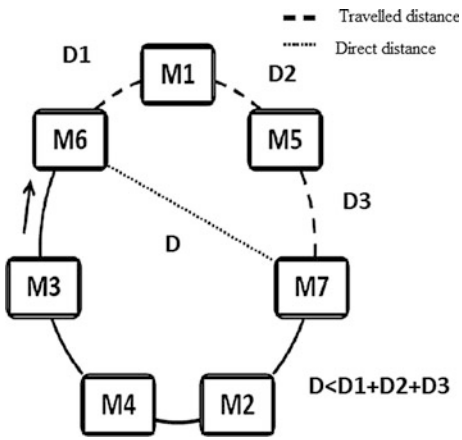
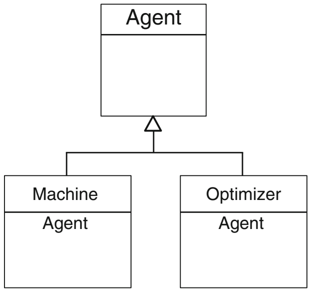



**Fig. 1** The traveled distance and the direct distance between the machines M6 and M7 in a loop layout configuration

**Fig. 2** Classes of agents




essence is how to determine the order of machines around the loop subject to a set of part-route constraints so as to optimize some measures. Computational results demonstrate that genetic algorithms can be a promising approach for loop layout design in flexible manufacturing systems. In another study, Tansel and Bilen [4] have suggested two heuristics MOVE and MOVE/INTERCHANGE using the concept of positional moves and local improvement algorithms based on moves or k-way interchanges. The two-move based heuristics indicates uniformly superior performance in comparison to the well-known pairwise interchange heuristic. Leung [9] presented a heuristic based on graph theory. The developed heuristic constructs a layout solution from linear-programming relaxation of the problem. Isli and Ozcelik [6] proposed a new operation of integrated mutation in the applied genetic algorithm to solve a specific case of the problem: balanced flow problem (balanced flow problem).

Away from genetic algorithms, differential evolution algorithm (DEA), another family of evolutionary algorithms has been used to meet the machine layout problem. Among the works that used the DEA, we can name the work of Nearchou [5] where a new DEA was implemented. In another formulation of the problem, Chaieb et al. [10]. References [11, 12] have adopted a more demanding environment and introduced three types of flexibility: the multiplicity of production resources, the flexibility of operating sequences, and the installation of a shortcut in manufacturing cells. As for the second approach, it is worth citing the work of Kumar [13] who used particles warm optimization (PSO) technique to fix the loop layout problem. The considered aspect of clearance between the machines aids in selecting the best layout. The method was validated with bench mark problems.

In this work, we choose to use a heuristic approach, and more precisely genetic algorithms. This choice can be explained by the fact that genetic algorithms become quite popular to solve this kind of problems. What distinguishes our approach from previous ones is taking into accounts the constraints proximity between machines. This modification will have an effect on the problem formulation and many parameters in genetic algorithms, especially the solution representation. The remainder of this paper is organized as follows. In Sect. 2, we present a new formulation for machine layout problem. In Sect. 3, we introduce a hybrid genetic algorithm that provides a solution for this formulation. In the Sect. 4, we present the experimental results. Finally, Sect. 4 discusses future works and conclusions.

## 2 Problem Formulation

Previous studies using the traveled distance focus on how to place machine on prefixed position. The major contribution of this paper relies on the use of direct distance which makes the calculation much more complex. In fact, our approach seeks the best machine positions by moving the machines in the available area one by one in order to respect proximity constraints and not like previous works by affecting machines in prefixed positions which explain the complexity of our approach. Our contribution consists in using direct distance to make sure the proximity constraints are respected and taking into account machine dimensions while calculating distances between machines. Figure 1 illustrates the two types of distances, traveled distance and direct distance, between two machines, in a loop layout configuration.

Given a set of M machines M1, M2,…MM with machine M1 constituting the Load/Unload (LUL) station, P number of horizontal cells of the grid G, Q number of vertical cells of G, TH, and TV width and height of grid cells (N * N) proximity constraints matrix, operating sequences and production ratios, we place machines on grid G in order to reduce the cost of transporting products without violating any proximity constraint. The objective function of our problem is to minimize the sum of flows time distances as described in following formula:

$$Min \sum_{i=1}^{N} \sum_{j=1, j \neq 1}^{N} f_{ij} d_{ij} \quad (1)$$

where $d_{ij}$ denotes the traveled distance between the two machines $i$ and $j$, and $f_{ij}$ the traffic of the parts between them.

Attempting to resolve this problem, we propose a two stage approach. The first step consists only in positioning the machines on a grid while respecting the proximity constraints and machines dimensions. The second step aim to optimize the path between these machines already positioned in order to minimize number of the loops traveled by parts. In this paper, we present only the first stage of this approach. The Eq. (1) cannot be used at this level since the path between different machines is not yet build. Thus, we should use a new objective function. We noticed that Eq. (1) depend on the length of the path between these machines. Meanwhile, to minimize the occupied area of these machines leads formally to minimize the length of the path between them. Hence, the objective function that we use is to minimize the occupied surface between placed machines.

## 3 Proposed Approach

There are many definitions of the agent concept, and there is no unanimity on this term. According to Ferber [14], an agent can be defined as an autonomous entity, real or abstract, which can act on itself and its environment, which, in a multi-agent context, may communicate with other agents whose behavior is a consequence of its observations, knowledge, and interactions with other agents. According to Wooldridge [15], an agent is a computer system capable of acting independently and in a flexible environment. Each agent can have a set of features with different degrees. This leads us to classify the agents into two main classes [14]: Cognitive Agents where each agent has a knowledge base containing all the information and know-how necessary to carry out its task and management of interactions with other agents and its environment. Reagents in which each agent has a mechanism to react to events, not taking into account either a clarification of goals or planning mechanisms. Other types of agents, called hybrid, using both types of behavior, appeared, therefore.

An SMA is a system consisting of agents that interact in and through an environment. According to Ferber [15] an SMA is divided into two levels. A micro level for the agent and a macro level for the system. Any approach to construction of SMA should take into account these two levels. According Ocello et al. [16], an SMA consists of four elements: Agent, Environment, Interaction, and Organization. This decomposition is called a decomposition Vowels.

The SMAs have two possible architectures. The first is the centralized architecture which is characterized by the absence of direct communication between agents. This role is provided by a blackboard that acts as an intermediary between the agents. This architecture is provided by an independent oversight mechanism. The second is the distributed architecture which is characterized by the total distribution of knowledge and control. Communication between agents is done by sending messages. In our work, we adopted the second architecture.

## *3.1 Identification of Agents*

The identification of agents and roles is a key step in the modeling of SMA [15]. In MAS, it should be noted that each agent can play one or more roles, and that each role can be played by one or more agents. For our problem, two types of agents are identified (Fig. 2): Machine Agent and Optimizer Agent.

**Machine Agent:** The role of a machine agent is to find the best position of the machine in question on the grid while respecting the constraints of proximity and size of the machines. Moreover, the machine agent intends to minimize the surface occupied by all the machines on the grid.

**Optimizer Agent:** In our system, the optimizer agent is a single agent that solves conflicts between machines. This agent records the movements made by each machine on the grid to find a feasible solution. Then in order to avoid local optima, the optimizer agent disrupts positions of all machines that allow starting a new search. In the end, after machines placement, the optimizer traces the path traveled by parts while trying to minimize the generated cost of transportation.

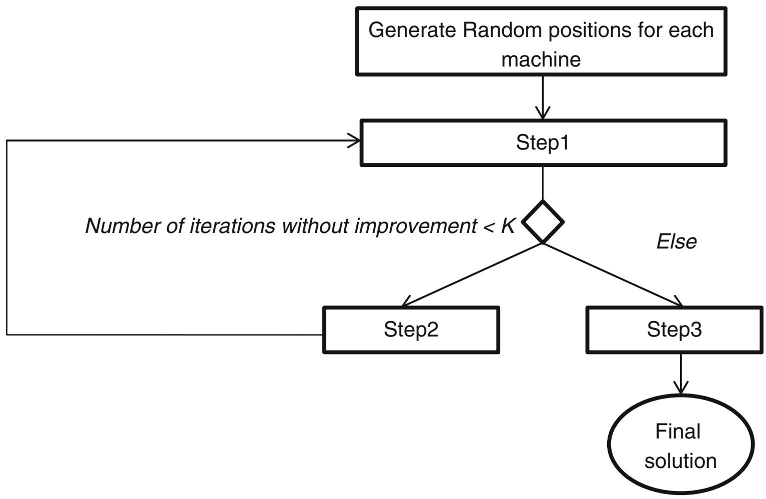



**Fig. 3** The resolution steps

As result, solving the problem involves the following steps as presented in Fig. 3:

- First Step: Assigning a position to each machine that meets the constraints that called a feasible solution.
- Second Step: Disrupting the found solution by assigning a random position to each machine in order to avoid local optima.
- Third Step: Tracing the path traveled by part while trying to minimize the generated cost of transportation.

## *3.2 Machine Agent Architecture*

To reach their goals, each machine agent Mi has a "smart" decision module which tries to find the best position of the machine at a particular point in time according to the positions of other machines. As regards the communication between the machines, it will be done by sending messages between different machine agents.

Each machine agent is defined by static knowledge which are the length and the width of the grid and the machines dimensions. And it is also defined by dynamic knowledge which are the coordinates of each machine, the status of each machine that notify if the proximity constraints are satisfied or not. In case of extension of our problem to take new constraints such as the failure rate of the machines we will just change the knowledge of machine agents to reflect these changes.

**Table 1** The description of the messages in our system

| Reference | Designation |
|---|---|
| CP | A request sent to change place |
| ACCEPT | A message sent from CP receiver to CP sender to inform that proposed action is accepted |
| REJECT | A message sent from CP receiver to CP sender to inform that proposed action is rejected |
| CONFIRM | A message sent from CP sender to other machine agents to confirm the proposed action |
| CANCEL | A message sent from CP sender to other machine agents to cancel the proposed action |

## *3.3 Identification of Messages*

We should note that each step needs communication and negotiation between agents. Thus, specific messages should be implemented for each step as detailed in Table 1.

## *3.4 The Principle of Functioning*

Figures 4, 5 show the colored Petri nets model of our system composed with different machine agents and an optimizer agent named "opt." Several studies are done to modeling multi agent systems with colored Petri nets [17–20]. In this model, the places Pi1, Pi2…, pi13 are describing the shared places for message sending. Transitions represent the actions of sending or receiving messages or decision making as described in Table 2.

Starting from a random arrangement of machines, the system must satisfy the proximity constraints. Therefore, each machine agent initiates a local search procedure for the best position based on its decision module. Then, they communicate and negotiate to find the best possible solution. This communication will be provided by several types of messages.

This procedure can be interrupted when a CP message arrived. At the end, the machine agent sends a message to other machines for permission to change the current position with the position generated by this search. Each machine agent that receives a CP message should check its priority (i.e., the older CP message has the highest priority). In case where two CP messages have the same dispatch date the highest priority granted to the message that have lower sender index (see Fig. 3).

Once the priority is solved, we calculate the gain or the losses made by the change of the new proposed position. In the case of gain, An ACCEPT message will be sent otherwise it will be a REJECT message. Note that to achieve or not a change of the position two cases emerge:

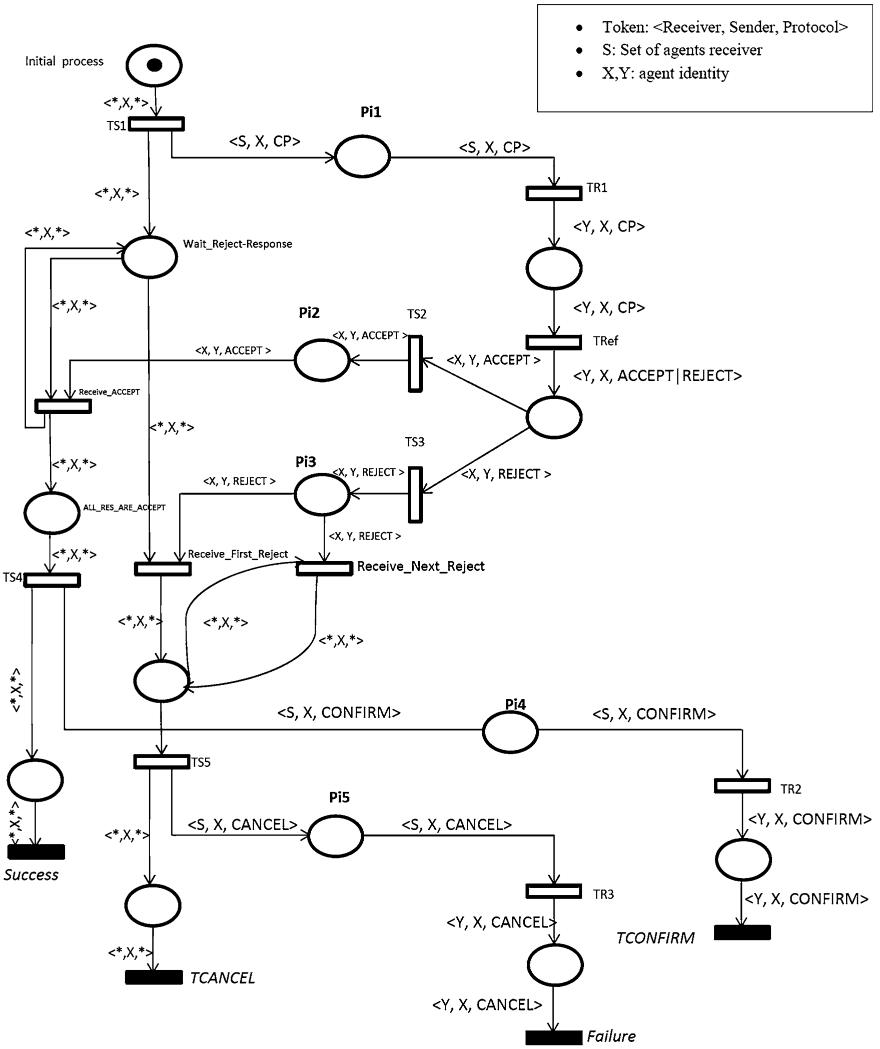



**Fig. 4** A coloured petri nets modeling of the first step with one iteration

- The machine agent, that have the highest priority CP message, must receive an ACCEPT message from all others machines. Then, they receive a CONF message to inform them that this movement should be approved. We note that the new status of the CP message's sender should be communicated.
- The required movement is canceled if one or more other machine agents send a REJECT message. Thus, a Cancel message is send to other machine agents by the machine agent that have the highest priority CP message.

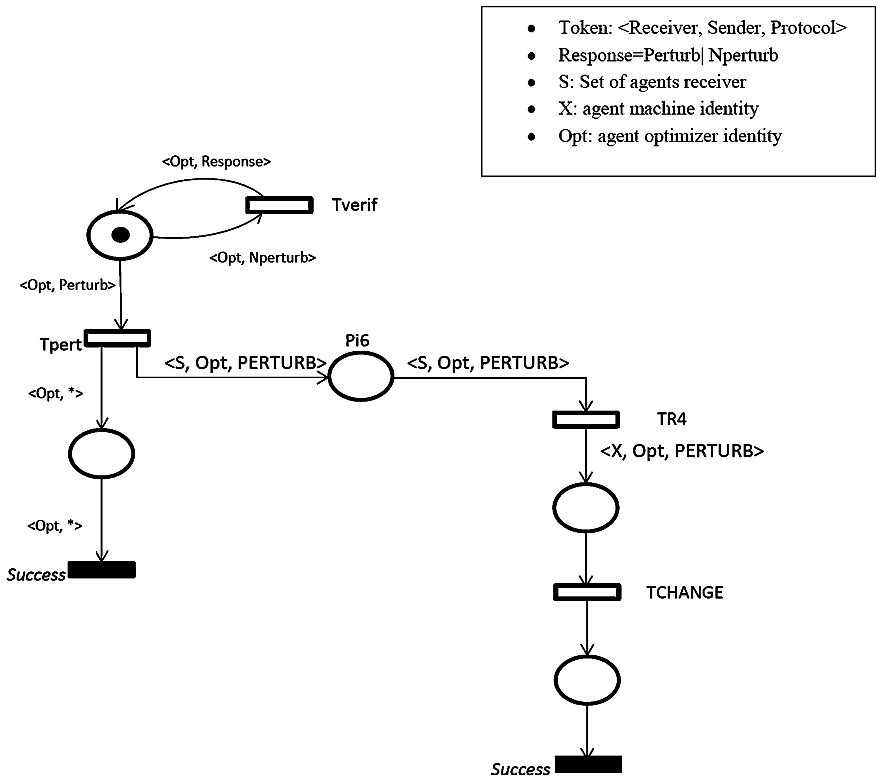



**Fig. 5** A coloured petri nets modeling of perturbation procedure

**Table 2** Description of different transition in our colored petri nets modeling

| Reference | Designation |
|---|---|
| TR | An action of receiving a message |
| TS | An action of sending a message |
| TREF | An action which is trigged after the reception of CP message. This action generates two types of feedback: Accept or Reject. The response results from validation procedure. This procedure verify two conditions<br>- The received message is the first request sent<br>- The proposed movement should not violate proximity constraints of receiver agent |
| TCONFIRM | The receiver agent confirms the proposed movement and updates its knowledge |
| TCANCEL | The receiver agent ignores the proposed movement |
| TPERT | The optimizer agent generates new random positions for all machines |
| TVERIF | The optimizer agent verify if all machines agent are satisfied or dysfunction of the system (no possible solution) |
| TChange | The receiver machine agent updates the positions and status of all machines |

In order to avoid a local solution, we repeat these procedure N iterations to increase the search area. Therefore, two procedures must be executed: save the current solution and generate new random positions for all machines and hence comes the key role of optimizer agent. It has a global view of status of all machines. Figure 4 illustrates the perturbation procedure.

## 4 Conclusion

In this paper, a multi agent system was proposed in order to place machines into grid while respecting proximity constraints. The objective function is to minimize the occupied area by these machines. Therefore we used a colored Petri Nets for modeling interactions between agents in our system. In future work, we will present the approach we used to construct the convex hull that aim to minimize transportation costs.

## References


1. Kim JG, Kim YD (2000) Layout planning for facilities with fixed shapes and input and out points. Int J Prod Res 38:4635–4653
2. Tompkins JA, White JA, Bozer YA (2003) Facilities planning, 3rd edn. Wiley, New York
3. Afentakis A (1989) A loop layout design problem for flexible manufacturing systems. Int J Flex Manuf Syst 1:175–196
4. Tansel BC, Bilen C (1998) Move based heuristics for the unidirectional loop network layout problem. Eur J Oper Res 108:36–48
5. Nearchou AC (2006) Meta-heuristics from nature for the loop layout design problem. Int J Prod Econ 101:312–328
6. Ozcelik F, Islier AA (2006) Unidirectional Loop Layout Problem with Balanced Flow. International Conference on Industrial, Engineering and Other applications of Applied Intelligent Systems. 4031:741–749
7. Drira A, Pierreval H, Hajri-Gabouj S (2007) Facility layout problems: a survey. Annu Rev Control 31:255–267
8. Cheng R, Gen M (1998) Loop layout design problem in flexible manufacturing systems using genetic algorithms. Comput Ind Eng 34:53–61
9. Leung J (1992) A graph—theoretic heuristic for designing looplayout manufacturing systems. Int J Prod Res 57:243–252
10. Chaieb I, Korbaa O (2003) Intra-cell machine layout associated with flexible production and transport systems. J Eng Manuf 217:883–889
11. Chaieb I, Korbaa O, Camus H (2001) Short term planning of cyclic production in FMSs, 29th International Conference on Computers and Industrial Engineering. Montreal, Canada
12. Chaieb I, Korbaa O, Gentina JC (2001) Machine layout problem in FMS design, International. Conference on Advanced Intelligent Mechatronics, vol. 2, Como, Italy, pp 1035–1040
13. Kumar RMS, Asokan P P, Kumanan S (2008) Design of loop layout in flexible manufacturing system using non-traditional optimization technique. Int J Adv Manuf Technol 38:594–599

14. Ferber J (1995) Les systèmes multi-agents. Vers une intelligence collective. InterEditions, Paris
15. Wooldridge M, Jennings N, Kinny D (2000) The Gaia methodology for agent- oriented analysis and design. Auton Agent Multi-Agent Syst 3(3):285–312
16. Occello M, Demazeau Y, Baeijs C (1998) Designing organized agents for cooperation with real time constaints. CRW 25–37
17. Fallah-Seghrouchni AEl, Serge H, Hamza M (2001) A formal study of interactions in multi-agent systems. Int J Comput Appl 8(1)
18. Kristensen LM, Christensen S, Jensen K (1998) The practitioner's guide to coloured petri nets. In: Jensen K (ed) Special section on coloured petri nets. Springer, Verlag. Int J Softw Tools Technol Transfer 2(2):98–132
19. Cost RS, Chen Y, Finin T, Labrou Y, Peng Y (1999) Modeling agent conversations with colored Petri nets. In gents: working notes of the workshop on specifying and implementing conversation policies. Seattle, USA
20. Huget MP, Koning MP (2002) Ingénierie des protocoles d'interaction pour les systèmes multi-agents. 10èmes Journées Francophones Intelligence Artificielle Distribuée et Systèmes Multi-Agents, JFIADSMA'02

# Organizational Procedures for the Integration of Process Planning and Scheduling in Job-Shop Manufacturing

**Sascha Häckel, Jan Keidel and Thomas Kehrer**

**Abstract** This paper presents two different models for the organizational procedure of Integrated Process Planning and Scheduling from scientific literature. These approaches try to connect both components of the Product Development Process to realize better results in planning. Objectives of these approaches are the reduction or even the elimination of capacity conflicts, the reduction of makespan, and the compliance of due dates as well as the adaption to disturbances at job floor. An introduction and a description of problems of the classical procedure as well as advantages of an integrated view will be followed by a presentation of both models of integration called Non-linear Process Planning (NLPP) and Closed-loop Process Planning (CLPP). Another main component of this paper is a further developed model based on NLPP, which is able to overcome the significant deficits of the models presented in scientific literature.

## 1 Introduction

In classical Production Planning and Control systems (PPC-systems) process planning and scheduling are implemented in a successive way. This procedure leads to separate and independent optimization processes without taking interdependencies between both planning tasks into consideration. Furthermore it is not possible to regard to alternative process plans with different sequences of operations or alternative resources. As a consequence scheduling is based on only one fixed work and assembly plan, which limited the degrees of freedom in optimization. The problem of uneven capacity utilizations (overload or underutilization of resources) occurs. Furthermore an extension of the completion time impends

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and might lead to a violation of due dates. In addition there is a risk of generating unfeasible schedules because of unsolvable resource bottlenecks. Regarding that fact the concept of Integrated Process Planning and Scheduling (IPPS) appears to be the most reasonable solution because in those concepts interdependencies between the planning stages could be taken into consideration within a global optimization process.

Process planning and scheduling are important planning tasks within the Product Development Process (PDP), which is dividable into the main phases of product engineering and product manufacturing. Product engineering includes product planning as well as construction and design, while product manufacturing consists of production planning together with production and assembling. Process planning plays a decisive role in manufacturing enterprises [1], because it represents the interface between product engineering and product manufacturing [2] and connects both phases. In process planning and scheduling (production planning) different objectives are focused. In process planning technical feasibility and the minimization of technological costs are aspired. In contrast, production planning aims at different time-referenced objectives, e.g., makespan and due dates as well as capital commitment costs [3–5]. To get better results in planning an integration of process planning and scheduling is intended to realize a simultaneous planning process. Figure 1 illustrates an overview of the Product Development Process and its components.

In the following sections two different models for the organizational procedure of IPPS from the scientific literature are presented. These concepts called Nonlinear Process Planning (NLPP) and Closed-loop Process Planning (CLPP) try to connect process planning and scheduling in order to reach better results in multi-criteria planning. Among several advantages those approaches are equipped with some disadvantages, too. In the following, the main characteristics of those concepts are ensued by the presentation of the further developed model based on

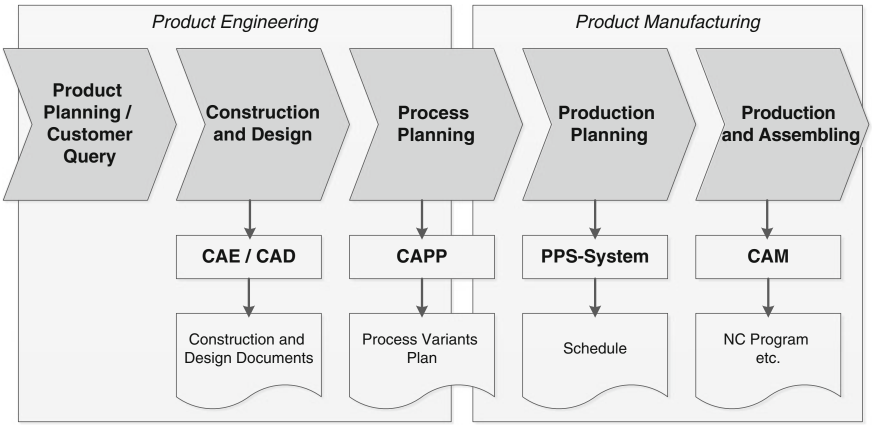


**Fig. 1** Procedure of product development process (PDP)

NLPP. The new model enables to overcome the most disadvantages of the two known approaches. In the conclusion the main results and findings as well as objectives for future research will be outlined.

## 2 Integrated Process Planning and Scheduling

Process planning and scheduling are two of the most important tasks of a manufacturing system. They represent the interface between construction and design (CAD) and manufacturing (CAM) [6]. In addition both tasks affect the profitability of the product manufacturing process, the capacity utilization of resources as well as delivery periods [7]. The process plan determines resources, operations, and sequences, which are necessary for product manufacturing and order satisfaction [6]. Chang and Wysk define process planning as a procedure of preparing detailed instructions for transforming an engineering product to a final product [8]. This results in a determination of machines respectively resources, process parameters, machining tools, and appliances as well as sequences of operations. Within the scheduling process these operations will be allocated to specific resources (machines, tools, etc.) with respect to an objective or to multiple objective functions, e.g., makespan or completion dates. Furthermore scheduling determines starting times und completion times for each operation based on the sequences of the underlying work and assembly plan [6].

However, the input of process planning and the availability of resources restrict the degrees of freedom in scheduling. Apart from scheduling, process planning affects available resources which emphasize the interdependencies of process planning and scheduling. Without regarding this fact the classical procedure handles these tasks independently in a successive way. The main advantage of this procedure is the division of the main planning task into two less complex ones to simplify the solution process. A disadvantage is the separation of the optimization of both tasks, which could lead to non-optimal solutions. This strategy is applicable for static environments like mass production [9] because in that case manufacturing of a product takes place without modification over a long period of time [10]. However, present-day production environments are characterized as dynamic systems and by a variety of requirements such as decreasing processing times, higher quality, product diversity, and competitive cost structures. Taking these aspects into consideration, it appears debatable whether achieving satisfying results by applying the traditional procedure is realistic [9].

Further reasons are listed below:

- Process planners assume an ideal shop floor with unlimited capacities and always available resources. They create an individual work and assembly plan for each order and choose most suitable resources. As a result a resource bottleneck for specific (high performance) resources can occur because the availability of the resource might not be given. This leads to an agglomeration and it becomes impossible to execute these work and assembly plans [11].

- In most cases schedules are determined after generating the work and assembly plans. Arising fixed process plans can cause unbalanced capacity utilizations and avoidable bottlenecks [6]. The approach ignores the opportunity of using alternative resources for operations [9].
- Even if the dynamic shop status with restrictions is considered during process planning, the time delay between planning and scheduling could cause changes. Thus, process plans may become suboptimal or even invalid. Kumar and Rajotia refer to investigations, in which 20–30 % of the total process plans had to be modified to adapt to dynamic changes in a production environment within a given time period [6, 11].
- In general within models of process planning and scheduling a single criterion optimization is realized to determine optimal solutions. In real manufacturing environments more than one criterion is important for optimization [11].
- Furthermore, in process planning and scheduling different, partially conflicting objectives are affected. Process planning emphasizes technological requirements and costs, while scheduling focuses on timing and resource utilization aspects. Without coordinating these two processes, it could cause competing problems [11].

To overcome the deficits of this traditional view, an integrated approach of process planning and scheduling is indispensable [6]. The integration of both tasks improves the efficiency of resources because of the elimination of capacity conflicts, reduction of makespan, and a better adaption to irregular disturbance in manufacturing such as machine breakdowns [12]. The integration concept is realized in various ways in different models of IPPS. A distinction is made between three different fundamental approaches called Non-linear Process Planning (NLPP), Closed-loop Process Planning (CLPP), and Distributed Process Planning (DPP) [6]. This paper refers to the concepts of NLPP and CLPP in more detail. Further information of DPP is presented in the scientific literature of Phanden, Jain and Verma [9].

## 3 Integration Models in the Scientific Literature

### *3.1 Non-Linear Process Planning*

The procedure of NLPP generates all possible alternative process plans for each product with a ranking according to the relevant process planning objective(s) before the scheduling procedure starts [9]. In this context flexibility regarding operations, sequences, and processes is given. Flexibility of operations means the possibility of manufacturing operations on different resources while sequence flexibility stands for exchangeability of operation sequences. Process flexibility contains the possibility to produce the same feature with alternative operations or alternative sequences of operations [13].

The underlying assumption is that potential problems can be solved before manufacturing starts. Consequently NLPP is based on a static production environment without back-coupling in case of disturbance. As described before NLPP starts with a ranking of potential work and assembly plans according to determined optimization criteria, such as processing time, which are stored in a database. As soon as an order should be manufactured the top priority process plan is selected by database query. After that the scheduling procedure starts. If the resulting schedule is adverse or not feasible within actual shop floor situation, the process plan with the second best priority is chosen. This strategy continues until a suitable process plan has been calculated [9]. In NLPP an increased flexibility can be realized because of the availability of alternative process plans for the given product(s). That fact could also turn into a disadvantage. A large amount of products is tendentially accompanied by a large number of alternative process plans, which might cause problems in memory capacity [9, 14]. Furthermore a higher effort in process planning exists because a variety of work and assembly plans has to be generated. By taking the real-time manufacturing environment into consideration, some of the generated plans might be unfeasible. If quantity of process plans increases the complexity of representation respectively modeling for scheduling rises, too. Information flow of NLPP takes place in one direction from process planning to scheduling [15]. Figure 2 shows NLPP procedure in a schematic way (based on [6]). Within this model planning is made in a successive way analogue to the information flow. Compared to the non-integrated classical procedure NLPP improves the degrees of freedom in scheduling with the possibility of shifting information from process planning to scheduling. On the contrary, the ranking of process plans restricts the just stated degrees of freedom because this ranking refers to process plans of only one order respectively product. Consequently this concept represents a local optimization without taking the overall situation (additional orders etc.) into account. In subsequent scheduling process the first schedulable process plan of an order respectively product, which meets specified requirements is chosen. From this fact it follows that the overall situation is not considered once more.

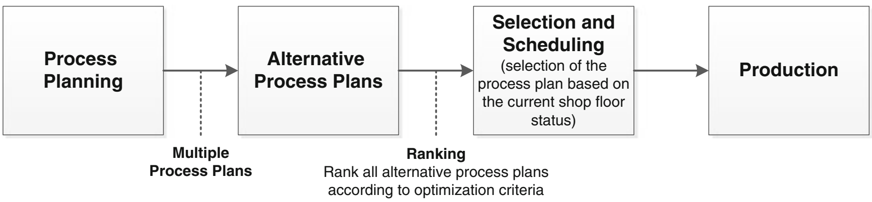


**Fig. 2** Procedure of non-linear process planning

## 3.2 Closed-Loop Process Planning

Closed-loop Process Planning tries to replace static manufacturing environment from NLPP by a dynamic back-coupling. Within CLPP process planning generates work and assembly plans on back-coupling basis using real-time information of available resources in shop floor. This ensures the generation of feasible process plans according to the capacity situation [6], which results in a decrease of effort in planning compared to NLPP. But the lower number of generated process plans limits the degrees of freedom in optimization. As soon as an operation is finished in shop floor the next operation and the resource utilization is determined on basis of feature-based part description. This procedure considers dynamic changes in shop floor since real-time information about different status is of supreme importance for CLPP. According to Iwata and Fukuda it might be necessary to restructure the departments of process planning and scheduling within an enterprise to profit from this approach [9, 16]. Another point is that the continuous availability of required real-time information could be problematic [6]. The CLPP-model is able to describe the actual integration of process planning and scheduling in a suitable way [6]. Figure 3 (based on [6]) schematically illustrates the CLPP-model.

In contrast to NLPP CLPP is equipped with a back-coupling information flow without a successive planning procedure. The scheduling department provides latest data about available resources, which enables the process planning department to generate work and assembly plans. By analogy to NLPP-model there is a local optimization process within both departments. A difference in both models can be identified in the consideration of current capacity situations, which is an advantage of CLPP. The fact that there is a successive planning of each existing production order could be emphasized as a disadvantage.

As a result the overall situation and different interdependencies of orders are not taken into consideration. Within CLPP a distinction is made between two types of reactions because of resource bottlenecks or malfunctioning. On the one hand there is a reaction in scheduling on basis of selected process plans, which is related with a limited number of process variants and a low responsiveness. On the other hand there is the possibility to react flexibly in process planning by creating new process plans. Under certain circumstances this might cause problems in timing. In this case a high responsiveness interconnected with a low reaction speed holds on.

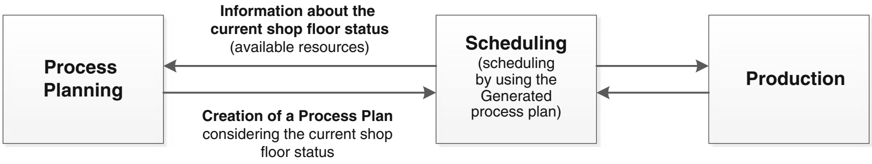


**Fig. 3** Procedure of closed-loop process planning

In summary, it can be stated that there is still optimization potential in NLPP and CLPP, which remains unused since the lack of taking the overall view into the models' consideration. Only if all possible process plans of each production order are included into planning process it would be a holistic view. The subsequent model named Extended Non-Linear Process Planning is able to overcome these deficits.

## 4 Extended Non-Linear Process Planning

Both integration models which have been presented in the previous section have different advantages and disadvantages for practical application. The model of Extended Non-Linear Process Planning (E-NLPP) targets to overcome the disadvantages of both models and to combine their advantages. E-NLPP is based on the basic model of NLPP, which realizes a shift of knowledge from process planning to scheduling. This procedure purposes to increase the degrees of freedom within scheduling. The work and assembly plans respectively the process variants are depicted in an implicit way as a process variants plan (PVP).

The PVP consists of all possible operations to manufacture the related product and technological as well as sequence-dependent interdependencies between them. In addition it is possible to represent any feasible alternative structure for manufacturing the product. The so called Common Integrated Selection and Scheduling Problem (CISSP) is used as basis of PVP. CISSP is a universal mathematical graph model for representing practical real-world problems focused on scheduling [3–5, 17]. The model enables to describe multi-stage as well as integrated tasks in combinatorial optimization and as a consequence a simultaneous optimization of process variants and scheduling becomes possible. The arising two-stage combinatorial optimization problem consists of a selection problem (selection of a feasible process variant) and a sequencing problem (scheduling of operations with respect to resource capacities) [5]. Figure 4 shows a process variants plan of two jobs as an example of the CISSP model which consists of nodes and arcs to describe the precedence relationships between the nodes. There are several different types of nodes within the model:

- *Start nodes* These nodes describe the initial point of a connected subgraph of the problem (source nodes). Source nodes do not have predecessors.
- *Operation nodes* Nodes of this type represent activities or elementary processes for sequencing and scheduling. Each operation node has to have at least one incoming arc.
- *Decision nodes* For modeling this problem it is necessary to allow making different decisions about continuation of paths in the graph. Operators are used to specify these decisions closer. A distinction is made between decisions of selection (operator: *XOR*) and decisions of sequencing (operator: *AND*).

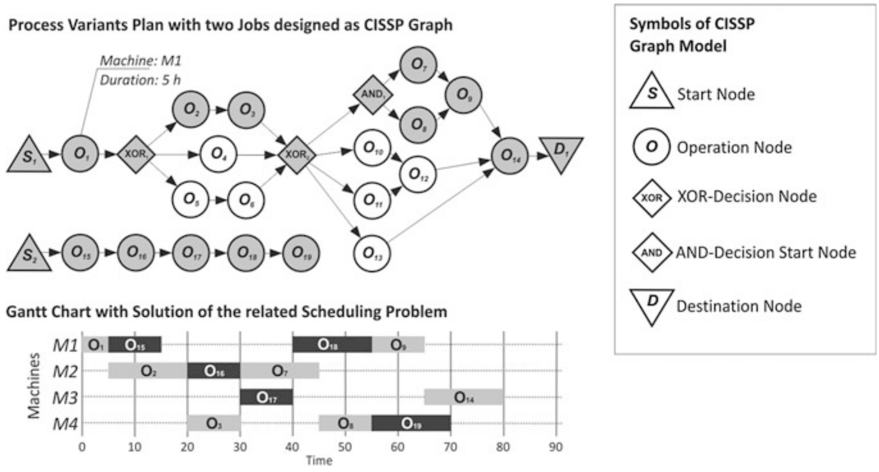


**Fig. 4** Example of a CISSP model

- *Destination nodes* This type of nodes describes the completion point of a connected subgraph in the sense of a drain node. Destination nodes do not have a successor node and are not obligatory within the graph model. It is possible to use this construct as a synchronization point or as in the example of application to model due dates.

Source nodes describe the initial point of different jobs ($S_1$ and $S_2$, see Fig. 4). Destination nodes can be used as completion point of a production order. They can include different information, e.g., due dates of the current order. Each single operation of the machines is modeled by operation nodes ($O_1$-$O_{19}$). Decision nodes with operator *XOR* implicitly describe different process variants of the process variants plan (alternative operations respectively process chains). Decision nodes with operator *AND* enable the modeler to describe sequence-flexible operations or process chains analogous to Open Job Problems. Moreover, CISSP model contains further components to assign different data such as time windows, resources (capacities), and durations as well as a system to define restrictions within the selection problem and different calendars to provide availability times of resources [3–5, 17].

Within the E-NLPP model an inclusion of all process variants plans of not yet released jobs (production orders considered in planning process) takes place. The optimization problem not only contains process variants selection of one new production order but rather there is a selection of process variants of all jobs of orders backlog. In this process of selection the generation of a process variants ranking according to an optimization criterion is not required. The evaluation of the process variant is made in combination with other determined optimization criteria (e.g., compliance of delivery dates, technological costs, makespan, etc.). A Genetic Algorithm (GA) is used to solve problems based on the presented

CISSP model. Within the GA a two-stage encoding mechanism based on permutation chromosomes according to the two-stage optimization task (problems of selection and scheduling) is implemented [18]. The CISSP model has been tested in the context of a research project by reference to a real production environment of an involved enterprise. The orders backlog contains 100 orders consisting of 12–14 operations with between 2 and 36 alternatives for each operation. The machine park consists of 60 different resources (machinery, tools, etc.) [19]. By using this approach the focused objectives, namely processing times of orders, makespan, and set-up times for resources, could be improved significantly.

Consequently the optimization process is a matter of taking the overall situation into consideration without separating the optimization of process planning from scheduling. This integrated optimization procedure of process planning and scheduling with the application of CISSP graph model has been a main topic of different author's publications [3–5, 17–19]. After the planning phases the results will be transferred to the manufacturing department in real time. In return information including current resource capacity is provided to the planning departments. As a result the information flow is directed in both ways, which enables a back-coupling between the planning and the manufacturing departments. This fact signifies a further development compared to NLPP since the back-coupling functionality enables a transfer of relevant information, which allows the realization of a Rolling Wave Planning and the possibility to start a replanning process. In addition the back-coupling has the function to react on potential problems, e.g., machine malfunction or technical service, which require replanning activities. In an ideal situation within E-NLPP all process variants plans of each order are available in an information technology way. As a consequence a high reaction speed on disturbances in production environment follows. A high responsiveness can be consternated because of two reasons. On the one hand a comprehensive knowledge database within process variants plan (CISSP model) provides the possibility to find feasible alternative work and assembly plans for production, which has already started. On the other hand it is possible to change process variants for non-critical orders to clear resource capacities for critical ones. In summary, different extensions of NLPP can be stated:

- Process variants respectively work and assembly plans are not explicitly generated. The representation is realized implicitly with a process variants plan on a graph model basis.
- E-NLPP model includes process variants plan of all of the not yet released jobs.
- It is not necessary to generate a ranking of alternative process plans according to an optimization criterion of process planning. Optimization procedure of process planning and scheduling takes place simultaneously by taking multiple optimization criteria (from process planning and scheduling) into consideration.
- By means of back-coupling function between manufacturing and optimization department it is possible to react on machine malfunction or the necessity of technical services, which imply a replanning procedure.

Together with the itemized advantages of E-NLPP the model shares a high planning effort within process planning as compared with NLPP. Each feasible process variant has to be generated and represented within information technology. The resulting degrees of freedom in scheduling are connected with a high complexity in process planning. This complexity can be controlled by new approaches in process planning. As an example it is possible to create process plans respectively work and assembly plans on a feature based product model basis in a partly automated way. This concept significantly reduces effort of process planning [20]. The procedure of Extended Non-Linear Process Planning is shown in Fig. 5.

For each new production order the process planning department creates a process variants plan which contains all feasible process variants in an implicit way. This new PVP together with all process variants plans of orders backlog are stored in a knowledge data base. Within optimization procedure this knowledge data base information acts as input. For each production order of the considered planning period the selection of a process variant and the scheduling on the required resources takes place. In this context different definable objectives are regarded simultaneously by a multi-stage and multi-criteria Genetic Algorithm. As a planning result a feasible schedule for manufacturing in the considered planning period follows from above-mentioned strategy. Potential machine malfunctions, other disturbances or alternations in planning will be reported back to the optimization procedure in real-time by the production department. In this case a new planning procedure in the sense of a Rolling Wave Planning will be initialized.

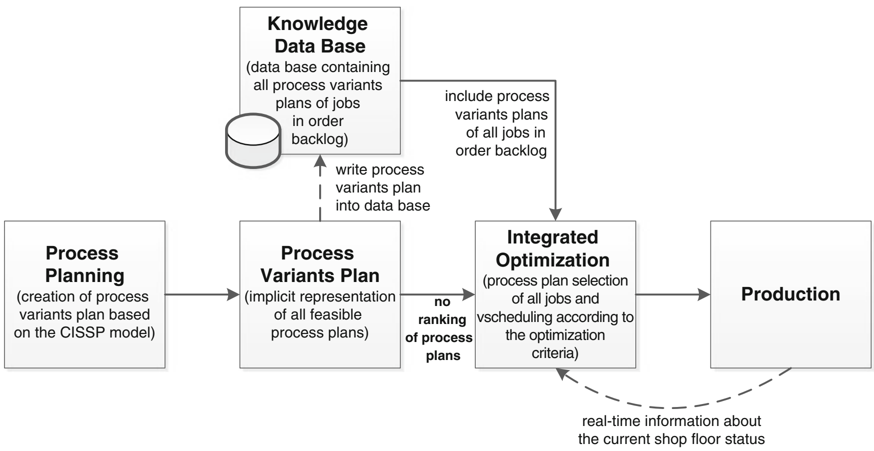


**Fig. 5** Procedure of the extended non-linear process planning

## 5 Conclusions

Process planning and scheduling belong to the most important tasks in a manufacturing system and represent the interface of construction and design (product engineering) and product manufacturing. Traditional approaches handle both tasks separately and successively. Today's production environments are dynamic and characterized by decreasing processing times, higher quality requirements, high product diversity, and the necessity of competitive cost structures. Consequently an integrated view of process planning and scheduling is essential. In this paper different models of integration have been introduced. Beside two models from scientific literature (NLPP and CLPP) the model of Extended Non-Linear Process Planning was presented as a further development of NLPP. Within NLPP a successive planning with one-way information flow is realized, which expands flexibility in manufacturing systems because of the availability of alternative work and assembly plans for products. The CLPP model supports the generation of process plans on a dynamic back-coupling basis, which provides real-time information about capacity situations from scheduling to process planning department. The model of E-NLPP differs from NLPP in a significant way. The representation of process variants is implicit and there is a back-coupling functionality from manufacturing to integrated optimization. This functionality enables to react on possibly occurring problems like disturbances (machine malfunction, absence of staff, etc.) with a replanning or a new selection of process variants for not yet started jobs.

## References

1. Eversheim W (2002) Organisation in der Produktionstechnik: Arbeitsvorbereitung, 4th edn. Springer, Berlin, Heidelberg, New York
2. Boos W, Zancul E (2006) PPS-Systeme als Bestandteil des product lifecycle management, Produktionsplanung und -steuerung: Grundlagen, Gestaltung und Konzepte, 3. Auflage, Springer, Berlin, Heidelberg, pp 781–808
3. Käschel J, Häckel S, Lemke S, Keidel J (2011) Integrated process planning and scheduling for job-shop manufacturing and temporary production networks. Supply Chain and Corporate Environmental Management, Verlag Dr. Kovač, Hamburg, pp 95–109
4. Lemke S, Häckel S, Keidel J (2012) A two-stage optimization model for integrated process planning and scheduling in job shop manufacturing. In: Proceedings of 22nd international conference on flexible automation and intelligent manufacturing, Helsinki, Finland, pp 457–464
5. Lemke S, Häckel S, Keidel J (2011) Das common integrated selection and scheduling problem (CISSP) am Beispiel der integrierten Prozessvariantenauswahl und Maschinenbelegungsplanung. In: Proceedings of 21st international conference Mittweida, Mittweida, Germany, pp 28–33
6. Li X, Gao L, Zhang C, Shao X (2010) A review on integrated process planning and scheduling. Int J Manuf Res 10(5):161–180

7. Yang Y-N, Parsaei HR, Leep HR (2001) A prototype of a feature-based multiple-alternative process planning system with scheduling verification. Comput Ind Eng 39(1):109–124
8. Chang TC, Wysk RA (1985) An introduction to automated process planning systems. Prentice-Hall, Englewood
9. Phanden RK, Jain A, Verma R (2011) Integration of process planning and scheduling: a state-of-the-art review. Int J Comput Integr Manuf 24(6):517–534
10. Larsen NE, Alting L (1992) Dynamic planning enriches concurrent process and production planning. Int J Prod Res 30(8):1861–1876
11. Kumar M, Rajotia S (2003) Integration of scheduling with computer aided process planning. J Mater Process Technol 138(1):297–300
12. Lee H, Kim S-S (2001) Integration of process planning and scheduling using simulation based genetic algorithms. Int J Adv Manuf Technol 18(8):586–590
13. Benjaafar S, Ramakrishnan R (1996) Modelling, measurement and evaluation of sequencing flexibility in manufacturing systems. Int J Prod Res 34(5):1195–1220
14. Usher JM (2003) Evaluating the impact of alternative plans on manufacturing performance. Comput Ind Eng 45(4):585–596
15. Jain A, Jain PK, Singh IP (2006) An integrated scheme for process planning and scheduling in FMS. Int J Adv Manuf Technol 30(11-12):1111–1118
16. Iwata K, Fukuda Y (1989) A new proposal of dynamic process planning in machine shop. In: Proceedings of CIRP international workshop on computer aided process planning, Hanover, Germany, pp 73–83
17. Lemke S, Keidel J, Häckel S (2012) Integrierte Prozessvariantenauswahl und Maschinenbelegungsplanung. Integrierte Planung der Produktentstehung—Feature-basierter Ansatz zur durchgängigen Planung von der Konstruktion bis zur Fertigungssteuerung, Mensch und Buch Verlag, Berlin, pp 135–174
18. Häckel S, Lemke S, Keidel J (2011) Ein Genetischer Algorithmus für das Common Integrated Selection and Scheduling Problem (CISSP). J Univ Appl Sci Mittweida 9:34–41
19. Keidel J, Häckel S, Lemke S (2012) Integrierte Prozessvariantenauswahl und Maschinenbelegungsplanung unter Berücksichtigung von mehreren Zielstellungen. In: Proceedings of conference Mobilität im Wandel, Zwickau, Germany, pp 20–27
20. ZKProSachs (2012) Integrierte Planung der Produktentstehung - Feature-basierter Ansatz zur durchgängigen Planung von der Konstruktion bis zur Fertigungssteuerung, Mensch und Buch Verlag, Berlin
21. Tan W, Khoshnevis B (2000) Integration of process planning and scheduling: a review. J Intell Manuf 11(1):51–63

# Intelligent Scheduling for Manufacturing Systems: A Case Study

**K. Efthymiou, A. Pagoropoulos and D. Mourtzis**

**Abstract** The aim of this paper is the presentation of a scheduling method, its implementation to a software system, and its application to a commercial refrigerator factory. The method employs the modeling of the factory's resources and the assignment of the workload of the resources in a hierarchical fashion. The developed software system simulates the operations of the factory and provides a schedule for the manufacturing system's resources. The system is integrated with a holistic virtual platform, namely Virtual Factory Framework that allows it to exchange data related to product, process, resources, and key performance indicators along with other software components also integrated with the Virtual Factory Framework. A set of digital scheduling experiments with data, coming from a real manufacturing system are conducted in order to validate the proposed method and the implemented system under different operational conditions.

## 1 Introduction

Modern manufacturing systems have to cope with the increased need for customized and personalized products in today's turbulent market demand. Producing a large number of different product models and variants, and having a fast response to customers' orders within a volatile environment are requirements in order for factories to be efficient and responsive. Factories of such characteristics may present high product and capacity flexibility, but they are also becoming more complex, and their planning and control is getting harder. Therefore, it is evident that scheduling of a production system that must satisfy at the same time cost, time, and quality constraints is of paramount significance [1].

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Planning and scheduling methods [2, 3] are applied in the majority of industrial sectors such as automotive, shipyards, ice cold merchandisers, and food and chemical industries [4, 5]. Several methods have been employed in literature toward addressing the problem of efficient scheduling under uncertainty. In [6], a rescheduling problem in parallel machine environment is considered and an optimizing algorithm that minimizes a certain stability measure is presented. The proposed method is applied on a given linear programming problem. In [7], a given heuristic method is described for determination of a good schedule alternative. The proposed method provides re-planning and re-scheduling options and is applied on a real case study featuring 100 tasks. In [8], a heuristic project scheduling method for human intensive projects is developed. The model takes into account the uncertainties that arise due to skill variation across different individuals as well as their learning rate. The efficacy of the approach is shown using real data from a software developing firm. In [9], a robust scheduling methodology based on fuzzy set theory is developed. A measure of schedule robustness based on qualitative possibility theory is proposed and a genetic algorithm is developed for solving the problem with acceptable performance. Moreover, Enterprise Resource Planning (ERP) systems have become prevalent throughout the international business world offering the effective maintenance of the bill of materials and bill of resources. ERP systems are capable of integrating resource management, commercial, after-sale, manufacturing, and other-business functions in one system around a database. However, the installation and the customization of ERP software packages to the needs of a specific manufacturing system are characterized of high complexity and large investment costs. Moreover, the planning and scheduling packages that are offered along with the ERP systems are not considered as efficient solutions [10]. On the other hand, mathematical programming approaches derived by operations research require the development of sophisticated mathematical constructs that are difficult applicable to real industrial problems. The majority of these approaches seem not capable of providing feasible solutions to many industrial problems and have rather limited practical use [5]. In conclusion, ERP systems require high cost for integration and installation to a company, while mathematical approaches present a poor applicability to real industrial problems.

This work presents the use of an intelligent scheduling method, its implementation as a software system that is integrated within the Virtual Factory Framework (VFF) and its application to the scheduling problem of a real manufacturing system. The short term scheduling approach is an intelligent method since it relies on a hybrid approach that combines game theory along with artificial intelligence techniques [11, 12]. The hybrid approach employed by this method allows the generation of feasible and efficient scheduling solutions in real time. VFF is a framework that provides a collaborative virtualized environment which facilitates the sharing of factory resources, manufacturing information and knowledge, and supports the factory planning phases ranging from the requirements definition up to factory dismantling [13]. A software system is developed following the method steps and is further integrated within VFF. The validity of the method and the software system is carried out with its application to the scheduling of the forming department of a commercial refrigerators factory under a workload of eight refrigerator models. Two different configurations of the forming department are investigated employing four different scheduling strategies. The first configuration concerns the organization of the department's resources in workcenters, while the second follows the grouping of machines in cells.

Section 2 includes the presentation of the manufacturing system under study. The departments of the factory and the material flow are described. A special emphasis is given to the forming department which is presented in detail along with the different types of refrigerators that are produced. Section 3 contains the planning method that is based on the hierarchical modeling of the factory, the work release, and the workload modeling. Section 4 presents the implementation and the integration of the software system to the VFF. Section 5 presents the results of the manufacturing system scheduling for different decision making approaches. The last paper focuses on the main issues and proposes future research and development activities.

## 2 Manufacturing System Model

The various departments, as well as the spectrum of different product variants that the system can manufacture are determined within this paper. The three types of processes that are performed for the production of a refrigerator concern the areas of steel sheet manufacturing processes, painting processes, and assembly operations. The aforementioned areas are further specified in seven manufacturing operations including, forming, subassembly, insulation, cooling mechanism subassembly, electrical mechanism subassembly, door's subassembly, and final assembly. The material flow of the refrigerators production and the interconnections of the processes is illustrated schematically in Fig. 1.

Forming contains the processes of cutting, punching, bending, shearing, and pressing. The material input in this section is steel sheet and the information input is the dimensions, the shape and quantity of the parts, as well as the production sequence for each part component of the refrigerator. Subassembly is related to the assembly of the external cabin, assembly of the internal cabin, and the assembly of external and internal cabin into one cabin. Insulation foaming is responsible for the

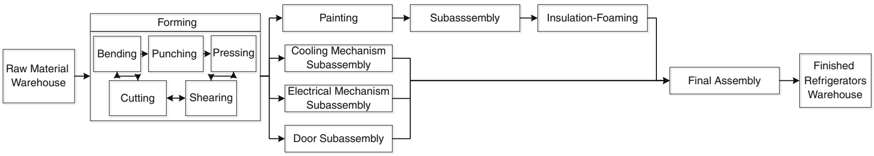


**Fig. 1** Material flow of refrigerators production and product's grouping and sequence

insulation of the cabin utilizing polyurethane injection. Painting involves the painting of the sheet metal parts of the refrigerator. In particular, parts are first washed, then drying follows and finally parts are painted. Electrical mechanism subassembly, cooling mechanism subassembly, and door's subassembly concern the assembly of the mechanisms and the doors, respectively. Final assembly is the final stage of refrigerator's production and involves the assembly of the components produced and assembled in the previous processes. Two assembly lines exist in the current factory capable of assembling one product model at the same time.

Forming department, responsible for the steel sheet manufacturing process, is the most complex department of the factory due to different types of the processes that are included, the variety resources types, the large number of machines, and the intricate relationships between the processes. Moreover, the performance of the forming department is crucial for the performance of other departments of the factory. The parts produced by forming must be ready in order to feed the following departments; otherwise the latter will be starved. In order to avoid starvation, the current practice of the factory is to keep a high inventory of parts produced by forming in order to ensure that the next departments will be fed properly. The high complexity of the forming department and its significant impact to factory's performance dictate the need for an efficient scheduling of this department's operations.

The forming department consists of 25 resources corresponding to the 5 processes, i.e., cutting, punching, shearing, bending, and pressing. Two alternative resources' configurations are investigated in this work. The first one organized the resources in workcenters including machines of the same process, while the second concerns the determination of cells producing a certain part family. The workcenter configuration of the department can be advantageous for a number of reasons. First, each operation can be assigned to a machine, which yields the best quality or the best production rate. Second, machines can be evenly loaded and third, machines breakdowns can be accommodated easily. The aforementioned advantages offer a high level of flexibility that is evident when a large variety of different parts with different process sequences are included. However, this flexibility requires making and implementing complex decisions for short term scheduling. On the contrary, a cellular configuration of the resources the short term scheduling is simpler since each product or product part is confined to a specific part and this allows the independent scheduling of each cell. However, the reduction of the scheduling difficulty comes with the reduction of the flexibility.

The first approach of grouping includes 5 workcenters, each one dedicated to a single process type where the included machines can work in parallel. Cutting workcenters contains 4 CNC machines, pressing workcenter includes 6 presses, shearing workcenter includes 4 shears, punching workcenter has 3 punching machines, and bending workcenter consists of 8 benders. The second configuration groups the machines in 3 cells. The first cell includes one shear, one press, one CNC cutting machine, two punching machines, and two benders. The second cell contains one shear, one pressing machine, one CNC cutting machine, and two benders. The third cell consists of two shears, four pressing machines, two CNC cutting machines, and four benders.

Eight different models of refrigerators are produced by the factory and the forming department under study. Produced models vary in terms of weight from 75 up to 225 kg, with external dimensions ranging from 50 to over 200 cm and a mean volume of 0.86 cubic meters. The models feature morphological differences, with some having one door, some two doors while some are open-front. The eight product models are categorized into two groups. The first group includes three product models while the second contains five product models. The forming department is confined to produce only one product model by each group at the same time. This restriction exists because the subassembly process and the final assembly process are organized with only two assembly lines that each line can work on simultaneously only one product model. Thus, although the forming department, either it is organized in workcenters or in a cellular form, is capable of addressing a product mix higher than two product models at the same time, the assembly lines dictate the number of product models to be produced at the same time.

## 3 The Planning Method

### *3.1 Factory Hierarchy*

A hierarchical model of four levels is employed in this work for the modeling of the factory for both configurations. The factory is considered as the highest level in the hierarchy and includes a number of jobshops. Each jobshop includes a number of workcenters or cells which in turn include a number of resources. Jobshops correspond roughly to the sections of the factory performing similar processes, workcenters and cells correspond, to some extent, to parts of the jobshops. The resources that belong to same workcenter are a sort of "parallel processors", namely they can process identical tasks. On the contrary, the resources of the same cell process different types of tasks. A resource is defined as an individual production unit, which can represent either a single machine or a group of machines with auxiliary devices. The hierarchical levels of the factory are shown in Fig. 2.

The sections of the factory that can be modeled as jobshops are these of forming, subassembly, insulation, cooling mechanism subassembly, electrical mechanism subassembly, door's subassembly, and final assembly. As previously mentioned, this work examines the short-term scheduling of forming, so only this section will be further detailed. In the case of workcenters organization, forming jobshops consists of the following five workcenters: (a) Cutting workcenter, including 4 CNC resources (RCNC#); (b) Pressing workcenter, including six pressing machines (RPress#); (c) Shearing workcenter, including four shears (RShear#); (d) Punching workcenter, including three punching machines

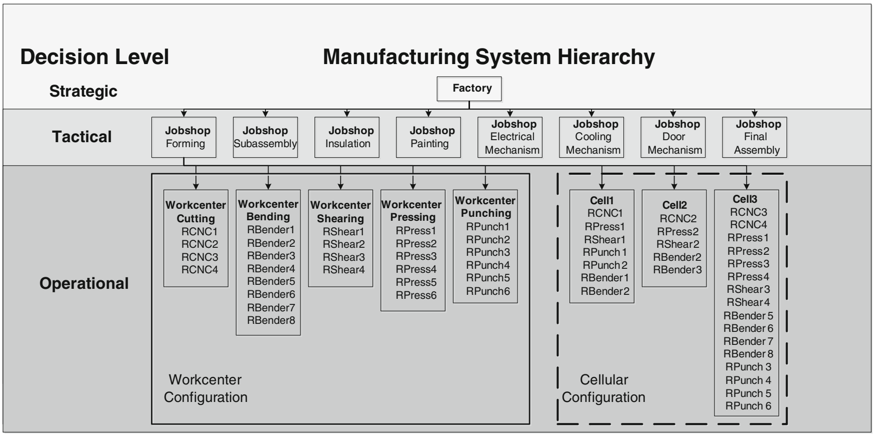


**Fig. 2** Factory model for the workcenter and cellular configuration

(RPuch#); and (e) Bending workcenter, including 8 benders (RBend#). In the case of cellular configuration the three cells constitute the forming jobshop are: (1) Cell 1, including one shear, one press, one CNC cutting resource, two punching machines, and two benders; (2) Cell 2, including one shear, one pressing machine, one CNC cutting machine, and two benders; (3) Cell 3, including two shear, four pressing machines, two CNC cutting machines, and four benders. The hierarchical models for both the configurations are presented in Fig. 2.

## *3.2 Work Release and Assignment*

Corresponding to the facilities' hierarchy, there is also the workload's hierarchical breakdown. The Orders consist of Jobs, which in turn consist of Tasks. The incoming Orders to the Factory are divided into Jobs, which are then released to Job Shops, and based on their specification are released to the proper Job Shop. In the case of workcenters configuration, the Tasks, included in a Job, can be again processed by only one Work Center and are therefore, released to the corresponding Work Centers. However, the Tasks can be processed by more than one of the Work Center's Resources. In the case of cellular configuration, Tasks are also assigned to resources of a cell and can only be processed by the available resources of the assigned cell no matter what if resources of another cell are capable and available for performing this task. For instance, a shearing task can be processed by all the shears that belong to shearing workcenter. On the contrary, the same task assigned to cell 1 can be assigned only to the available shears of cell 1 and not to the available shears of cell 2. The assignment of the requisite tasks to produce the final product to the factory's resources, results in a schedule for each resource of the factory and thus, a detailed plan and schedule for the critical parts of the entire

**Table 1** Workload information

| Product type | A1 | A2 | A3 | B1 | B2 | B3 | B4 | B5 |
|---|---|---|---|---|---|---|---|---|
| Demand (product units) | 5,900 | 3,796 | 5,190 | 1,400 | 2,630 | 5,190 | 400 | 150 |
| Number of tasks | 19 | 34 | 28 | 44 | 29 | 41 | 34 | 32 |

process is produced. The task assignment can be performed employing either dispatching rules such as FIFO or an Intelligent Scheduling (IS) algorithm.

### *3.3 Workload Model*

The manufacturing system under study executes orders for different customers. The main characteristics of an order are the quantity and the model of the refrigerator. The nature of the workload (parts, jobs, tasks) in each separate section of the factory under study is different. Each job arrives at every section of the factory, accompanied by a process plan (namely, a set of instructions that determine the sequence of the different tasks as well as their technological constrains). In the current work only one type of job is studied, this of forming. Workload consists of 20 different customer orders, which contain 8 different models of refrigerators to be produced. In total 24,656 units are to be produced, requiring 261 different types of tasks to be executed. Table 1 presents in detail the units and the tasks for each product model.

## 4 Software System Implementation and Integration

### *4.1 Implementation*

The system uses event driven simulation to simulate the manufacturing process and the execution of the workload by the factory's resources. The software is implemented using Java and is thus capable of operating on any system with a Java virtual machine (JVM). It consists of two main components the core and the graphical user interface (GUI). The core is responsible for reading/writing input/output files and generating and evaluating possible schedule alternatives. XML is used to represent both input and output data, the core leverages the Java DOM XML parser to read/write data. The GUI is responsible for visualizing the factory hierarchy and the workflow model and the optimum schedule. Furthermore, the GUI provides appropriate facilities for editing the input data according to the user's requirements (add/remove/edits elements, such as resources and tasks or change working time of the resources). The GUI is implemented using the Swing Java GUI toolkit.

### 4.2 Integration

The current software system is integrated with the Virtual Factory Framework (VFF) and is able to: (1) load data concerning manufacturing system's bill of material, bill of processes and resource; (2) write data concerning the short term scheduling of the manufacturing system, in particular the Gantt chart and the key performance indicators (KPIs) derived by the scheduling. VFF is a framework providing a collaborative virtualized environment, which facilitates the sharing of factory resources, manufacturing information and knowledge, and supports the factory planning phases ranging from the requirements definition up to factory dismantling [13]. The interoperability between different SW modules used during the phases of factory lifecycle that is offered by VFF reduce time and effort required for data translation to the various formats of each SW module.

The integrated software system communicates with VFM by consuming the IEP web service. In addition, two components were created, using Java, to support import and export procedures. Both procedures are using SPARQL notation to acquire the necessary individuals that constitute the module's input. The software system incorporates the two components and thus is capable of communicating with the VFM. The component diagram, presented in Fig. 3, provides an overview of the connector's architecture.

At the import phase, the client component proceeds by extracting individuals and their respective properties using the SPARQL Protocol and RDF Query Language SPARQL endpoint of VFM. The SPARQL component processes their sequence and hierarchies based on the VFDM based modeling in integrated software system below and stores them in memory for further processing, an XML file, consistent with the software system data model, is created as input for software system. Finally, when the schedule is completed, the KPIs calculated by VF-SSS are added using the built-in SPARQL export component. The SPARQL update component transforms information extracted from the modules output file in a suitable SPARQL update query, according to VFDM structure, and the client

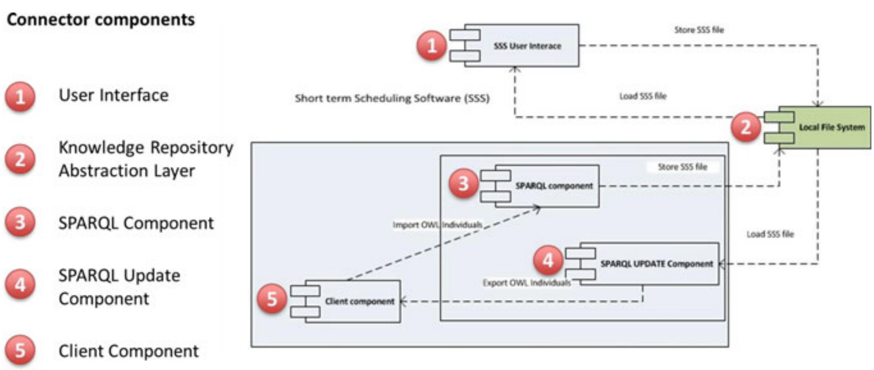


**Fig. 3** Connector diagram

component executes a SPARQL update through the VFM SPARQL endpoint, thus adding new individuals to the accessed file [10].

## 5 Results and Discussion

The validation of the proposed intelligent scheduling (IS) method (described in detail in [11, 12]) and the implemented software is carried out with the application of the approach to a real manufacturing system, in particular the forming department of commercial refrigerators production facility. Two sets of experiments are conducted, one for workcenters and another one for cellular configuration. Each set of experiments includes four different scheduling strategies. The first three strategies are dispatching rules, namely First In First Out (FIFO), Last In First Out (LIFO), and Shortest Process Time (SPT) that are used in industrial practice [1]. The last strategy aims to minimize the makespan of the product models operations employing an intelligent heuristics search (IS). Each schedule is assessed with the following conflicting performance measures: (1) Makespan of the whole production; (2) Mean flowtime of product models; and (3) Mean and standard deviation of resources utilization. Makespan is defined as the time it takes for the system to process a given amount of orders. Mean flowtime is defined as the mean time a batch of product models stays in the system and is computed as the sum of process time and idle time. Mean utilization is defined as the ratio of the total time a given resource is occupied to its available time, averaged over all the resources in the system.

### *5.1 Workcenters versus Cellular Configuration*

Workcenter configuration outperforms significantly cellular configuration in terms of all the performance measures. As it is presented in Table 2, workcenter configuration present smaller makespan (MS) and mean flowtime (MFT) for all the scheduling strategies, while the mean utilization (MUT) is higher. First, it is indicative that the maximum makespan in the case of workcenter is around 18 h using as dispatching rule SPT while the minimum makespan of cells is almost 31 h

**Table 2** Product models flowtime for different scheduling strategies

| | Workcenter configuration | | | | Cellular configuration | | | |
|---|---|---|---|---|---|---|---|---|
| Performance measure | FIFO | LIFO | SPT | IS | FIFO | LIFO | SPT | IS |
| Makespan (hrs) | 392,7 | 407,3 | 427,8 | 403,8 | 770,3 | 716,4 | 749,7 | 791,3 |
| Mean flowtime (hrs) | 94,6 | 98,7 | 96,6 | 97,2 | 121,5 | 98,9 | 120,4 | 123,8 |
| Mean utilization (%) | 27.0 | 27.1 | 27.7 | 27.9 | 16.1 | 17.4 | 16.5 | 17.1 |
| Utilization St. Dev. (%) | 19.0 | 18.6 | 20.0 | 18.0 | 24.1 | 24.6 | 23.7 | 24.3 |

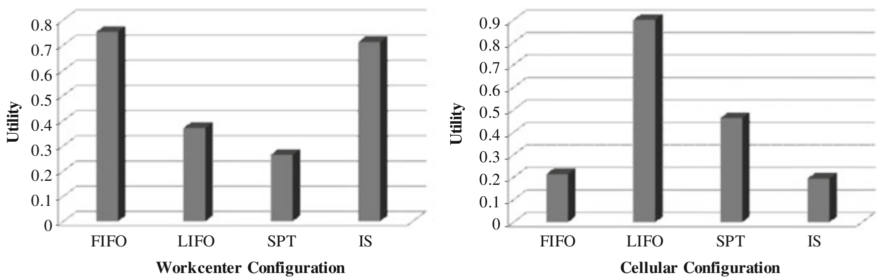


**Fig. 4** Utility for all the scheduling strategies for both configurations

for LIFO. The optimized behavior of workcenter configuration against cells configuration is quite evident in Fig. 4, where it is clear that the makespan in the case of cellular configuration is almost the double of the workcenter configuration. Second, the mean utilization of the resources grouped in workcenters is also higher than this of the cellular configuration resources independently of the scheduling strategy. It is interesting that the majority of workcenter configuration resources present a higher utilization while the maximum resource utilization belongs to cellular configuration resources. Moreover, it is quite evident from Table 2 that the utilization is more evenly distributed in the case of workcenters than in case of cells since the standard deviation of the utilization (SDUT) is higher for the cellular configuration. Third, the mean flowtime of the product models is smaller for workcenter configuration. The excellence of the workcenters should be expected since cellular systems are characterized by lower level of flexibility that leads to greater makespan and flowtime and lower utilization. The lower level of flexibility characterizes cellular configuration since product tasks can be assigned to every available suitable resource in the case of workcenters whereas in the case of cells a task can be assigned only to the available suitable resources of the cell that is responsible for the product.

## *5.2 Scheduling Strategies*

As it is already stated, four different strategies are employed for the scheduling of the two configurations of the forming department. In the case of workcenter configuration FIFO seems to produce the schedule with the best performance in terms of makespan and mean flowtime per product model. In addition FIFO mean resource utilization is the second best and is very close to the higher mean utilization. In the case of cellular configuration, LIFO is the scheduling strategy providing the best performance measures. The minimum makespan and mean flowtime comes from the schedule produced by LIFO while the mean utilization presents its higher value for the case of LIFO. A simple utility function is described in order to investigate the overall performance of each scheduling

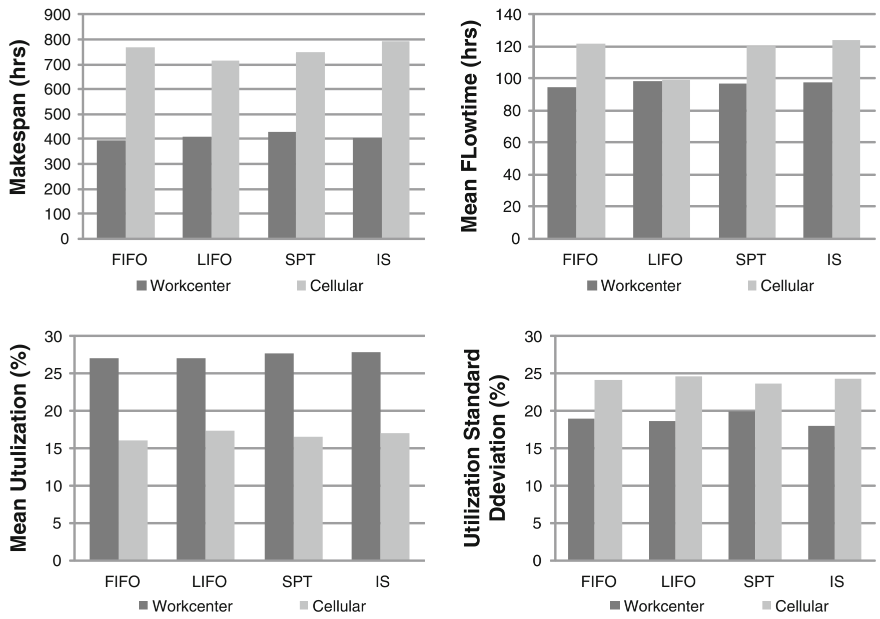


**Fig. 5** Performance measures for all the scheduling strategies for both configurations

strategy. The utility function is calculated by Eq. 1. The values of makespan, mean flowtime, and standard deviation of utilization are normalized as cost criteria, while the utilization values are normalized as a benefit criterion. The weighting factors for makespan, mean flowtime, mean utilization, and utilization standard deviation are, 0.5, 0.2, 0.2, and 0.1. Figure 4 shows that in the case of workcenters FIFO presents the highest utility, while IS is quite close. In the case of cellular configuration LIFO is the best scheduling strategy followed by SPT (Fig. 5).

$$\begin{aligned} \text{Utility} = 05\,\frac{\max(\text{MS}) - \text{MS}}{\max(MS) - \min(MS)} + 02\,\frac{\max(\text{MFT}) - \text{MFT}}{\max(MFT) - \min(MFT)} \\ + 02\,\frac{\text{MUT} - \min(\text{MUT})}{\max(\text{MUT}) - \min(\text{MUT})} + 01\,\frac{\max(\text{SDUT}) - \text{SDUT}}{\max(\text{SDUT}) - \min(\text{SDUT})} \end{aligned} \quad (1)$$

## 6 Conclusion

The work presents an intelligent scheduling to flexible manufacturing systems, the implementation of the method to a software system integrated within the Virtual Factory Framework. The integration allows the software systems to seamlessly exchange product, process, resource, and key performance indicators data with other software systems belonging to the whole range of the factory lifecycle. The validity of the approach is presented with the application of the method and the system to a commercial refrigerator's production facility, in particular the forming department. Two alternative configurations of the forming department are examined, workcenters and cellular, under different scheduling strategies. Workcenters' scheduling results in terms of makespan and flowtime outperform the results of cellular configuration for all the scheduling strategies. In the case of workcenters FIFO seems to be the most promising scheduling strategy, while in the case of the cellular configuration LIFO presents the minimum makespan.

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## References

1. Chryssolouris G (2006) Manufacturing systems: theory and practice, 2nd edn. Springer, New York
2. El Moudani W, Mora-Camino F (2000) A dynamic approach for aircraft assignment and maintenance scheduling by airlines. J Air Transp Manage 6(4):233–237
3. Herroelen W, Leus R (2005) Project scheduling under uncertainty: survey and research potentials. Eur J Oper Res 165:289–306
4. Michalos G, Makris S, Mourtzis D (2011) A web based tool for dynamic job rotation scheduling using multiple criteria. CIRP Ann Manuf Technol 60(1):453–456
5. Chryssolouris G, Mourtzis D, Geronimaki M (2003) An approach to planning of industry: a case study for a refrigerators producing facility. CIRP J Manuf Syst 32(6):499–506
6. Alagoz O, Azizogl M (2003) Rescheduling of identical parallel machines under machine eligibility constraints. Eur J Oper Res 149:523–532
7. Calhoun KM, Deckro RF, Moore JT, Chrissis JW, Van Hove JC (2002) Planning and re-planning in project and production planning. Omega 30:155–170
8. Ozdamar L, Alanya E (2000) Uncertainty modelling in software development projects (with case study). Ann Oper Res 102:157–178
9. Wang J (2004) A fuzzy robust scheduling approach for product development projects. Eur J Oper Res 152:180–194
10. Efthymiou K, Michalopoulou M, Sipsas K, Giannoulis C, Mourtzis D, Chryssolouris G (2012) On plant reconfiguration following a collaborative engineering and knowledge management approach. In: (MITIP 2012) 14th International conference on modern information technology in the innovation processes of the industrial enterprises, Budapest, Hungary ISBN: 978-963-311-373-8
11. Chryssolouris G, Chan S (1985) An integrated approach to process planning and scheduling. CIRP Ann 34(1):413–417
12. Chryssolouris G, Lee M, Dicke K (1991) An approach to short interval scheduling for discrete parts manufacturing. Int J Comput Integr Manuf 4(3):157–168
13. Ghielmini G, Pedrazzoli P, Rovere D, Terkaj W, Boër CR, Dal Maso G, Milella F, Sacco M (2011) Virtual factory manager of semantic data. In: Proceedings of DET2011 7th international conference on digital enterprise technology Athens, Greece

# Application of Firefly Metaheuristic Algorithm for the Single Row Facility Layout Problem

**Özlen Erkal Sönmez and Ş. Alp Baray**

**Abstract** Facility layout is the arrangement of machines, equipments, or other resources in a manufacturing environment to designate an ideal configuration for minimizing the total cost by affecting the production flow. Layout design has a significant impact on the performance of manufacturing systems, and the layout problems are generally regarded as NP-Hard problems. In the literature, a considerable amount of attention is granted to biology-inspired metaheuristic algorithms in order to find efficient solutions to deal with many optimization problems. In this study, the general features and the mechanism of the Firefly Algorithm are presented initially. In order to illustrate how to adapt the proposed algorithm to a real manufacturing problem, a numerical application is shown for the solution of single row facility layout problem. A candidate solution array for 15 departments is obtained through the presumptions of the proposed algorithm. For a sample size of 500 iterations, 95 % confidence interval is constructed between the values of 8,306.53 and 8,378.22 with a standard error value of 18.288.

## 1 Introduction

System efficiency has crucial impact on many science and engineering areas. The optimization methods are generally convenient techniques to help the decision makers evaluate the alternative ways for the solution of any optimization problem. However, even many seemingly simple problems would be difficult to solve in practice, as clearly stated in [1]. In some cases, even medium-sized problem instances become intractable and cannot be solved using the exact methods of optimization. Rothlauf [2], emphasizes that the optimization techniques involve not only the exact methods but also various approximate search methods including heuristic algorithms which do not guarantee finding an optimal solution.

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Metaheuristic techniques are global optimization methods that attempt to reproduce natural phenomena or social behaviors. Two important characteristics of metaheuristic optimization methods are intensification and diversification. Intensification serves to search around the current best solutions and to select the best candidate designs. Diversification allows the optimizer to explore the search space more efficiently, often by randomization [3]. The nature inspired metaheuristic algorithms are mainly based on natural intelligence, and can be converted into viable iterative processes. They specifically focus on a maximization or minimization problem to improve candidate solutions which are obtained through specified objective functions and constraints.

In the literature, a considerable amount of interest is granted to various nature inspired metaheuristic algorithms. Widely used and relatively popular ones can be noted as genetic algorithms, tabu search method, artificial bee algorithms, ant colony algorithms, simulated annealing, and particle swarm optimization etc. The existing algorithms inspire researchers to improve the present algorithms or to find distinctly novel algorithms based on the wealth and diversity in nature.

## 2 Firefly Algorithm

Fireflies are well-known insects for their bioluminescent signaling, which is used for species recognition, interactions with potential predators, and also mate choice [4]. They produce luminescent flashes as a signal system to communicate with other fireflies, especially to prey attractions [7].

Firefly Algorithm is a metaheuristic optimization algorithm based on the social characteristics and flashing patterns of fireflies. It is a population-based algorithm to find the global optimum of the objective functions based on swarm intelligence. Individuals are randomly distributed in search space at the outset [5]. According to the algorithm; the initial positions of individuals are determined as;

$$x_{ij}^{(0)} = x_{i,min} + rand\left(x_{i,max} - x_{i,min}\right), i = 1, 2, \ldots, n$$

where $x_{ij}^{(0)}$ shows the initial value of the ith variable for the jth individual. $x_{i,min}$ and $x_{i,max}$ are the minimum and the maximum allowable values for the ith variable [5].

The following assumptions are adopted in order to configure the proposed algorithm:

- Fireflies are unisex. Each firefly can be attracted by other fireflies regardless of their sex.
- Attractiveness is proportional to the brightness degree or light intensity, which is directly related to the distance between two fireflies.
- For any pair of fireflies, the less bright one moves toward the brighter individual. However; if there is no primacy of the brightness of the fireflies, the movement will be random [3].

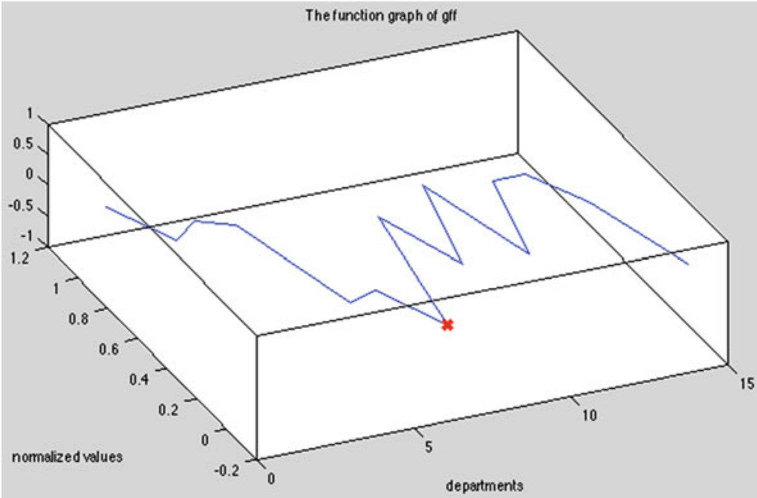


**Fig. 1** The function graph of 'gff'

For the application, the attractiveness formulation and the variation of light intensity have great importance. For maximization problems, the brightness can simply be proportional to the value of the objective function [1]. As light intensity and thus attractiveness decreases as the distance from the source increases, the variations of light intensity and attractiveness should be monotonically decreasing functions [6].

For an assumed light absorption coefficient $\gamma$, the light intensity "I" varies with the distance "r".

$$I = I_0 e^{-\gamma r}$$

As a firefly's attractiveness is proportional to the light intensity, the attractiveness "$\beta$" of any firefly is determined as below:

$$\beta = \beta_0 e^{-\gamma r^2}$$

The distance between any two fireflies i and j at xi and xj is determined by the Cartesian distance.

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2}$$

The movement vector of firefly i which is attracted to brighter firefly j is described as

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2} \left( x_j - x_i \right) + \alpha \varepsilon_i$$

In the formula, the second term is related to the attraction level. The third term includes randomization parameter indicated with $\alpha$, and $\varepsilon$i indicates the vector of random numbers drawn from a Gaussian distribution [1].

Firefly Algorithm was developed by Xin-She Yang in 2007. Many researchers were interested in this algorithm. Zang [7] proposed a review of nature-inspired algorithms involving ant colony optimization, bees algorithm, genetic algorithm, and firefly algorithm with a general perspective. Hereby, Firefly Algorithm started to be compared with other well-known algorithms. Senthilnath et. al. [5], studied clustering benchmark problems with Firefly Algorithm. The results are compared with the results obtained by artificial bee colony and particle swarm optimization methods. Gandomi et al. [3] evaluated mixed variable structural optimization using Firefly Algorithm. In 2013, Gandomi et. al. [6] introduced chaos into the algorithm so as to increase its global search mobility for robust global optimization. Kazem et.al. [8] analyzed support vector regression with chaos-based Firefly Algorithm for stock market price forecasting. The knowledge about the algorithm is incrementally enhanced in the literature. However, the lack of applications for the Firefly Algorithm in especially layout problems is unignorable.

## 3 Single Row Facility Layout Problem

The efficient arrangement of resources (e.g., machines, departments, or workforce) and the proper layout within the facility results in a well-coordinated and productive workflow. Layout affects the coordination so that the processes are safe for workers. The accumulation of work in process inventories and over-utilization of any resource are avoided. Due to the decrease in material handling cost; the total cost is also reduced. Thus, an efficient and productive layout contributes to the overall efficiency of the operations [9].

Single Row Facility Layout Problem is specifically interested in arranging departments on a straight line in any given direction. The problem is a particular case of linear ordering problem and it is strongly NP-Hard as stated in [10]. Many researchers have tried to solve the problem via different methods. For instance, Anjos and Yen [11] presented a study to generate provably near-optimal solutions for very large single row facility layout problems. Samarghandi et.al [12] used a particle swarm optimization algorithm by employing a new coding and decoding technique to solve the Single Raw Facility Layout Problem. Moreover, a sub-algorithm was also developed to search the promising areas comprehensively. Experimentally derived rules were used to set the values of the control parameters in different problems. Datta et al. [13] preferred a permutation-based genetic algorithm to solve the same problem. Individuals are obtained by using rule-based permutations which are improved toward the optimum value by means of specialized mutation and crossover operators. Solimanpur et.al. [14] made studies on developing an ant algorithm for the single row layout problem in flexible manufacturing systems. The problem is formulated as a nonlinear 0–1 programming model in which the distance between the machines is sequence dependent.

The facility layout problem is basically defined as a global optimization problem that seeks to arrange a given number of rectangular facilities so as to minimize the total cost associated with interactions between them [11]. It involves n departments to be arranged in a straight line.

In this paper, the numerical application is performed on a Single Row Facility Layout Problem to show the basic mechanism of Firefly Algorithm. The main objective of the problem is defined as determining the optimum layout for the departments in a facility. Minimizing the weighted sum of distances between each pair of departments has importance in this regard. At the computational phase, distance is defined as the length between the centroids of the two departments being considered [10].

The problem used for the application in this paper is obtained form the publication of Amaral [10]. The ($n \times n$) sized transportation matrix C = [cij] is given where cij values represent the flow intensity between the departments i and j. Given lj values in the same matrix represent the length of the related departments. For any determined array, the distance between two departments changes due to not only the length of each aforementioned department but also the length of the other(s) in between. The values for the problem are presented in Table 1.

When the sequence of the departments is even slightly changed, the distance between any two departments may vary to a great extent. That's because any change in the array would totally affect the distance of any two centroids of departments which may cause a huge computational complexity.

For the application, an initial population of n fireflies is created randomly. The light intensity (I) is treated as the fitness function of the population. $\beta$o, $\gamma$ parameters are determined, and incorporated into the model in accordance with related formulation. Movements are determined according to the light intensity level. In an inner loop, attractiveness is calculated using an unstable distance

**Table 1** Transportation matrix for the problem [10]

| P15 | j | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | – | 10 | 0 | 5 | 1 | 0 | 1 | 2 | 2 | 2 | 2 | 0 | 4 | 0 | 0 |
| 2 | | – | 1 | 3 | 2 | 2 | 2 | 3 | 2 | 0 | 2 | 0 | 10 | 5 | 0 |
| 3 | | | – | 10 | 2 | 0 | 2 | 5 | 4 | 5 | 2 | 2 | 5 | 5 | 5 |
| 4 | | | | – | 1 | 1 | 5 | 0 | 0 | 2 | 1 | 0 | 2 | 5 | 0 |
| 5 | | | | | – | 3 | 5 | 5 | 5 | 1 | 0 | 3 | 0 | 5 | 5 |
| 6 | | | | | | – | 2 | 2 | 1 | 5 | 0 | 0 | 2 | 5 | 10 |
| 7 | | | | | | | – | 6 | 0 | 1 | 5 | 5 | 5 | 1 | 0 |
| 8 | | | | | | | | – | 5 | 2 | 10 | 0 | 5 | 0 | 0 |
| 9 | | | | | | | | | – | 0 | 10 | 5 | 10 | 0 | 2 |
| 10 | | | | | | | | | | – | 0 | 4 | 0 | 0 | 5 |
| 11 | | | | | | | | | | | – | 5 | 0 | 5 | 0 |
| 12 | | | | | | | | | | | | – | 3 | 3 | 0 |
| 13 | | | | | | | | | | | | | – | 10 | 2 |
| 14 | | | | | | | | | | | | | | – | 4 |
| 15 | | | | | | | | | | | | | | | – |
| lj | 20 | 3 | 9 | 3 | 7 | 3 | 7 | 5 | 9 | 6 | 5 | 3 | 9 | 3 | 7 |

value. The iterative process from the ith firefly to the nth is repeated until reaching the maximum generation level, and light intensity values are updated. Then, the fireflies are ranked and the current best is found until the stop condition occurs.

Application is performed on MATLAB 07.12.0 (R2011a). A Matlab function is defined whose outputs are threefold. The 'gff' (global best cost value for the algorithm), 'Igff' (the intensity value of the global best), and the 'solution array' of departments are obtained with the outputs of 'nff' (number of fireflies), the transportation matrix (C = [cij]), and length vector for departments. Gamma, beta, and alpha values are determined after sufficient trials within appropriate intervals for each. The maximum generation number can be as large as necessary because of the computational ease due to computer speed. The Matlab code is proposed below:

```
function [gff, Igff, solutionarray] = firefly(nff,TRANSPORTATIONMATRIX, lengthvector)
   gamma = 1;
   beta0 = 1;
   alpha = 0.2;
   MaxGeneration = 50000;
   t = 1;
n = size(TRANSPORTATIONMATRIX, 1);
X = rand(n, nff);
           for i=1:nff
      Intensity(i) = -1*calculatefitness(X(:,i),TRANSPORTATIONMATRIX, lengthvector);
           end
           while (t < MaxGeneration)
      for i=1:nff
         for j=1:nff
            if(Intensity(i) < Intensity(j))
               r = norm((X(:, i) - X(:, j)));
               beta = beta0 * exp(-gamma*r.^2);
               X(:, i) = X(:, i) .* (1 - beta) + X(:, j) .* beta + alpha .* (rand(n, 1) - 0.5);
            elseif(Intensity(i) == Intensity(j))
               X(:, j) = rand(n, 1);
            end
         end
      end
      for i=1:nff      Intensity(i)=1*calculatefitness(X(:,i),TRANSPORTATIONMATRIX,
lengthvector);
      end
      t = t + 1;
      gff = X(:, Intensity == max(Intensity));
      Igff = calculatefitness(gff, TRANSPORTATIONMATRIX, lengthvector);
      [~, solutionarray] = sort(gff);
   end
end
```

Number of fireflies is chosen as a close value to the total number of departments which is 15. The alternative of 18 fireflies giving the best (minimum) cost result is chosen as "nff" value. Candidate solution arrays and some computation details can be observed in Table 2. The result clearly shows that the alternative of "7-15-5-6-

**Table 2** 'nff' alternatives evaluation

| nff | Cost | Solution array | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 8310 | 7 | 10 | 13 | 4 | 12 | 14 | 5 | 6 | 15 | 11 | 8 | 3 | 9 | 2 | 1 |
| 11 | 8541 | 6 | 1 | 5 | 10 | 2 | 15 | 4 | 9 | 14 | 13 | 12 | 11 | 3 | 8 | 7 |
| 12 | 9211 | 13 | 7 | 6 | 2 | 15 | 8 | 14 | 12 | 9 | 5 | 11 | 4 | 1 | 10 | 3 |
| 13 | 8330 | 6 | 15 | 8 | 10 | 2 | 13 | 9 | 3 | 14 | 11 | 5 | 12 | 7 | 4 | 1 |
| 14 | 7983 | 1 | 15 | 4 | 7 | 6 | 10 | 3 | 2 | 8 | 12 | 5 | 13 | 14 | 9 | 11 |
| 15 | 8721 | 1 | 5 | 14 | 8 | 6 | 11 | 7 | 12 | 10 | 4 | 13 | 9 | 2 | 3 | 15 |
| 16 | 8708 | 1 | 7 | 3 | 8 | 5 | 2 | 11 | 12 | 10 | 4 | 6 | 13 | 9 | 15 | 14 |
| 17 | 8995 | 11 | 6 | 5 | 8 | 7 | 13 | 15 | 14 | 3 | 10 | 4 | 9 | 12 | 2 | 1 |
| 18* | 7460 | 7 | 15 | 5 | 6 | 11 | 9 | 14 | 8 | 12 | 13 | 2 | 4 | 10 | 3 | 1 |
| 19 | 8766 | 1 | 4 | 13 | 5 | 15 | 14 | 9 | 7 | 2 | 6 | 11 | 8 | 3 | 10 | 12 |
| 20 | 8190 | 7 | 1 | 5 | 13 | 2 | 14 | 4 | 12 | 3 | 8 | 10 | 6 | 9 | 11 | 15 |

11-9-148-12-13-2-4-10-3-1" department array gives a relatively low cost value for the current problem.

For evaluation, a sample size of 500 iterations is found adequate. In this case, mean value of the sample is 8,342 and standard deviation is 408.95. Range is calculated as 2,246 where the minimum value of the sample is 7,460 and the maximum value is 9,706. Being an indicator of the computational sensitivity, standard error value is calculated as 18.288, and a 95 % confidence interval is constructed between the values of 8,306.53 and 8,378.22.

The computation takes 2.56 s on MATLAB 07.12.0 (R2011a) on a 2.3 GHz Intel Core i5 processor of Mac OS X (Version 10.7.5). However, making comparisons with the results of other studies would not be favorable for this study because of the absence of similar studies performed on computers which have the same computational ability.

## 4 Conclusion

Since layout design has a significant impact on the production flow, the total cost factor has been under a direct effect of the arrangement of resource units in a facility. The main motivation of this research is the awareness of the lack of studies with Firefly Algorithm especially applied to layout problems. Hereby, Single Row Facility Layout Problem is chosen with an illustrative problem obtained from Amaral [10], and a candidate solution for this problem is generated by Firefly Algorithm in MATLAB 07.12.0(R2011a) demonstratively. This relatively novel algorithm is proved to generate valid results in various application areas with other very popular metaheuristic methods in literature.

During the application phase, the mathematical formulation is constituted based upon the main characteristics and general rules of Firefly Algorithm. The number of individuals (fireflies) is determined by experimental method, and relatively low cost is obtained by the "7-15-5-6-11-9-148-12-13-2-4-10-3-1" department array. For a sample size of 500 iterations, 95 % confidence interval is constructed between the values of 8,306.53 and 8,378.22 with a standard error value of 18.288.

In the gff function graph in Fig. 1, it can be observed that the departments which have close values at minimum level (e.g., 7th and 15th departments) are relatively closely located in the solution array. However, the maximum value promising departments (e.g., 1st department) are located as far as possible from the beforementioned ones (7th and 15th departments).

For further research, parameter optimization techniques can be applied to determine the coefficients used in the study, and the ways of enhancing the system performance should be investigated.

## References

1. Yang X-S (2010) Engineering Optimization—An Introduction with Metaheuristic Applications. Wiley, New York
2. Rothlauf F (2011) Design of modern heuristics—principles and application, Springer, Berlin
3. Gandomi AH, Yang X-S, Alavi AH (2011) Mixed variable structural optimization using firefly algorithm. Comput Struct 89:2325–2336
4. Long SM, Lewis S, Louis L, Ramos G, Richmond J, Jakob EM (2012) Firefly flashing and jumping spider predation. Anim Behav 83:81–86
5. Senthilnath J, Omkar SN, Mani V (2011) Clustering using firefly algorithm: Performance study. Swarm Evol Comput 1:164–171
6. Gandomi AH, Yang X-S, Talatahari S, Alavi AH (2013) Firefly algorithm with chaos, Commun Nonlinear Sci Numer Simulat 18:89–98
7. Zang H, Zhang S, Hapeshi K (2010) A review of nature-inspired algorithms. J Bionic Eng 7(Suppl):S232–S23
8. Kazem A, Sharifia E, Hussainb FK, Saberic M, Hussain OK (2013) Support vector regression with chaos-based firefly algorithm for stock market price forecasting. Appl Soft Comput 13:947–958
9. McKendall AR Jr, Shang J, Kuppusamy S (2006) Simulated annealing heuristics for the dynamic facility layout problem. Comput Oper Res 33:2431–2444
10. Amaral ARS (2006) On the exact solution of a facility layout problem. Eur J Oper Res 173:508–518
11. Anjos MF, Yen G (2009) Provably near-optimal solutions for very large single-row facility layout Problems. Optim Methods Softw 24(4–5):805–817
12. Samarghandi H, Taabayan P, Jahantigh FF (2010) A particle swarm optimization for the single row facility layout problem. Comput Ind Eng 58:529–534
13. Datta D, Amaral ARS, Figueira JR (2011) Single row facility layout problem using a permutation-based genetic algorithm. Eur J Oper Res 213:388–394
14. Solimanpura M, Vrat P, Shankar R (2005) An ant algorithm for the single row layout problem in flexible manufacturing systems. Comput Oper Res 32:583–598

# Geometrical Optimization of Micro-Mixer with Wavy Structure Design for Chemical Processes Using Taguchi Method

**Nita Solehati, Joonsoo Bae and Agus P. Sasmito**

**Abstract** Micro-mixer has been widely used in mixing processes for chemical and pharmaceutical industries. Conventional design of micro-mixer T-junction has poor mixing performance; while improved micro-mixer design typically requires expensive manufacturing processes due to complex geometrical structure. In previous work, we introduced improved yet easy to manufacture micro-mixer design utilizing wavy structure micro-channel T-junction which can be easily manufactured using simple stamping method. To extend our work, we optimize the geometrical parameters, i.e., wavy frequency, wavy amplitude, width and height of the micro channel. A robust Taguchi statistical method is employed for this purpose with regard to the mixing performance (mixing index), pumping power, and Figure of Merit (FoM). The results indicate that high mixing performance does not always associates with high FoM due to higher pumping power. The advantages and limitations of the designs and objective functions are discussed in the light of present numerical results.

## 1 Introduction

Recent advances in micro-reactor technologies have enabled chemical processes and pharmaceutical industries to produce high quality products due to its ability to control the extreme/unusual reaction environments, such as highly exothermic or explosive chemical reaction, highly viscous fluids which difficult to mix in larger

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scale mixing equipment etc. There are many other advantages of micro-reactor technology such as higher transport rate, safer environment, compact design, and simpler process control. Despite its advantages, micro-reactor also has limitations, especially when large throughput product in industrial scale is desired, while small size micro-reactor can only produce small amount of yields; whence enlarging the micro-reactor size (scale-up) decreases the product quality. One way to increase the product output is by numbering-up the micro-reactors into several modular; the modular comprises several mixing zones (mixers) and reaction zones (reactors). However, one of the major draw back of this design is the flow uniformity for which the reactant flow may not be uniformly distributed throughout each micro-channel which cause non-uniform product quality. Liu et al. [1] proposed structural bifurcation of flow channel to improve flow uniformity throughout the micro-reactor/micro-mixer modular.

Conventional micro-mixer design typically using T-junction with straight micro-channel; the T-junction consists of at least two inlets for reactant to enter and further mix in the straight micro-channel. This design is widely used in chemical and pharmaceutical industries due to its ease of manufacture. However, this design has poor mixing quality as small scale mixing depends mainly on the molecular diffusion. Thus relatively long channel and higher pumping power is required to achieve desired mixing, which can be impractical. Several designs have been proposed by many researchers (see [2–4] for reviews of these) to improve the mixing quality. However, most of the proposed designs require complex geometrical structures which is difficult/expensive to manufacture and some others requires additional equipment to improve mixing performance which adds cost and complexity. In previous work [5], we introduced micro-mixer with wavy structure for improved mixing performance yet easy to manufacture by using stamping method similar to conventional micro-mixer design. We also investigated the details flow and mixing behavior in this type of new micro-mixer design [6]; it was found that our new design of micro-mixer with wavy structure has superior performance as compared to conventional design and has comparable performance with micro-mixer with complex geometrical structure which is difficult and/or expensive to manufacture. However, for best and better performance of our micro-mixer design with wavy structure, optimization of geometrical design is required which is the theme of this work.

In previous work [7], we had successfully utilized computational fluid dynamics (CFD) approach together with Taguchi statistical method to optimize the performance of fuel cell. Recently, we also implemented Taguchi statistical method together with PROMETHEE multi-criteria decision software to search for best combination of weight values of search engine factors [8]. To continue our work on the area of micro-mixer design and optimization using Taguchi statistical method, the aim of the study presented is twofold: (1) to optimize geometrical design—wavy frequency, wavy amplitude, micro-channel width and height; (2) to evaluate the objective function of optimization with regard to the mixing performance (mixing index), parasitic load (pumping power), and Figure of Merit for different industrial application.

The layout of the paper is as follows. First, the model development using CFD is introduced; it comprises conservation equations of mass, momentum, and species for mixing. The mathematical model is then solved numerically utilizing finite-volume based CFD software Fluent 6.3.26. Taguchi statistical method is then employed to study the sensitivity of each design parameter. Optimum parameters are then calculated based on the mixing performance, pumping power, and figure of merit defined later. Finally, advantages and limitations of the design are highlighted, and conclusions are drawn based on the results presented.

## 2 Model Development

The physical model (see Fig. 1) comprises of micro-wavy-channel design for which liquid A enters the channel from the right inlet (red arrow in Fig. 1); whereas liquid B flows from the left inlet (blue arrow in Fig. 1). Liquid A and B mix in the opposing streams in a T-junction. The channel height ($h$), width ($w$), wavy frequency ($f$), and wavy amplitude ($a$) are varied according to the Taguchi array. For comparison purpose, we keep the length to be the same for all cases.

### 2.1 Governing Equations

The conservation equations of mass, momentum, and miscible species are given by

$$\nabla \cdot \rho \mathbf{u} = 0 \tag{1}$$

$$\nabla \cdot \rho \mathbf{u} \otimes \mathbf{u} = -\nabla p + \nabla \cdot \left( \left[ \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^{\mathbf{T}} \right) \right] - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right) \tag{2}$$

$$\nabla \cdot (\rho \mathbf{u} \omega_{\mathrm{i}}) = -\nabla \cdot (\rho D_{\mathrm{i}} \nabla \omega_{\mathrm{i}}) \tag{3}$$

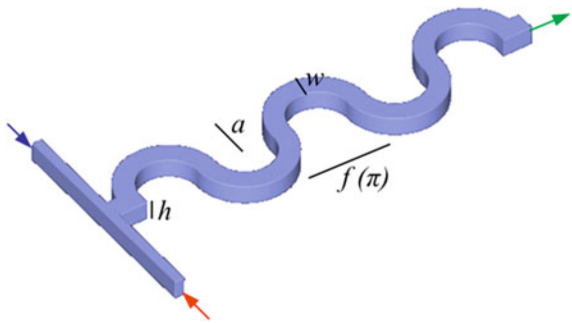


**Fig. 1** Schematic of micromixer T-junction with wavy structure

In the above equations, $\rho$ is the fluid density, $\mathbf{u}$ is the fluid velocity, $p$ is the pressure, $\mu$ is the dynamic viscosity, $\omega_i$ is the mass fraction of species i, $D_i$ is the diffusion coefficient of species i.

The mixing performance is evaluated using mixing index, defined as

$$\tau^2 = \frac{1}{n}\sum_{i=1}^{n}(\omega_i - \omega_\infty)^2 \tag{4}$$

$$M_i = 1 - \sqrt{\frac{\tau^2}{\tau_{\max}}} \tag{5}$$

where $\tau$ indicates the variation of concentration for each cross section, $\tau$ max is the maximum variance over the range of data, n is the number of sampling points inside the cross-section, $\omega_i$ is the mass fraction at sampling point i, $\omega_0$ is the initial concentration, $\omega_\infty$ is the concentration at infinity, and $M_i$ is the mixing index. The mixing index is unity for complete mixing, and zero for no mixing. The values at the sampling points were obtained by interpolation with the values from adjacent computational cells.

To ensure the fidelity of comparison for both micromixer designs, the concept for Figure of Merit (FoM) is introduced for the first time in the micromixing area to evaluate the effect of Reynolds number and the effect of geometry on the pressure drop and mixing performance. FoM is defined as the ratio of the mixing index per unit pressure drop required, given by:

$$FoM = \frac{M_i}{\Delta p} \tag{6}$$

## 2.2 Boundary Conditions

The boundary conditions for the flow inside the micro-channel T-junction are as follows

- *Right inlet:* liquid A is introduced to the channel; we prescribe inlet velocity and species mass fraction.

$$u = U_A,\ \omega_A = 1,\ \omega_B = 0 \tag{7}$$

- *Left inlet*: liquid B enters the channel; constant inlet velocity and species mass fraction are prescribed.

$$u = U_B,\ \omega_A = 0,\ \omega_B = 1 \tag{8}$$

- *Outlet*: we specify the pressure and stream wise gradient of the temperature and species mass fraction is set to zero. The velocity is not known a priori but needs to be iterated from the neighboring computational cells.

$$p = p_{\text{out}},\ \mathbf{n} \cdot \nabla\omega_i = 0 \tag{9}$$

- *At the walls*: we specify no slip condition and no species flux at the channel wall.

$$\mathbf{u} = 0,\ \nabla\omega_{\text{i}} = 0 \tag{10}$$

## *2.3 Taguchi Statistical Method*

Taguchi method is a well-known statistical method developed by Genichi Taguchi. It is a powerful engineering tool for experimental optimization and one of the most well-known robust design methods. Generally, it is used to find the sensitivity of each parameter and determine the optimum combination of the design factors [9, 10]. Here, we have four key parameters, e.g., wavy frequency, wavy amplitude, channel width, and channel height, with three level values for each parameter. An $L_9$ orthogonal array (OA) was employed in the experiment matrix, as shown in Table 1.

In this paper, we evaluate the objective function of the optimum parameters based on the mixing index, Eq. (5), pumping power (pressure drop) and Figure of

**Table 1** Orthogonal array for $L_9$ with four parameters and three level designs

| No | Frequency ($\pi$) | Amplitude (mm) | Width (mm) | Height (mm) |
|---|---|---|---|---|
| 1 | 2 | 0.5 | 0.25 | 0.25 |
| 2 | 2 | 1 | 0.5 | 0.5 |
| 3 | 2 | 2 | 1 | 1 |
| 4 | 5 | 0.5 | 0.5 | 1 |
| 5 | 5 | 1 | 1 | 0.25 |
| 6 | 5 | 2 | 0.25 | 0.5 |
| 7 | 10 | 0.5 | 1 | 0.5 |
| 8 | 10 | 1 | 0.25 | 1 |
| 9 | 10 | 2 | 0.5 | 0.25 |

Merit, Eq. (6); therefore, we evaluate the signal-to-noise ratio (S/N) based on Larger-the-better for mixing index and FoM:

$$S/N = -10\log_{10}\left(\frac{1}{n_r}\sum_{i=1}^{n_r}\frac{1}{Y_i^2}\right) \tag{11}$$

While for pumping power, we calculate the signal-to-noise ration (S/N) based on Smaller-the-Better:

$$S/N = -10\log_{10}\left(\frac{1}{n_r}\sum_{i=1}^{n_r}Y_i^2\right) \tag{12}$$

Once the optimum combination of each parameter has been determined, we verify the predicted results from Taguchi method with CFD results. The confidence interval (CI) of the estimated value is calculated by:

$$CI = \sqrt{F_{\alpha,v_1,v_2}V_{ep}\left(\frac{1}{n_{eff}}+\frac{1}{r}\right)} \tag{13}$$

where $F_{\alpha,v_1,v_2}$is the F-ratio required, $v_1$ is the number of degree of freedom of the mean, $v_2$ is the number of degree freedom of the error, $v_{ep}$ is the error of variance, r is the sample size in the confirmation test, and $n_{eff}$ is the effective sample size, defined as

$$n_{eff} = \frac{N}{1 + DOF_{opt}} \tag{14}$$

where $N$ is total number of trials and $DOF$opt is the total degree of freedom that are associated with items used to estimate $\eta_{opt}$.

## 3 Numerics

The computational domains (see Fig. 1) were created in AutoCAD 2010; the commercial pre-processor software Gambit 2.3.16 was used for meshing, labeling boundary conditions, and to determine the computational domain. Three different mesh designs—$1 \times 10^7$, $2 \times 10^7$, and $4 \times 10^7$—were implemented and compared in terms of the local pressure, velocities, species mass fractions, and temperatures to ensure a mesh independent solution. We found that the mesh numbers around $2 \times 10^7$ give about 1 % deviation compared to a much finer mesh size of $4 \times 10^7$; whereas the results from the mesh size of $1 \times 10^7$ deviate up to 10 % as compared to those from the finest mesh design. Therefore, a mesh consisting of around $2 \times 10^7$ elements was found to be sufficient for the numerical experiments: a fine structured mesh was used near the wall to resolve the boundary layer and an increasingly coarser mesh in the middle of the channel in order to reduce the computational cost.

The equations were solved with the well-known Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm, first-order upwind discretization and Algebraic Multi-grid (AMG) method. As an indication of the computational cost, it is noted that on average, around 5000–10000 iterations are needed for convergence criteria for all relative residuals of $10^{-9}$; this takes around 2 days on a computer cluster with 16 processors.

The key operating parameters is then analyzed using Taguchi statistical method in Minitab 14 software. A variance analysis (ANOVA) was performed in order to see the sensitivity of each parameter, to determine the optimum combination of operating parameters, and to evaluate the confidence levels between Taguchi prediction and CFD results.

## 4 Results and Discussion

The numerical simulations were carried out for typical conditions found in micro-channel T-junctions; the base-case conditions together with the physical parameters and geometric parameters are listed in Table 2. In the following, sensitivity analysis of each design parameter is investigated from the response of signal-to-noise ratio of OA. Optimum design parameters are then examined based on the mixing index, pressure drop (pumping power), and figure of merit (FoM)

### *4.1 Mixing Performance*

This study examines the mixing performance based on OA of Taguchi method which is tabulated in Table 3 for which the best mixing is achieved by design number 9 and the worst performance is given by design number 2. The sensitivity of each parameter is then analyzed by employing analysis of variance (ANOVA). Typically, for high quality and expensive chemical and/or pharmaceutical products, product quality—in this regard is reflected by mixing quality—is of

**Table 2** Physical and geometrical parameters

| Parameter | Value | Unit |
|---|---|---|
| Channel length | 10 | mm |
| Density liquid | 998 | $kg/m^3$ |
| Viscosity | $1 \times 10^{-3}$ | kg/ms |
| Diffusivity | $2.2 \times 10^{-9}$ | $m^2/s$ |
| Velocity inlet A | 0.04 | m/s |
| Velocity inlet B | 0.04 | m/s |

**Table 3** Numerical results of various combination of design factors

| No | Mixing index | Pressure drop (Pa) | Figure of merit |
|---|---|---|---|
| 1 | 0.171 | 286.76 | $5.98 \times 10^{-4}$ |
| 2 | 0.105 | 87.2 | $1.21 \times 10^{-3}$ |
| 3 | 0.149 | 41.85 | $3.56 \times 10^{-3}$ |
| 4 | 0.115 | 68.36 | $1.68 \times 10^{-3}$ |
| 5 | 0.142 | 238.73 | $5.93 \times 10^{-4}$ |
| 6 | 0.563 | 3747.13 | $1.50 \times 10^{-4}$ |
| 7 | 0.203 | 103.58 | $1.96 \times 10^{-3}$ |
| 8 | 0.582 | 3,506.95 | $1.66 \times 10^{-4}$ |
| 9 | 0.649 | 13,729 | $4.73 \times 10^{-5}$ |

paramount importance. Thus, the objective function of our optimization is based on the mixing index. The higher the mixing index, the better is the mixing quality.

Earlier work [5] showed that wavy amplitude and frequency plays significant role to the mixing performance; this is indeed the case as can be inferred from Fig. 2, where wavy frequency results in the most significant parameter influencing the mixing performance, followed by wavy amplitude. Higher wavy frequency and longer wavy amplitude improve mixing performance. This can be adequately explained by the fact that at higher wavy frequency and longer wavy amplitude, secondary flow generated by curves geometry is stronger which enhances mixing. Further, increasing frequency and amplitude increases the total microchannel length which in turn increases the residence time of the fluid mixing. On the other

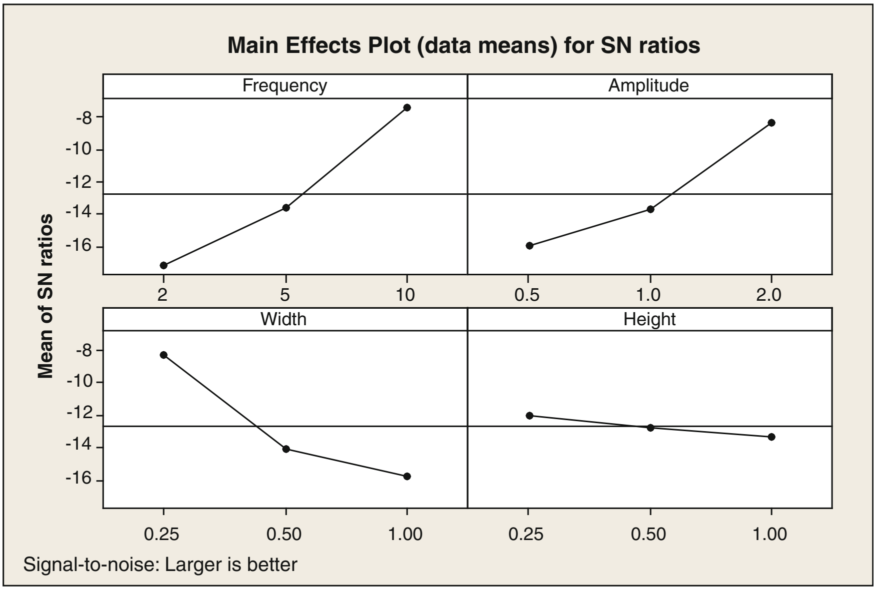


**Fig. 2** S/N response graph for mixing performance

**Table 4** Optimum combination of design factors

| Parameter | Mixing index | Pressure drop | Figure of merit |
|---|---|---|---|
| Frequency | 10 | 2 | 2 |
| Amplitude | 2 | 0.5 | 0.5 |
| Width | 0.25 | 1 | 1 |
| Height | 0.25 | 1 | 1 |
| Optimized design | 0.8 | 21.75 | $3.77 \times 10^{-3}$ |
| CI (%) | 94.6 % | 93.8 | 95.8 |

contrary, the width of microchannel has less significant effect; whereas micro-channel height has the least significant effect to the mixing performance. We note that mixing performance improves as the width and height are decreased. This is attributed to the smaller channel dimension which reduces the diffusion path between two fluids to penetrate each other and mix.

Thus far, the sensitivity of each parameter has been examined. Now, the optimum combination of design parameters is determined. We further predict the optimum mixing performance using Taguchi method and run the confirmatory test from CFD model. The results are depicted in Table 4 for which good agreement between Taguchi prediction and CFD mode were obtained within the maximum error of less than 6 % which is sufficient for engineering purpose. The optimum mixing index for the optimized design is found to be 0.8.

## 4.2 Pumping Power

Generally, in cheap and mass production of chemical products, production cost becomes the most significant factor. One of the factors that constitute the production cost is the pumping power required to drive the flow mixing. Here, we evaluate the pumping power by looking at the pressure drop required. In essence, to reduce production cost, the pumping power which is represented by pressure drop should be as low as possible. The results for pressure drop required of OA are summarized in Table 3. It is seen that the highest pressure drop required is in design number 9 which is about three order-of-magnitudes higher than that of design number 3 which yields the lowest pressure drop. It is important to note that design number 9 has the higher mixing performance with the expense of much higher pressure drop. Thus, for cheap and mass production chemical product, this design seems to be not attractive as they would prefer to implement design with the lowest pumping power to save for power/electricity cost.

With regard to the pumping power, the sensitivity of each design parameter is evaluated. Figure 3 shows the behavior of each parameter which is somewhat different than when it was evaluated in term of mixing performance. Here, several features are apparent; foremost among them is that the low pressure drop can be obtained at low wavy frequency, low wavy amplitude, longer width, and longer

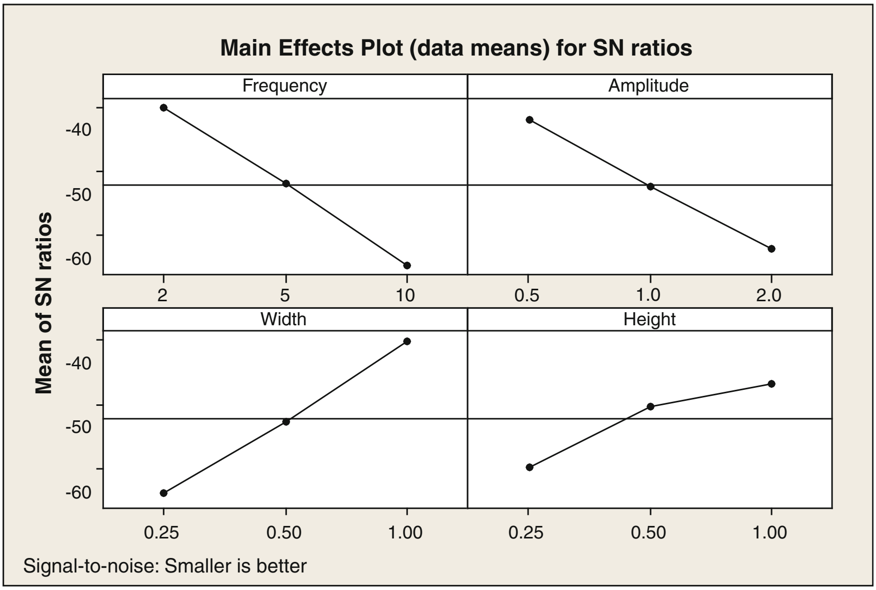


**Fig. 3** S/N response graph for pumping power

height, which is opposite as in mixing performance. This is due to the fact that reducing frequency and amplitude reduces flow resistance throughout the microchannel.

Now, the combination of optimum factors is evaluated to get design with the lowest possible pumping power. Table 4 depicts the optimum (minimum) pumping power required. It is noted that at optimum condition the pumping power required is 21.75 Pa which is about half than that of design number 3. The level of confidence from Taguchi prediction is observed to be 91.8 % which is good enough for engineering design.

## 4.3 *Figure of Merit*

So far, we evaluate the micro-mixer based on mixing performance and pumping power separately. To balance and take into account both effect, we consider figure of merit which basically is defined as mixing performance per unit pumping power. Table 3 shows the FoM of OA condition. We note that the higher FoM is achieved by design number 3 due to reasonable mixing performance with the lowest pressure drop requirement; whereas the lowest FoM is seen in design number 9 since the pumping power is very high (about three order-of-magnitudes) that design number 3.

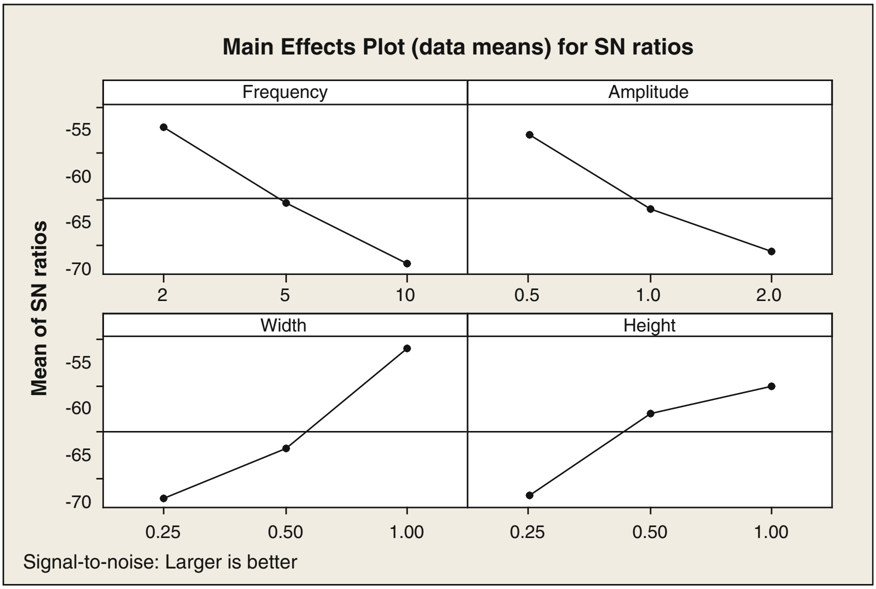


**Fig. 4** S/N response graph for figure of merit (FoM)

Looking further to the sensitivity response of S/N ratio for each parameter in Fig. 4, it reveals that the trend is similar to that in pumping power: lower wavy frequency, shorter wavy amplitude, longer microchannel width and longer microchannel height. Thus the combination of optimum parameters is evaluated. As can be inferred from Table 4, the optimum FoM is seen to be $3.77 \times 10^{-3}$ which is higher than that of design number 3 which is $3.56 \times 10^{-3}$. The level of confidence from Taguchi prediction is observed to be 95.8 % which indicates that Taguchi statistical method is a robust method to select for optimum combination of design parameters in micromixer.

## 5 Concluding Remarks

A computational study of micro-mixing in microchannel T-junction with wavy structure has been carried out together with Taguchi statistical method to evaluate the significance of key design parameters with regard to the mixing performance, pumping power, and figure of merit. The Taguchi method is found to be robust to determine the optimum combination of design parameters with the maximum relative error of less than 7 %.

It has also been shown that for high value chemical product such as in pharmaceutical industry, optimization based on mixing index is suggested; while for cheap value and mass production product for which production cost is of important, for example in food industries, optimization based on pumping power is recommended. On the other hand, one can also optimize the design based on the figure of merit for middle-value product by taking into account both mixing performance as well as pumping power. The results presented herein can aid engineers to determine best design for micro-mixer performance. Future work will focus on the more rigorous optimization procedure in order to alleviate current limitation of discrete level optimization parameters. Possible coupling of optimization software with CFD software will also be explored.

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## References

1. Liu H, Li P, Lew JV (2010) CFD study on flow distribution uniformity in fuel distributors having multiple structural bifurcations of flow channels. Int J Hydrogen Energy 35:9186
2. Kumar V, Paraschivoiu M, Nigam KDP (2011) Single-phase fluid flow and mixing in microchannels. Chem Eng Sci 66:1329
3. Nguyen NT, Wu Z (2005) Micromixers—a review. J Micromech Microeng 15:R1
4. Hessel V, Lowe H, Schonfeld F (2005) Micromixers—a review on passive and active mixing principles. Chem Eng Sci 60:2479–2501
5. Solehati N, Bae J, Sasmito AP (2012) Computational study of improved yet easy-to-manufacture micro-mixer design for chemical processes and pharmaceutical industries. In: Proceedings of 22th international conference on flexible automation and intelligent manufacturing, Helsinki, Finland, p 1261
6. Solehati N, Bae J, Sasmito AP (2012) Numerical investigation of multi-scale mixing in microchannel T-junction with wavy structure. In: Proceedings of the ASME 2012 international mechanical engineering congress and exposition, Houston, TX, US
7. Solehati N, Bae J, Sasmito AP (2012) Optimization of operating parameters for liquid-cooled PEM fuel cell stakcs using Taguchi method. J Ind Eng Chem 18:1039
8. Solehati N, Bae J, Liu L, Bae H (2013) Predicting Search Engine Ranking with PROMETHEE: A Multi-Criteria and Feedback-Driven Approach, ACM T-Web, 2013 (to be submitted)
9. Barker TA (2005) Quality by experimental design. CRC Press, Boca Raton
10. Fowlkes WY, Creveling CM (1995) Engineering methods for robust product design using Taguchi methods in technology and product development. Addison-Wesley Publishing Company, Massachusetts

# A Multi-Agent Self-Adaptive Architecture for Outsourcing Manufacturing Supply Chain

**Sushma Kumari, Akshit Singh, Nishikant Mishra and Jose Arturo Garza-Reyes**

**Abstract** In present day's economy of recession and frequent market fluctuations, it is difficult to satisfy the customer with the products and services at reasonable price. The prices of resources are increasing consistently and the manufacturing industries have to optimize the use of resources so as to make a trade-off between the cost incurred and the services provided to the customer. Realizing this scenario, this article proposes an automated system equipped with artificial intelligence to deal with these complexities and difficulties. This automated system has the capability of self-decision-making and is further complemented by the feature of reconfiguring its operation according to the various uncertainties in the Supply Chain. It utilizes multi agent architecture for its operations. It focuses on adding some additional features to the conventional multi agent architecture for improving the efficiency of the Supply chain and optimizing the make span. It exploits the "Outsourcing of operations" feature by its agents to conclude the manufacturing processes faster and reduce the idle time of certain machines. This article also presents the concept of outsourcing of the manufacturing plant. This multi agent architecture will facilitate small scale manufacturing industries to execute their manufacturing process and complex logistics issues efficiently.

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## 1 Introduction

In this modern age of Globalization and competitive market, customers have numerous options and their sole approach is to get the high quality product in minimal cost. The manufacturing industries have to do lots of alterations in their traditional work ethics in order to meet this requirement like cost cutting in terms of the raw materials and other mandatory inputs purchased and bringing down the miscellaneous expenses within the plant. Furthermore, they have to smartly reframe their policies to tackle the serious issue of current slowdown in global economy and the consequent market fluctuations.

Traditionally, manufacturing industries used to get only the raw material from external industrial partners or vendors but these days due to the market scenario getting complex day-by-day, they are even outsourcing some of their internal operations to external industries. This outsourcing of certain operations to external industrial partners has significantly brought down the expenses incurred and the time taken in manufacturing a product. Furthermore, there is lot of crucial decisions taken by manufacturing industries in terms of choosing a proper supplier for their raw materials, an outsourcing partner, selection of materials etc. In all these processes, the manufacturing plant has to interact with more than one industry and negotiate the price and terms and conditions of the deal. To ease off all these complexities, demand for automated system incorporating artificial intelligence in the manufacturing industries is rising.

In the past plenty of research has been conducted to resolve the issues related to information sharing in distributed manufacturing environment [1–3]. Knowledge and communication within different segment is an integral part of manufacturing supply chain. Chan and Chan [1] suggested a multi-agent architecture to establish the effective communication and coordination among the distributed global manufacturing networks. References [2, 4–6] proposed a decentralized information system to establish the link between the global manufacturing networks. The goal was to address the issue related to due date of customer in distributed manufacturing supply chain. Li et al. [7] proposed genetic algorithm (GA) based approach to generate plans for single and distributed manufacturing systems. Ulieru and Norrie [8] utilized the beauty of fuzzy rule and developed multi agent architecture to address the issue related to the imprecise information and fault recovery in a distributed network. Gefang et al. [9] suggested a distributed multi-agent architecture for fault diagnosis system in artillery command system. To minimize the production cost and lateness of the customer order [10] proposed a multi agent scheduling systems for a distributed manufacturing environment. Multi agent mediator architecture for distributed manufacturing was proposed by Maturana and Norrie [11]. In distributed architecture for knowledge sharing [12] proposed a Multi agent System (MAS) in an e-business domain. Lee and Kim [13] reviewed the development and use of a multi-agent modeling techniques and simulations in the context of manufacturing and supply chain management. Leitão [14] cdecides the amount of raw materialonducted a study to find out the challenges and research opportunity related to application of multi agent architecture in holonic manufacturing systems.

This article proposes multi-agent architecture to address this issue. The beauty of this automated system lies in the ability of precise multi-tasking of its agents. Outsourcing and material planning agent and supplier selection agent are responsible for outsourcing some of the internal operations of the manufacturing industry to the external industrial partners in order to bring down the manufacturing time and manufacturing price of the final product. Maintenance agent looks after the planning and execution of the maintenance policies for the machines in the manufacturing plant. Additionally, it can also make provision for outsourcing of the maintenance of certain machines to some external industrial partners according to the circumstances. Purchase order collection agent takes the order from the client and interacts with the planning agent to finalize the due date of delivery for the products. If there is a case where the client wants the delivery of the products earlier and is adamant in its approach leaving no room for negotiation then purchase order collection agent interacts with planning agent and outsourcing and material planning agent to outsource certain number of the internal operations of the manufacturing plant to external industries in order to meet the deadlines proposed by the client. These agents interact with each other using an agent communication language called Multi agent logic language for encoding Teamwork (MALLET).

## 2 Agent Framework

The proposed multi-agent architecture for outsourcing supply chain is presented in Fig. 1. It consists of purchase order collection agent, outsourcing and material planning agent, supplier selection agent, planning agent, knowledge base agent, maintenance agent, reconfiguration agent, and forecasting agent. All these agents work in collaboration with each other. The properties of each agent are described.

Purchase order collection agent: This agent receives the order from the clients for the manufacturing unit. It confirms the due date for the delivery of the ordered products by interacting with planning Agent. If the client mentions a deadline and the planning agent (after looking at its manufacturing plan) says that it cannot meet the deadlines looking at its capacity (number of machines available) and the current workload. Then, the purchase order collection agent tries to negotiate with the client. If the client is strict about the deadline then some of the operations are outsourced to an outsourcing partner by taking help of outsourcing and material planning agent and gets the product manufactured within the given time limit. Then it decides the mode of payment whether it is cash, cheque, online banking, wires transfer, bank draft, or paying in installments depending on its communication with administrative agent and hence confirms with the client. He further decides the way of delivery of the ordered products with the help of Transport agent. It could be either through road transport using Lorries, via Railways, or using air freight by reaching a consensus with the client. This agent is in

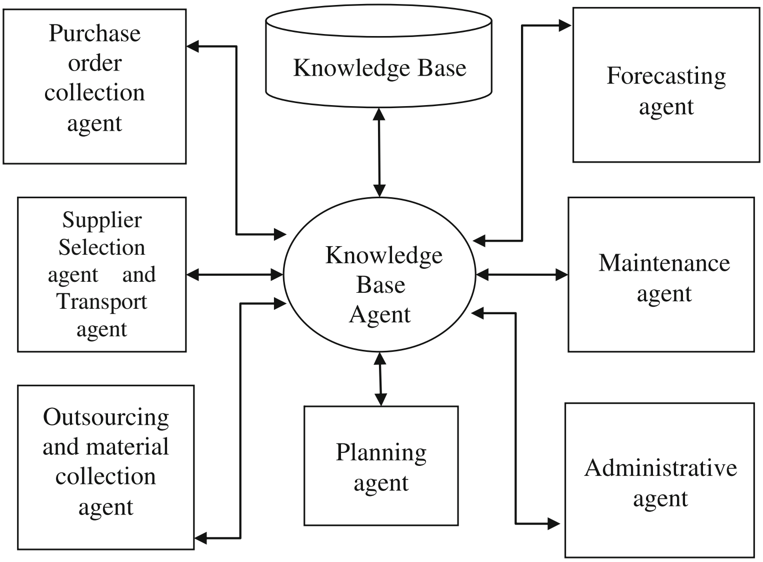


**Fig. 1** Proposed multi-agent architecture

continuous touch with the knowledge base agent throughout its activities. This agent can update itself both online and offline.

Outsourcing and material planning agent: This agent is in continuous communication with planning agent and forecasting agent. It has all the records of the available raw material within the manufacturing unit. The moment forecasting agent sends information about the future demand, it makes a decision about the different kinds of material and their respective quantities needed and sends this information to the supplier selection agent to look for the appropriate supplier to get it from. It also takes decision if a particular operation/part has to be implanted or outsourced and this decision will be based on the due date, expectations of the customer, and available resources in plant. If he finds that particular operation/part has to be outsourced it looks for the outsourcing partner or if there is any accessory which needs to be imported in order to complete the product being manufactured.

Supplier selection agent: The moment this agent get information from outsourcing and material planning agent it starts looking for the available suppliers of the raw. It could use the database of knowledge base agent and look for the company records of past deals with various suppliers and check their feedback. It can have a look in catalogues (online and printed) of various reputed suppliers, supplier and commodity directories, Trade journals and trade shows, and various trade advertisements. It can use its professional contacts and networking or might look for the other capable suppliers on the Internet. Selection of the supplier is being done by evaluating it with three different and independent procedures. Firstly, it looks for the few major factors which are listed below in order of their priority:-

1. Availability
2. Quality of the material being supplied
3. Cost
4. Reliability
5. Distance of the supplier from manufacturing unit.

Then, it also takes into account the technical expertise of the supplier by considering factors like design engineering capability, sustaining engineering capability, Facilities and equipment used, output capacity, Long term potential, Flexibility to ramp up and down quickly and responsiveness, Logistics expertise, and Track record of cost reductions.

Finally, it looks at the Financial and management aspects of the supplier. It reviews the supplier by their financial history, Balance sheet, Income statement, and credit worthiness. It further looks at the efficiency of the their executive and management team, management controls, and information systems. Then it checks their policy framing techniques like Policies organization structure and decision making, Alignment with the mission, corporate culture, values and goals of their corporate structure and their ability to integrate procurement systems.

Planning Agent: This agent deals with the planning and organization of various operations in manufacturing unit. It generates the manufacturing plan which includes when the products will be manufactured, their quality, and the methods used. This agent depicts which machine will be used and when it will come into operation in order to manufacture a particular product. This agent is continuously in touch with the maintenance agent. It is done in a way to minimize the idle time for the machines. These days the manufacturing lines are flexible in nature. It also decides the storage for the raw material and other materials needed for the manufacturing, Furthermore; it chooses the optimum place to store the raw materials considering the minimum logistics and storage expenses. It is also responsible for the easy availability of raw materials to the machines in the manufacturing unit and make sure that exact amount of raw material is available in the manufacturing unit as excess or deficiency of the material can affect the efficiency of the manufacturing unit.

As soon as the new order arrives the planning agent takes appropriate manufacturing decision using employing artificial intelligence technique such as genetic algorithm (GA), simulated annealing (SA), tabu search (TS), ant colony optimization (ACO), and bee colony optimization (BCO). However, in the literature it was observed that no random search algorithm exists that can be regarded as best suited strategy for a particular type of problem. Selection of the algorithm depends on nature of the problem. Keeping the same in mind in this article planning agent uses algorithm portfolio concept [15]. Algorithm portfolio is a collection of different algorithms and/or different copies of the same algorithm running on different processor. The portfolio algorithm is exploited through combining the algorithms and analyzing their performances on multiple processors as well as on a single processor. The main task of the portfolio is to choose the algorithms that lead to a high level of performance on a given problem instance, that is, to bring out near-optimal solutions in stipulated time frame. This leads to minimization of the computational cost, increase in the diverse problem solving capability, and maintenance of the quality from the best. The algorithm portfolio system will start working as soon as the new problem instance arrives and will be characterized by allocating a time limit to provide the solution. Thus, initially the allocator will assign an experimentation time to various algorithm agents and will decide the priority order of the algorithm agents. The data collected during the experimentation from each algorithm agent will be fetched to the selector agent on the basis of whom it decides the algorithms to be bunched in a portfolio to solve the stage problem at hand. These algorithms are run for an over a number of iterations. At the end of iteration, the control agent will assign improved knowledge to each algorithm agent. Thus, rather than making a single decision about the final selection of an algorithm agent for the remaining time, the selector will revisit its choice over and over.

Knowledge Base Agent: This agent is connected with all the other agents such as outsourcing and material planning agent, supplier selection agent, planning agent, forecasting agent, and maintenance agent. This agent stores all the information related to the manufacturing processes. It is done by collecting information from all the other agents and monitoring their activities. It holds the information about the current status of components being processed in order to manufacture a product, the order in which they are processed and their processing times Furthermore, it stores the information regarding the successful and unsuccessful decisions made by other agents. It helps so that the mistakes committed in the past are not repeated. This agent can update itself both online and offline.

Forecasting Agent: This agent decides the amount of raw material to be ordered and pass this information to purchase order collection agent, outsourcing and material planning agent, and supplier selection agent. This decision is taken in accordance with the market fluctuations prevailing at that moment of time. Forecasting agent consists of high performance tools for forecasting and estimating the quantitative and qualitative demands of the current trends of the market. The main objective of this agent is to minimize the error in the estimated demand pattern by considering the market fluctuations. This agent utilizes a vast set of judgmental and mathematical tools depending upon the nature of forecasting data available. It is a very complicated job to choose the best method for forecasting the demand pattern.

In the literature there are plenty of methods available for judgmental and mathematical forecasting methods such as Unaided judgment, Prediction markets, Delphi, Structured analogies, Game theory, Judgmental Decomposition, Judgmental bootstrapping, Expert systems, Simulated interaction, Intentions and expectations surveys, Conjoint analysis, Extrapolation, Quantitative analogies, Rule-based forecasting, Neural nets, Data mining, Casual model, and Segmentation. Choosing the best forecasting method for any particular situations is a very tough task, and sometimes more than a method may be appropriate. In order to choose the best forecasting method among the available, forecasting agent adopts a decision making methodology. For example in a particular situation if the agent decides to go ahead with the quantitative methods, the selection of the appropriate method will be based on the intercession tree.

Maintenance Agent: It utilizes the sensor in the machines to monitor their maintenance requirements, breakdown status, idle or in process stages etc. There are various maintenance policies being followed in the manufacturing sector having their respective advantages and shortcomings. This agent will prioritize the sequence of machine which needs maintenance or repair. It will also take decision about whether a machine can be repaired or it needs to be replaced. It will prepare a maintenance schedule in a way so that there will be minimum alterations in the working of other agents. It will further make a decision about the maintenance of machine whether it will be done in the premises or it needs to be outsourced. It maintains all the records such as information regarding repair date, warranty/ guarantee of the machines. Furthermore, it has the information regarding which machines are dependent on other machines. It will communicate with the knowledge base agent for selecting the new machines. It keeps the record of the spare parts, necessary tools, lubricating oils etc. which needs to be ordered for the respective maintenance of the machines.

The Maintenance Agent is responsible for monitoring the maintenance requirements of conveyances and therefore has the ability to both access appropriate data sources and to monitor the operational state of conveyances and high value loading facilities through the interpretation of sensor data.

Administrative Agent: This agent will make sure that all the operations performed by various agents are within the legal boundaries. It will take care of agreements, warranties, guaranties, transport security, and other Health and Safety measures. It will maintain all the Accounts like salaries of employees, payments of supplier, customer's payments, and other overheads.

Communication Ontology: In the proposed agent architecture an agent can co-operate with other agent by sending help signal. Help signal can only be responded by agents who come in perceptory region of the agent who has sent signal. Mathematically, 'help' signal Hti send by ith agent for collaborative help in task 't' is defined as:

$$H_i^t = (a_i, t_t) \, \forall \, A^{PR_i} \ldots \tag{1}$$

where, $A^{PR_i}$represents the set of agents within the perception range (PR) of agent '$i$' and is defined as:

$$A^{PR_i} = \left\{ a_j \in a / a_j^{PR_i} \right\} \ldots \tag{2}$$

$$\exists A^{PR_i} \in a, \quad A^{PR_i} \wedge \neg(a_i) \ldots \tag{3}$$

and $a_j^{PR_i}$represents the 'j' agent lying in the perceptory range of agent 'i' and is defined as;

$$a_j^{PR} < \left| d_{ij} \right| < PR_i \ldots \tag{4}$$

$|d_{ii}|$ represents the distance between the agents $i$ and $j$. In this architecture, Manhattan distance has been taken into account because of its effectiveness compared to Euclidean.

Distance in parallel computing scenario [16, 17]. Upon receiving a 'help' signal form agent $i$, agent $j$ send a 'reply' signal $r_j^i$ defined as

$$r_j^i = (a_j, a_i, H_i^t) \tag{5}$$

## 3 Case Study

A medium size manufacturing industry is being considered to demonstrate the execution process of proposed architecture. As soon as new customer has arrived, purchase order collection agent collects all information related to the order like design of the product, its specification, due date etc. Now he communicates with all other agents such as supplier selection agent, planning agent, outsourcing and material ordering agent, maintenance agent to know the current status of the plan. On the basis of the collected information such as raw material stock, machine availability, current orders in process, purchase order collection agent estimates the due date for the new order. If the industry is not able to meet the due date of his new customer, purchase order collection agent try to negotiate with the customer on due date. As soon as order is finalized purchase order collection agent pass all the information related to order to all appropriate agents. Thereafter outsourcing agent decides the production policies that are if all the operations would be implanted or few of them needs to be outsourced. Similarly material ordering agent looking at existing stock decides how, when, and what has to be ordered keeping in touch with forecasting agent. When all these are decided supplier selection agent selects appropriate partner or suppliers of the raw material. In all these process agents consult knowledge based agent to collect information related to the similar deals in the past. The history of any deal with the selected supplier is being checked in its database and if the feedback is positive then the deal is being finalized. Now planning agent plans the entire process of manufacturing. In this process planning agent uses algorithm portfolio for manufacturing planning, scheduling, and execution. After manufacturing the order is delivered to the customer. All these processes and the decision made is being tracked and stored in the Knowledge base agent for future reference.

In this case Study Company got two orders from different customer. Each order consisted of manufacturing of 5 parts. In order to manufacture the products, one of the operation needs to be outsourced which cannot be performed in the manufacturing unit. So, the outsourcing agent decided to outsource one of the operations. Detailed information related to the order such as due date, precedent relationship and type of operation is given in Tables 1 and 2. The final operation sequence generated by planning agent using algorithm portfolio is mentioned in Fig. 2. The final outcome shows the efficacy and the execution process of the proposed architecture.

**Table 1** Processing time and available machines

| Part no | Operation number | Processing/ outsourcing unit | Processing time |
|---|---|---|---|
| 1 | 1 | M1 | 5 |
| | | M2 | 3 |
| | 2 | M2 | 7 |
| | 3 | M3 | 6 |
| | 4 | M2 | 3 |
| | | M4 | 3 |
| | | M5 | 4 |
| 2 | 5 | M1 | 7 |
| | 6 | M2 | 4 |
| | | M3 | 6 |
| | 7 | M3 | 7 |
| | | M4 | 7 |
| | 8 | M2 | 4 |
| | | M5 | 10 |
| 3 | 9 | M1 | 4 |
| | | M2 | 5 |
| | | M3 | 8 |
| | 10 | M4 | 5 |
| | 11 | M4 | 6 |
| | | M5 | 5 |
| | 12 | M1 | 4 |
| | | M5 | 4 |
| 4 | 13 | M2 | 2 |
| | | M3 | 6 |
| | 14 | M3 | 8 |
| | 15 | M3 | 3 |
| | | M4 | 8 |
| | 16 | M2 | 6 |
| | | M4 | 7 |
| | | M5 | 4 |
| 5 | 17 | M1 | 3 |
| | | M3 | 5 |
| | 18 | M3 | 7 |
| | 19 | M4 | 9 |
| | | M5 | 6 |
| | 20 | M1 | 6 |
| | | M5 | 3 |

**Table 2** Precedent relationship between operations

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

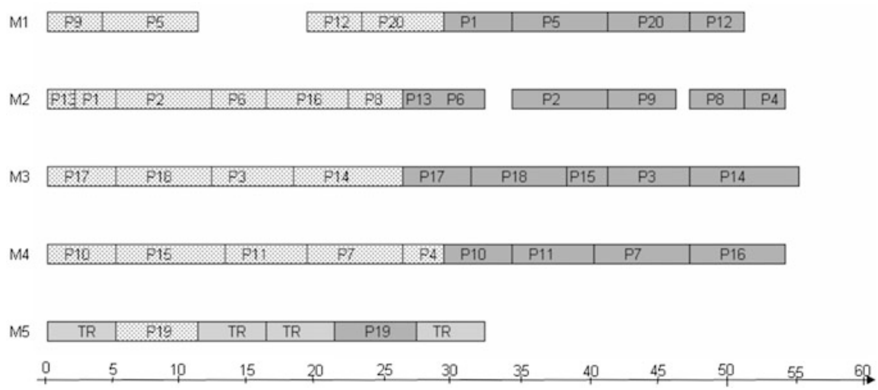


**Fig. 2** Final manufacturing plan suggested by planning agent

## 4 Conclusion

The manufacturing industries at present are suffering from the serious consequences of inflation (in terms of resources and other inputs) and decline of global economy. The Multi agent framework proposed in this article is being devised to combat this complexity prevailing in the market. This framework being flexible in nature can be modified as per the requirement of manufacturing industries.

The other existing agent architectures in literature are generally not self-adaptive in nature. The proposed architecture is self-adaptive in nature. As soon as new order arrives it negotiate with customer on due date, automatically decides on outsourcing policy and supplier selection. In the earlier architectures, if the agent were not capable of acting alone then they usually required user's interference. However, in this proposed architecture the agents communicate among themselves to develop new skills to automatically accommodate new changes.

In the literature there is no set rule for selection of appropriate planning algorithm. While in the proposed agent architecture for a corresponding order planning agent exploit the beauty of algorithm portfolio and automatically select the suitable efficient algorithm for planning process. The maintenance agent apart from planning and execution of the maintenance policies is also capable of out-sourcing the maintenance operations of the machines if they cannot be done cheaply and conveniently within the manufacturing plant. The selection of the correct forecasting method usually depends on problem environment. In literature agent architecture used only one method for forecasting. However, in this agent architecture, more than one forecasting method has been used and the agent automatically selects a particular method for a specific problem. The proposed agent architecture composed of multi agent architecture is capable of resolving the decision-making issues in manufacturing industries. This framework is capable of automatic decision making without the inputs from user interface.

## References


1. Chan FTS, Chan HK (2004) A new model for manufacturing supply chain networks: a multi agent approach. Proc Inst Mech Eng, Part B: J Eng Manuf 218(4):443–454
2. Azevedo AL, Sousa JP (2000) A component-based approach to support order planning in a distributed manufacturing enterprise. J Mater Process Technol 107(1–3):431–438
3. Jia HZ, Fuh JYH, Nee AYC, Zhang YF (2002) Web-based multi-functional scheduling system for a distributed manufacturing environment. Concurr Eng 10(1):27–39
4. Shi Y, Gregory M (1998) International manufacturing networks—to develop global competitive capabilities. J Oper Manage 16:195–214
5. Rudberg M, West BM (2008) Global operations strategy: coordinating manufacturing networks. Omega 36(1):91–106
6. Vereecke A, Dierdonck RV, De Meyer A (2006) A typology of plants in global manufacturing networks. Manage Sci 52(11):1737–1750
7. Li L, Fuh JYH, Zhang YF, Nee AYC (2005) Application of genetic algorithm to computer-aided process planning in distributed manufacturing environments. Robot Comput-Integr Manuf 21(6):568–578
8. Ulieru M, Norrie D (2000) Fault recovery in distributed manufacturing systems by emergent holonic re-configuration: A fuzzy multi-agent modeling approach. Inf Sci 127(3–4):101–123
9. Gefang W, Xizhi F, Guoshun C (2007) Research on intellectualized fault diagnosis system based on distributed multi-agent technology. Electronic measurement and instruments, 2007. ICEMI '07, 8th international conference on publication, pp 3-405–3-409
10. Shen W (2002) Distributed manufacturing scheduling using intelligent agents. IEEE Intell Syst 17(1):88–94

11. Maturana FP, Norrie DH (1996) Multi-agent mediator architecture for distributed manufacturing. J Intell Manuf 7(4):257–270
12. Oliveira E, Pereira G, Gomes C (2002) Reliable framework architecture for multi-agent systems interaction. The 7th international conference on computer supported cooperative work in design, pp 276–281
13. Lee J-H, Kim C-O (2008) Multi-agent systems applications in manufacturing systems and supply chain management: a review paper. Int J Prod Res 46(1):233–265
14. Leitão P (2009) Agent-based distributed manufacturing control: a state-of-the-art survey. Eng Appl Artif Intell 22(7):979–991
15. Gomes CP, Selman B (2001) Algorithm portfolios. Artif Intell 126(1–2):43–62
16. Freitas AA, Timmis J (2003) Revisiting the foundations of artificial immune systems: a problem-oriented perspective. Artif Immune Syst 2787:229–241
17. de Castro LN, Timmis J (2002) Artificial immune systems: a new computational intelligence approach. Springer, London

# Inventory Based Multi-Item Lot-Sizing Problem in Uncertain Environment: BRKGA Approach

**Felix T. S. Chan, R. K. Tibrewal, Anuj Prakash and M. K. Tiwari**

**Abstract** In this paper, Multi-Item Capacitated Lot-Sizing Problem (MICLSP) has been taken into consideration. Demand for each item in each period is uncertain and it is known at the starting off first time period. This paper also addresses the backlogging and a high penalty cost occurred for backlogging. Simultaneously, the penalty cost for exceeding the resource capacity is also occurred. These both penalty costs are included in the main objective function. In this connection, the main objective is to achieve such a solution so that the total cost should be minimized. The ingredients of total cost are the setup cost, production cost, inventory holding cost, and aforementioned both the penalty cost. To solve this computationally complex problem, a less explored algorithm Biased Random Key Genetic Algorithm (BRKGA) has been applied. According to the authors' knowledge, this paper presents the first study for the application of BRKGA in lot-sizing problem. The encouraging results proved that the proposed algorithm is an efficient algorithm to tackle such complex problems. A comparative study with other existing heuristics shows the supremacy of proposed algorithm on the basis of quality of the solution, number of generation and computational time.

**Keywords** Production planning · Multi-item capacitated lot-sizing problem (MICLSP) · Inventory control · Biased random key genetic algorithm (BRKGA)

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## 1 Introduction

The lot-sizing is one of the most critical issues in planning and managing of manufacturing processes. It's a decision making problem of manufacturing the demanded products in different lot sizes in such a way that the demand must be fulfilled while the cost should be minimum. Many a researchers like [1, 2] etc. have considered only a single item lot-sizing problem. If there is a demand of various items over multi period and setup time, production time, shortage cost, setup cost, production cost, and holding cost with resource capacity are taken into account, the lot-sizing problem is referred as Multi-Item Capacitated Lot-Sizing Problem (MICLSP). The MICLSP problem encompasses to search an efficient production plan which minimizes the sum of setup cost, production cost, and holding cost by considering the resource capacity, demand shortage over the complete planning horizon. According to W.H. Chen and J.M. Thizy [3] the multi-item capacitated lot-sizing problem with setup time is an NP-hard problem. However, the modeling and searching for optimal solution become difficult if the planning horizon increases due to the exponential expansion of solution space. Nowadays, due to a competitive pressure of reasonable execution time the decision maker has to find a better feasible solution or in other words decision makers are seeking for a near optimal solution within less time.

In the last decade, meta-heuristics are widely used to solve mixed integer programming problem which are having exponential solution space. Most of the researchers are attracting toward nature inspired algorithm like GA and PSO. Few researches address the application of PSO to reveal the complexity of the lot-sizing problem [2, 4]. Whereas, since 1990's, a lot of researchers have employed Genetic Algorithm to solve the different versions of lot-sizing problem with different objectives and issues [5–7]. Therefore, it can be said that genetic algorithm is enough efficient to solve the computationally complex lot-sizing problem. Nowadays, there is a need to evolve new algorithms for faster convergence and better quality solutions. To keep it in mind, a Biased Random Key Genetic Algorithm (BRKGA), a modified version of GA, has been employed in the present study to solve the intricacies of lot-sizing problem.

In this paper, multi-item capacitated lot-sizing problem with time varying demand or in uncertain environment, setup times, and various factors of cost has been addressed. The lot-sizing schedule should fulfill the demand of each item in each time period and also satisfy a restricted capacity of resources. The main objective of this study is to minimize the total cost, which is the sum of setup cost, production cost, and holding cost. To imitate the realistic situation, a penalty cost is occurred if inventory is not sufficient to fulfill the demand. Another penalty is occurred in case of insufficient resource capacity to manufacture the required number of products. By considering both penalties, the main objective, i.e., total cost is modified and both the penalties also participate in main objective of the study. Therefore, this study provides a multi dimensional objectives: (1) minimize the total cost (2) fulfill the customer demand and (3) satisfy the capacity constraints. To solve this NP-hard problem, a meta-heuristic BRKGA is applied. To show the effectiveness, BRKGA has been applied on numerical example which is taken from the literature. The efficacy of BRKGA is also proven by applying it on more complex multi-item capacitated lot-sizing problem. It has also been compared with other existing heuristics to show the supremacy of BRKGA. From the numerical analysis it has been proved that BRKGA can efficiently tackle the lot-sizing problem and provides the better result within less number of generation.

The remainder of this paper is organized as following: Sect. 2 presents the related literature review in lot-sizing problem; whereas, the description of lot-sizing problem with mathematical modeling is presented in Sect. 3. Section 4 describes the background of proposed algorithm and the steps for application in presented model. Section 5 illustrates the numerical analysis along with various complex natured numerical examples. Finally, in Sect. 6, the paper is concluded with future scope of the research.

## 2 Literature Review

Capacitated lot-sizing problems are computationally complex and it is considered as NP-hard problem. Many researchers have proposed a lot of optimal or heuristics lot-sizing procedures to evaluate such complex problems. To show the complexity of lot-sizing problems, X. Liu et al. [8] have modeled an algorithm for a lot-sizing problem with bounded inventory, lost sales, non-increasing production cost function, and non-decreasing inventory capacity with respect to the time period. N. Absi and S. Kedad-Sidhoum [9] proposed a lagrangian relaxation of the resource capacity constraints and developed a dynamic programming algorithm to solve multi-item capacitated lot-sizing problem. T. Wu and L. Shi [10] proposed a New Heuristic algorithm for capacitated lot-sizing problem. L. K. Gaafar and A.S. Aly [11] have investigated the applicability of particle swarm optimization (PSO) to the dynamic lot-sizing problem with batch ordering. They have carried out a comparative study using both modified Silver-Meal Heuristic and Genetic Algorithm (GA). There comparison was based on the relative frequency of obtaining the optimum solution and the percentage deviation from the optimum solution. T. Wu et al. [12] have proposed hybrids Nested Partitions and Mathematical Programming (HNP-MP) approach to achieve feasible high quality solution for multi-item capacitated lot-sizing problem with setup times.

This paper investigates the applicability of Biased Random Key Genetic Algorithm (BRKGA) to the targeted problem and compares its performance with Simple GA [13], annealing penalty hybrid genetic algorithm (APHGA) [14] and Knowledge Evolution Algorithm [15]. In this paper BRKGA is employed for solving the multi-item capacitated lot-sizing problem. Firstly random key genetic algorithm was introduced by Bean [16] and he extended it to tackle a vide class of combinatorial optimization problem. BRKGA was first introduced by [17] for sequencing problem. The main feature of BRKGA is to select one parent from elite group for crossover therefore; it performs better than simple Genetic Algorithm.

From the literature review it can be concluded that multi-item capacitated lot-sizing problem plays a vital role in production planning. This problem has been explored by various researchers but still it needs more exploration with real time constrains and real world manufacturing system environment. Another exploring segment is the use of meta-heuristic for solving such complex problem with uncertain environment. This study explores the multi-item capacitated lot-sizing problem and provides a new in site about the application of meta-heuristic for this problem.

## 3 Problem Description

Consider the following multi-item capacitated lot-sizing problem (MICLSP). Given the external demand for N items over a time horizon of T periods, find a solution which minimizes total cost including setup, production, holding, and lost sales cost satisfying the prior mentioned assumptions.

For each period, demand must be satisfied and capacities are supposed not to be exceeded otherwise, expensive lost sales or capacity shortage will result to a high cost. In this section, the notations are presented first before providing the basic formulation of the problem.

Indices and Index Sets:

$T$ Number of periods
$I$ Number of items
$J$ Number of resources
$t$ Periods, $t = 1, \ldots\ldots, T$
$i$ Items, $i = 1, \ldots\ldots, I$
$j$ Resources, $j = 1, \ldots\ldots, J$.

Parameters:

$SC_{it}$ Setup cost for item i in period t
$HC_{it}$ Inventory holding cost for one unit of item i in period t
$PC_{it}$ Production cost for one unit item i in period t
$ST_{ij}$ Setup time for item i on resource j
$PT_{ij}$ Production time required to produce one unit of item i on resource j
$GD_{it}$ Gross demand of item I in period t
$C_{jt}$ Total available resource capacity in period t
$\delta_{it}$ Penalty for lost sale for one unit of item i in period t
$M$ Large integer.

Variables:

$Y_{it}$ Number of item i produced on period t

$L_{it}$ Amount of lost sales of item i in period t
$S_{it}$ Inventory of item i at the end of period t
$X_{it}$ Binary decision setup variable.

Then the general formulation of multi-item lot-sizing problem can be given as follows:

$$\min\left(\sum_{i=1}^{I}\sum_{t=1}^{T}\left(PC_{it}*Y_{it}+SC_{it}*X_{it}+HC_{it}*S_{it}\right)\right) \tag{1}$$

The objective function (1) means to minimize the total cost which includes setup, production, and holding costs. In this paper multi-item capacitated lot-sizing problem has been considered with lost sales and multiple resources. Objective function for this kind of problem is taken as,

$$\min\left(\begin{array}{l}\sum_{i=1}^{I}\sum_{t=1}^{T}\left(PC_{it}*Y_{it}+SC_{it}*X_{it}+HC_{it}*S_{it}+\delta_{it}*L_{it}\right)\\ +M*\left(\sum_{j=1}^{J}\sum_{t=1}^{T}\max\left(0,\sum_{i=1}^{I}\left(ST_{ij}*X_{it}+PT_{ij}*Y_{it}\right)-C_{jt}\right)\right)\end{array}\right) \tag{2}$$

$$S_{i(t-1)}+Y_{it}-\left(GD_{it}-L_{it}\right)=S_{it}\quad i=1,\ldots\ldots,I,t=1,\ldots\ldots,T \tag{3}$$

$$\sum_{i=1}^{I}\left(ST_{ij}*X_{it}+PT_{ij}*Y_{it}\right)\leq C_{jt}\quad j=1,\ldots\ldots,I,t=1,\ldots\ldots,T \tag{4}$$

$$Y_{it}\leq M*X_{it}\quad i=1,\ldots\ldots,I,t=1,\ldots\ldots,T \tag{5}$$

$$X_{it}(Y_{it})=\begin{cases}1 & if\ Y_{it}>0\\ 0 & if\ Y_{it}=0\end{cases}\quad i=1,\ldots\ldots,I,t=1,\ldots\ldots,T \tag{6}$$

$$Y_{it}\geq 0\qquad i=1,\ldots\ldots,I,t=1,\ldots\ldots,T \tag{7}$$

$$S_{it}\geq 0\qquad i=1,\ldots\ldots,I,t=1,\ldots\ldots,T \tag{8}$$

$$S_{i0}=S_{iT}=0\qquad i=1,\ldots\ldots,I \tag{9}$$

The objective function (2) minimizes the total cost induced by production plan that is production costs, inventory costs, setup costs, and penalty cost due to lost sales and penalty cost due to insufficient resource capacity. The constraint (3) represents the material balance for the inventory ensuring the demand satisfaction of all periods for all items and constraint (4) enforces the capacity feasibility. Inequality (5) guarantees that the production quantity is zero when production is not placed. The constraint (6) implies that the setup cost analogous to an item must be paid before producing the item. The nonnegative restriction for production in equation (7) and inventory in equation (8) assures non occurrence of backlogging and the last equation (9) guaranties that no initial inventory and final inventory is available. Use the International System of Units (SI) only. Never combine SI units and CGS or other units. If you must use other units, always state the units for each quantity that you use in an equation or in a figure.

## 4 Biased Random Key Genetic Algorithm

The general working mechanism of BRKGA is shown in Fig. 1. From Fig. 1, it can be said that it is divided in two part: problem independent and problem dependent. In the problem independent part, the generation of the random keys and selection of random keys, introduction of mutants and crossover are included. Therefore, the structure of BRKGA can be developed without the knowledge of problem or in other words the general framework can be developed for all problems. Whereas, the decoder is the problem dependent part. The decoder calculates the fitness value of all the solutions on the basis of main objective of the problem. Thus, it depends on the nature of the problem. Therefore, if the general framework of BRKGA is prepared, the user should have the knowledge of chromosome size and working of decoder. So it can be said that it is very easy for the users due to its general framework and for each problem, the decoder should be defined.

Therefore, BRKGA provides the better result as it has the elite group of the solutions in each generation and keeps an eye on the tracking of the good solution and on the other hand it takes one parent from elite group and other from non-elite group for crossover. This crossover is also helpful to improve the quality of newly generated solutions.

## 5 Numerical Analysis

To show the efficacy of proposed algorithm in MICLSP, a real world manufacturing lot-sizing problem with numerical data has been taken into account. The numerical example is identical as [15]. In this example, there are five items are manufactured according to their demand in each period. The production cost for each item in each period is different. The inventory cost and setup cost are also varied according to item and time period. The demand is generated for each period of each item. There are two resources with different capacity in each time period. The setup time and production time for each item have also been provided. The sum of setup time and total production time should be less than the capacity of the resources.

To address this computationally complex problem, BRKGA is employed due to its efficiency of random keys. For this problem the initial population is 50. The best 30 % solutions are considered as the member of elite group and theses are employed as one parent for the crossover. The crossover probability is taken as

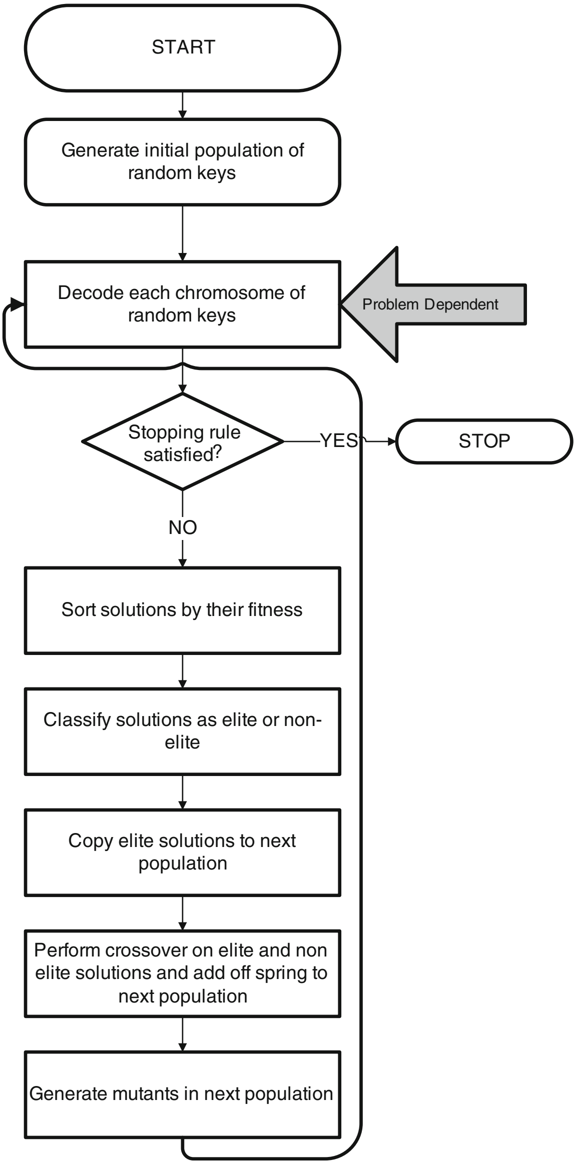


**Fig. 1** Flowchart of biased random key genetic algorithm

0.7. The detailed working procedure of proposed algorithm is given in Sect. 4. The main objective of this study is to manufacture different items with minimal total cost to fulfill the demand. The ingredients of total cost are setup cost, production cost, inventory holding cost, and penalty cost for lost sales and insufficient resource capacity. The results obtained from BRKGA for MICLSP are presented in Table 1. The table shows the lots of each item to be manufactured in each time horizon. The obtained near optimal value of performance measure, i.e., total cost is

**Table 1** Lot-sizing result of BRKGA

| Items | Periods | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | 23 | 0 | 44 | 0 | 0 |
| 2 | 24 | 0 | 18 | 20 | 0 |
| 3 | 12 | 29 | 0 | 16 | 12 |
| 4 | 12 | 50 | 0 | 0 | 0 |
| 5 | 12 | 11 | 43 | 0 | 0 |

1,700 cost units. The result provides an insight that the manufacturing for anticipated demand is also beneficial in some cases where the inventory cost is not very large but the penalty for lost sale is very high. The convergence rate of BRKGA is also very fast as it is converting in only 6 numbers of iterations. The converging trend of BRKGA is depicted in Fig. 2.

To show the supremacy of BRKGA, it is also compared with the results obtained from various algorithms which are addressed in various literatures. The comparative results are shown in Table 2. The total cost obtained from GA is 1,761 and Annealing Penalty Hybrid Genetic Algorithm (APHGA) provides the result with 1,709 cost units whereas, Knowledge Evolution Algorithm (KEA) provides the similar result as BRKGA. The number of iterations for GA is very large whereas, APHGA and KEA computes the near optimal result in same number of iterations [15]. There is small difference in number of iteration for APHGA and KEA with BRKGA but there is a big difference in computational time.

From the above results, it can be concluded that BRKGA is enough efficient to tackle such decision making problems which are computationally complex. BRKGA also proves the supremacy over other heuristic as the quality of obtained solution is better and it is achieved in less number of generations. For MICLSP, the proposed algorithm is coded in MATLAB programming language and the experiment has been carried out on Intel core i3 2.13 Ghz processor.

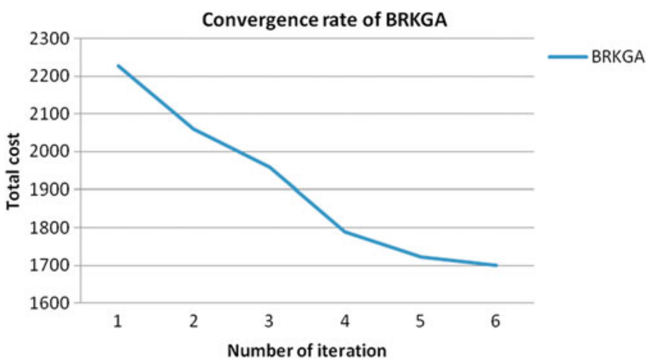


**Fig. 2** Convergence rate of BRKGA

**Table 2** A comparison of the result of GA, APHGA, KEA and BRKGA

| Heuristics | GA | APHGA | KEA | BRKGA |
|---|---|---|---|---|
| Optimal | 1,761 | 1,709 | 1,700 | 1,700 |
| Iterations | 21 | 10 | 10 | 6 |
| Time of CPU(s) | 26 | 14 | 1 | 0.6552 |

## 6 Conclusion

The present paper provides a new insight to the practitioners as well as researchers to the complexity of multi-item capacitated lot-sizing problem. The main objective of this study is to minimize the total cost which is sum of total setup cost, production cost, and inventory holding cost and penalty for lost sales and insufficient resource capacity. Therefore, it is very difficult to predict and evaluate the appropriate lot-size to fulfill the customer demand with minimal total cost. To solve such complex combinatorial problem, Biased Random Key Genetic Algorithm has been proposed. It is evident from the Sect. 5 that the BRKGA can efficiently handle this complex lot-sizing problem. The comparative study with other algorithm proves the supremacy of BRKGA. The BRKGA has the capability to understand the requirement of the real world attributes. Therefore, this study will provide a new vision to the managers to achieve the solution in such a way that can fulfill the demand of the customer with minimum total cost while considering the capacity of resources.

As a future scope this research can be done by considering other factors like outsourcing, remanufacturing, back ordering etc. It is also interesting aspect to observe the behavior of algorithm with other objectives like profit margin, customer satisfaction, time minimization, quality improvement etc. This research can also be applied as multi criteria decision making problem by considering two or more conflicting natured objectives at the same time.

## 7 Acknowledgments

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## References


1. Pochet Y, Wolsey LA (2010) Single item lot-sizing with non-decreasing capacities. Math Prog 121:123–143
2. Piperagkas GS, Konstantaras I, Skouri K, Parsopoulos (2012) Solving the stochastic dynamic lot-sizing problem through nature-inspired heuristics. Comput Oper Res 39:1555–1565
3. Chen WH, Thizy JM (1990) Analysis of relaxation for the multi-item capacitated lo-sizing problem. Ann Oper Res 26:29–72
4. Gaafar LK, Nassef AO, Aly AI (2009) Fixed-quantity dynamic lot sizing using simulated annealing. Int J Adv Manuf Technol 41:122–131
5. Zhong J, Huang L (2009) Application progress of genetic algorithm for economic lot sizing problem. In: Proceedings of the 1st IEEE international conference on information science and engineering, Nanjing, pp 2858–2861
6. Moon I, Silver EA, Choi S (2010) Hybrid genetic algorithm for economic lot-scheduling problem. Int J Prod Res 40(4):809–824
7. Goncalves JF, Sousa PSA (2011) A genetic algorithm for lot sizing and scheduling under capacity constraints and allowing backorders. Int J Prod Res 49(9):2683–2703
8. Liu X, Chu F, Chu C, Wang C (2007) Lot sizing with bounded inventory and lost sales. Int J Prod Res 45(24):5881–5894
9. Absi N, Kedad-Sidhoum S (2009) The multi-item capacitated lot sizing problem with safety stocks and demand shortage costs. Comput Oper Res 36:2926–2936
10. Wu T, Shi L (2009) A new heuristic method for capacitated multi-level lot sizing problem with backlogging. In: Proceedings of IEEE international conference on automation science and engineering, Bangalore, pp. 22–25
11. Gaafar LK, Aly AS (2009) Applying particle swarm optimization to dynamic lot sizing with batch ordering. Int J Prod Res 47(12):3345–3361
12. Wu T, Shi L, Duffie NA (2010) An HNP-MP approach for the capacitated Multi-item lot sizing problem with Setup Times. IEEE Trans Autom Sci Eng 7(3):500–511
13. Tang LX, Yang ZH, Wang MG (1997) New genetic heuristic algorithm to solve CLSP with multi resources in CIMS. J Control Theor Appl 4:39–44
14. Xu ZX, Ding YL, Xiong ZY (2001) Annealing penalty hybrid genetic algorithm for solving production scheduling problem. J Nanjing Univ Aeronaut 33(2):91–95
15. Ma H, Ye C, Zhang S (2009) Knowledge evolution algorithm for capacitated lot sizing problem. In: Proceedings of the IEEE international conference on computational sciences and optimization, Sanya, pp 999–1002
16. Bean JC (1994) Genetic algorithms and random keys for sequencing and optimization. ORSA j Comput 6:154–160
17. Gonçalves JF, Almeida JR (2002) A hybrid genetic algorithm for assembly line balancing. J Heuristics 8(6):629–642

# Part IV
# Manufacturing Organization and Strategies

# Challenges for Better Sustainable Manufacturing

**Lihui Wang and Z. M. Bi**

**Abstract** Sustainable manufacturing is regarded as a new manufacturing paradigm that provides an abstract representation of a manufacturing system. Although many manufacturing paradigms have been proposed, most of them are based on the assumption that the boundary of a manufacturing system can be defined based on customers' requirements. However, sustainable manufacturing is different. It has evolved from the past manufacturing paradigms and brings new challenges to today's practice. Within the context, the objective of this work is to examine the manufacturing requirements in a wider scope, to revisit existing paradigms so as to clarify the limitations and bottlenecks, and eventually to identify future challenges for better sustainable manufacturing. This paper reports our findings on what the requirements and challenges are, and reveals a Cloud-based approach toward better sustainability.

## 1 Introduction

Recently, Sustainability of economy, society and environment has been recognized as the priority to fundamental engineering research [1]. In manufacturing, many new terminologies related to sustainability, such as environmentally conscious manufacturing, green manufacturing, remanufacturing, and sustainable manufacturing, have been proposed [2]. However, the majority of the studies are limited to the general discussions of new requirements for next-generation manufacturing

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systems. The corresponding manufacturing paradigms for the implementation have not been studied systematically. Coincidently, with recent economic recession, research efforts on manufacturing paradigms have decreased significantly. Particularly, the true challenges of sustainable manufacturing are unclear.

The objective of this work is to relate sustainable manufacturing to the next-generation manufacturing paradigms. To achieve this objective, a brief review is given in Sect. 2 on the importance of manufacturing and how the paradigms have been evolved in the dynamic environment. In Sect. 3, the concept of sustainability is discussed and a literature survey is conducted to understand the state-of-the-art in this area. Particularly, the studies on the matrices of sustainability are compared and summarized. The roles of manufacturing paradigms to sustainability are examined in Sect. 4, by mapping the functions of manufacturing paradigms to the matrices of sustainability, where the missing connections between them are identified. Section 5 outlines the challenges and a Cloud-based approach toward better sustainable manufacturing. Finally in Sect. 6, conclusions and future work are provided.

## 2 Evolution of Manufacturing Paradigms

The selection of a manufacturing paradigm relies on customers' requirements and the complexity of manufacturing environment. The complexity depends on the number of design variables and their dynamic behaviors with respect to time [3]. Manufacturing systems have evolved over time to meet emerging needs from customers and the manufacturing environment.

As shown in Fig. 1, manufacturing systems become more and more complicated due to the expanded activities and the dynamics of manufacturing environment. The markets before 1913 were short of products thus customers cared only about the functions; companies aimed at cost reduction to gain more profit. Since 1960, global manufacturing capabilities were sufficient enough to bring the competitions among suppliers; customers could demand more than basic functions of products; therefore, how to improve product quality became the key strategy of success from 60 to 70 s. With an abrupt advancement of information technology (IT) from 1980, the global manufacturing markets were gradually saturated, thus companies were pressured to manufacture new products at a fast pace to catch earlier marketing opportunities. Today, we are more conscious to the deterioration of the global living environment and the shortage of natural resources in the near future; manufacturing companies are forced to change their system paradigms to accommodate the needs for better sustainability. In Fig. 1, the evolution of manufacturing paradigms has been divided into six phases. The symbolised concepts at each phase transition are *mass production*, *lean manufacturing*, *mass customisation*, *reconfigurable manufacturing*, and *sustainable manufacturing*, respectively [4], e.g. 1913 was the year when manufacturing transited from craft production to *mass production*.

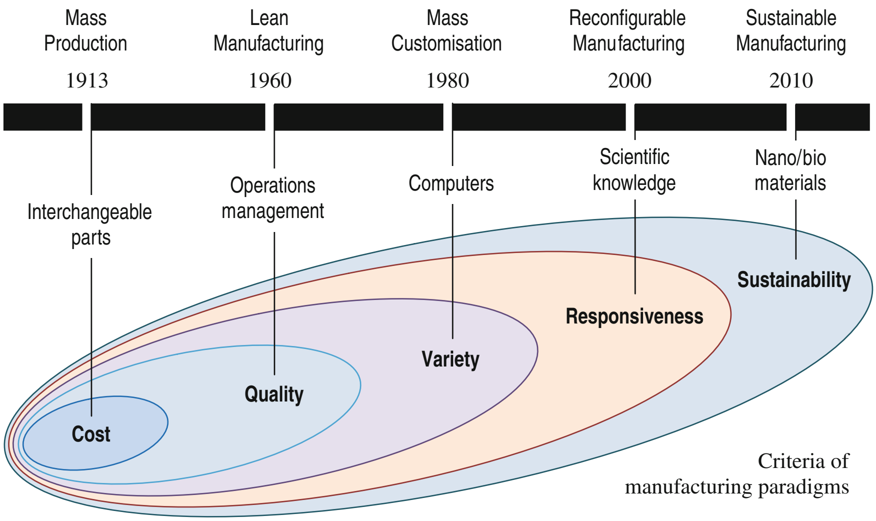


**Fig. 1** Manufacturing paradigms vs. criteria (modified from [4])

Numerous factors such as applicable strategies and technologies have their impact on the implementation of a new manufacturing paradigm. The success of a manufacturing paradigm can be viewed as the optimization of both hardware and software. It is helpful to relate companies' manufacturing objectives to existing theories and technologies [5]. Figure 2 depicts these relations. It consists of four layers. At the first layer, four key manufacturing requirements are listed. At the second layer, the strategies for meeting these system requirements are shown. At the third layer, the domains of a manufacturing system, where the strategies are applied, are illustrated. At the fourth layer, various production paradigms are classified in terms of the applied strategies and domains.

Production paradigms to date include *Lean Production*, *Just-in-Time Production*, *Flexible Manufacturing*, *Agile Manufacturing*, *Concurrent Engineering*, *Make-To-Stock*, *Make-To-Order*, *Engineer-To-Order*, *Assembly-To-Order*, *Virtual Enterprise*, *Computer Integrated Manufacturing*, *Global Manufacturing*, *Reconfigurable Manufacturing*, *Mass Customisation*, and *Total Quality Management*. Many paradigms, such as reconfigurable manufacturing and lean production, can meet the requirements in different ways since their implementations fit well in different strategies. Moreover, it is challenging to tell that one paradigm is better than another without the consideration of unique situation of specific enterprise. All paradigms have their strategies to meet certain requirements in one way or another, while none of them applies all strategies simultaneously to meet all requirements.

It has been shown that existing system paradigms have been developed to meet the requirements of short lead-time, personalization (or more variants), low and fluctuating product volumes, and cost reduction. Their capabilities to deal with the

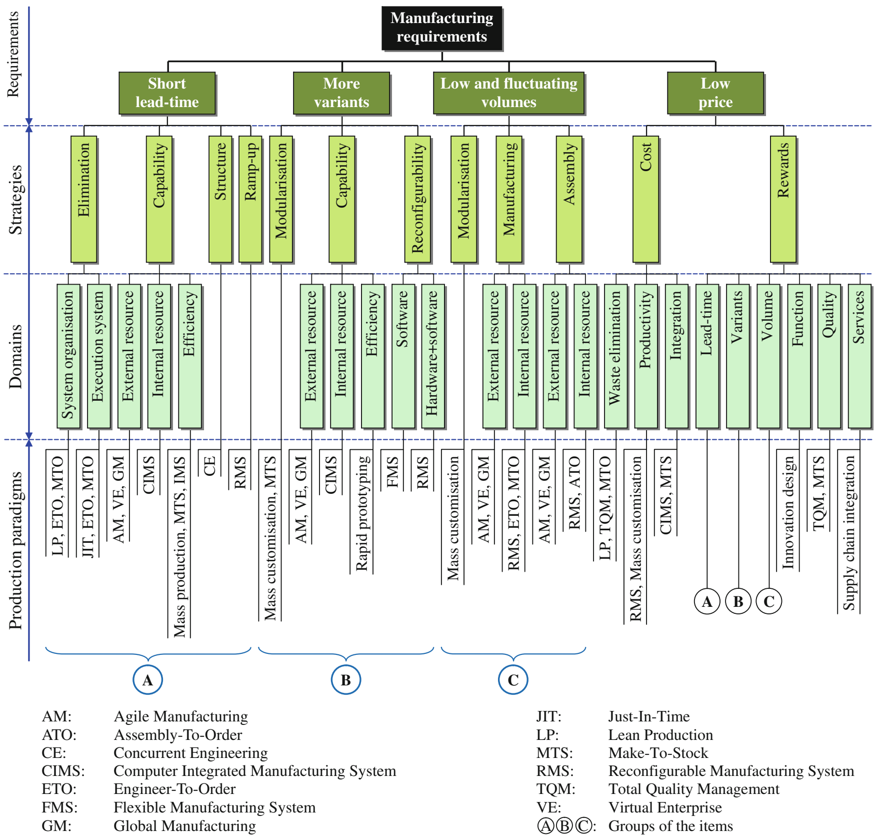


**Fig. 2** Manufacturing requirements, strategies, domains and production paradigms

requirements of sustainability of economy, society and environment have to be re-examined systematically. From the viewpoints of manufacturers, the limitations of the existing system paradigms to cope with sustainability requirements have been identified in [6]. It is now worth of exploring new system paradigms that can meet the sustainability requirements, effectively.

For most of the manufacturing systems, an essential condition for survival is to make profit through manufacturing activities. Eventually, the criteria of system design can be linked to the increased values of products from a manufacturing system. As shown in Fig. 3, the changing trends of manufacturing paradigms are predicted [7, 8]. It is suggested that a new system paradigm, i.e. sustainable manufacturing, will possess the capabilities of 6R (*reduce*, *recycle*, *reuse*, *recover*, *redesign*, and *remanufacture*) to maximize the increased value of products, whereas the green manufacturing is mainly capable of addressing the first 3R (*reduce*, *recycle*, and *reuse*).

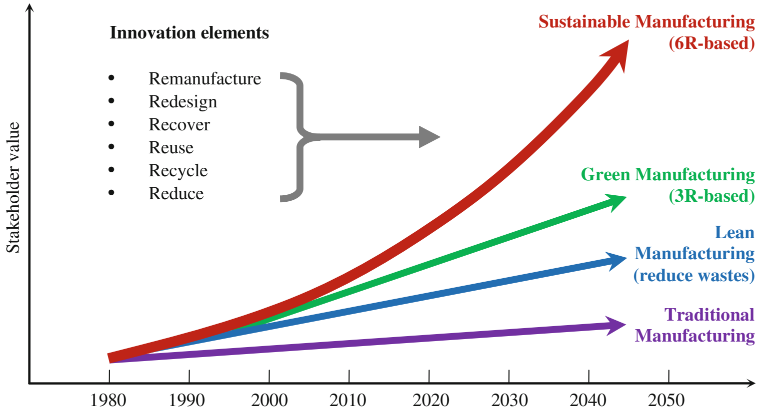


**Fig. 3** Four manufacturing paradigms versus their stakeholder values (modified from [7])

# 3 Study on Sustainability

There are five typical drivers for sustainability research: (1) shortage of natural resources, (2) dramatic increase of world population, (3) global warming, (4) pollution, and (5) unstoppable global economy [9]. As for sustainable manufacturing, three most important strategies are (1) selection and application of appropriate metrics for measuring manufacturing sustainability, (2) completion of comprehensive, transparent and repeatable life-cycle assessments (LCA), and (3) adjustment/optimization of manufacturing systems to minimize environmental impacts and cost based on the chosen metrics and the LCA [10].

## *3.1 Current Situation*

Consideration of sustainability in manufacturing is widely accepted, although not widely practiced yet. Current practices of product development in manufacturing companies are still predominantly based on traditional cost/profit models, aiming at achieving high quality of products at low cost and high profit. The prospects for sustainable manufacturing include (1) how manufacturers will respond the future challenges in the socio-economic business environment and technological change, (2) what the scope is for sustainable manufacturing in different socio-economic development paths, and (3) how the manufacturers will adapt their sustainability strategies to these developments [11]. Existing researches on sustainable manufacturing are focused on the following aspects [12]:

- metrics and analytical tools for assessing the impact of processes, systems and enterprises,

- modeling of sustainable, environmentally conscious manufacturing systems and processes,
- green supply chains,
- manufacturing technologies for reduced impact, and
- manufacturing technologies for producing advanced energy sources/storage.

### *3.2 Metrics of Sustainability*

A sustainable manufacturing strategy requires metrics for decision making at all levels of an enterprise. It is suggested to follow the framework of goal and scope definition. The distinction is made between environmental cost metrics and sustainability metrics [10]. Various standards, such as ISO 14000, ISO 14064, WEEE, RoHS, REACH, and ELV, have been developed in the last two decades. Kibira et al. [13] discussed the approaches by authorities to classify environmental policy procedures, which determine the incentives used to achieve compliance with environmental safety requirements. Dornfeld [12] suggested to measure sustainability in terms of gases emission ($CO_2$, methane $CH_4$, and $N_2O$), per capital, per GDP, per area/nation, recyclability, reuse of materials, energy consumption, pollution (air, water, land), ecological footprint, energy (available energy) or other thermodynamic measures.

According to the definition of sustainable manufacturing [14], the activities in a manufacturing system can be classified into two types, i.e. activities on materials and activities on processes. As shown in Fig. 4, these activities have their impact on the living environment and the society. The living environment has the aspects of ‘environmental impact’, ‘conserve energy’, and ‘natural resource’; whereas the society has the aspects of ‘customers’, ‘employee’, and ‘community’. Various criteria have been identified to evaluate the performances of a sustainable system paradigm.

## 4 Roles of Manufacturing Systems for Sustainability

Recently, manufacturers have begun to realize the need for the responsible use and management of resources in the lifecycle of a manufactured product [15]. The roles of manufacturing systems to sustainability really rely on how the boundaries of a manufacturing system are defined. As shown in Fig. 5, traditional manufacturing systems did not take into consideration of many factors such as waste management, pollution, recovery and reuse of used products.

However, as depicted in Fig. 6, with the increasing conscious of environmental issues, many activities are introduced in the lifecycle of products. Manufacturers today have the choice of either including these activities in their operations and optimizing the overall structure based on the required tasks, or paying the cost for

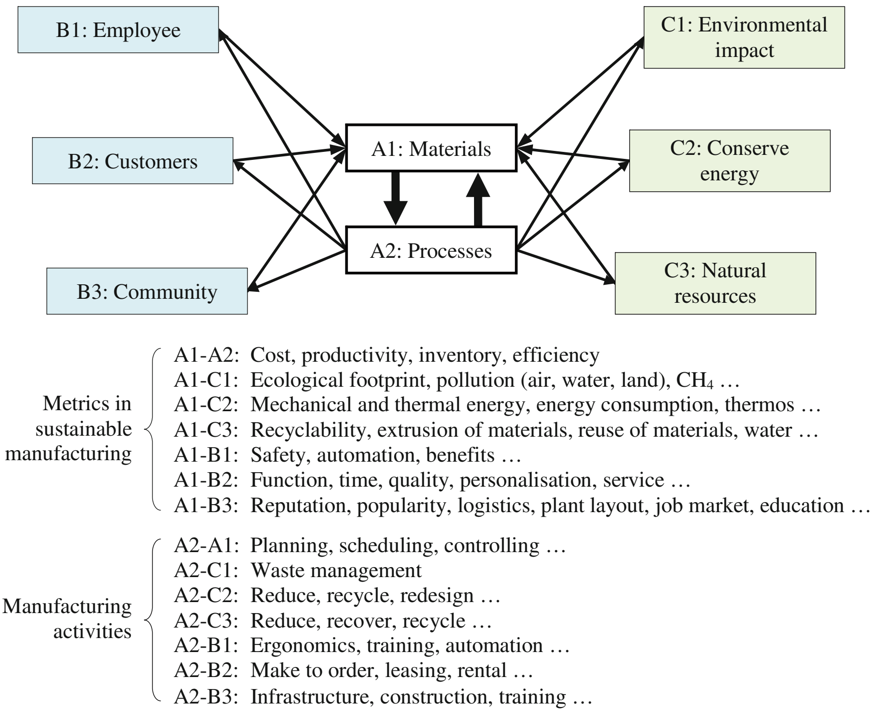


**Fig. 4** Activities and metrics in sustainable manufacturing

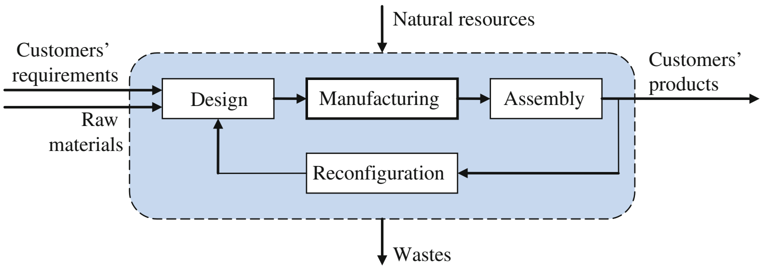


**Fig. 5** A traditional manufacturing system

waste management and disposal etc. Therefore, the roles of manufacturing systems are dependable to the definition of a manufacturing system, and it varies from one company to another.

Sustainable manufacturing has an impact on the sustainable eco-environment that consists of three pillars, i.e. environment, society and economy, as shown in Fig. 7. The phases in a product's lifecycle can be divided into 'pre-manufacturing', 'manufacturing', 'use', and 'post-use'. The aspects of evaluation on the impact from the four phases are illustrated, and the overall impact has been

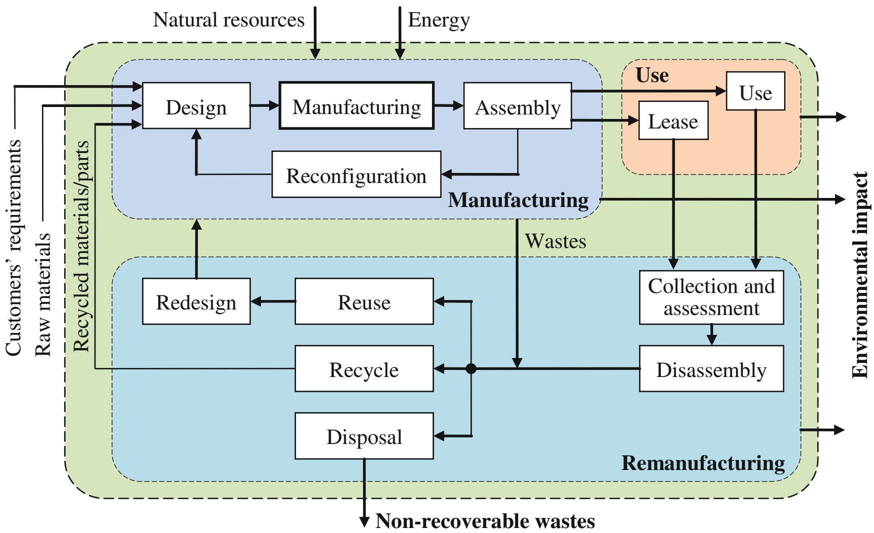


**Fig. 6** A sustainable manufacturing system

accumulated. It has shown that the limited contribution to sustainability is from manufacturing sector. Similar portions of contributions are from the activities at the phases of 'pre-manufacturing', 'use', and 'post-use'. While sustainable manufacturing is important to system sustainability, it is unrealistic to expect that the next-generation manufacturing paradigm can meet the requirements of sustainability completely.

Another issue is the relation of sustainability and sustainable manufacturing. Although there are some overlapping between the design of sustainability and the design of sustainable manufacturing, it can be completely different according to the scope of a manufacturing defined in the figure. On one hand, a manufacturing system can be confined to one product with a limited consideration of product life time; the main difference from traditional manufacturing system is that some new criteria on waste management and environmental impact have to be taken into consideration in its design. On the other hand, an extreme case is to include all activities in one company; therefore, the design of a sustainable manufacturing becomes design for sustainability. Note that when the boundaries of a system are considered, the inputs and outputs beyond system control have to be valued or devalued for the sake of system optimization, and this brings the uncertainties and fidelity of design results.

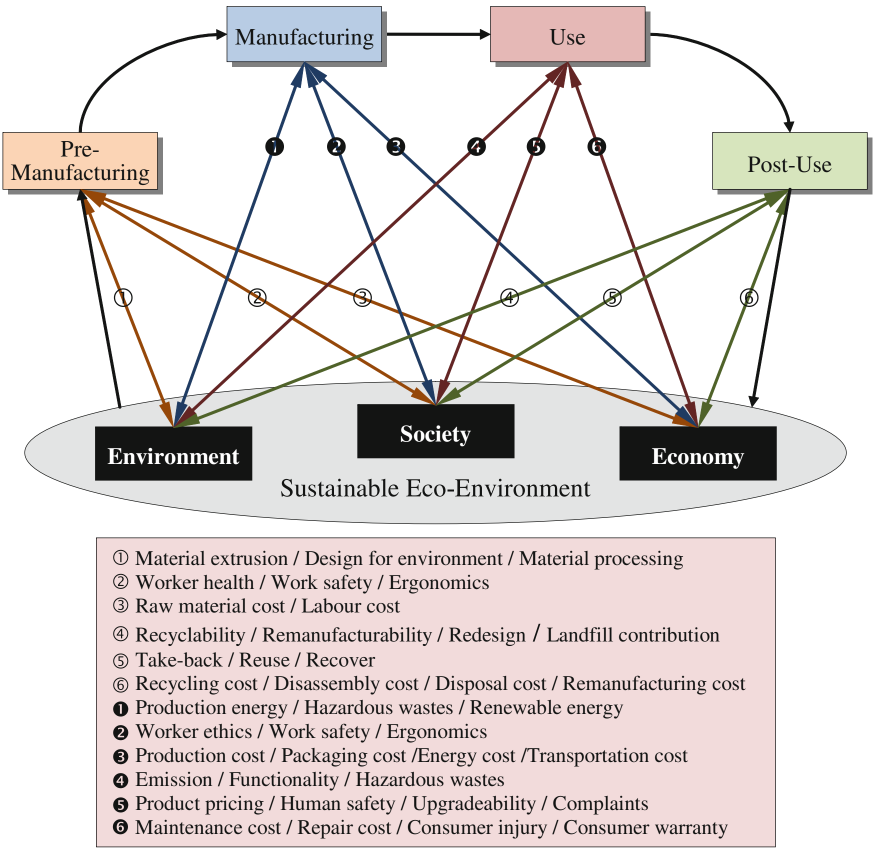


**Fig. 7** Manufacturing contributions to sustainable eco-environment

## 5 Towards Better Sustainable Manufacturing

As analyzed so far, sustainable manufacturing needs to address the challenges not only for better economy but also toward harmonized environment and society. Sustainable manufacturing cannot be achieved by a single company but a network of enterprises in a global dimension. This brings in other challenges such as efficient and effective data and information sharing as well as secrecy of proprietary information that may relate to mission-critical operations or intellectual properties of networked companies. Solutions to the latter challenges can be delivered as services based on Cloud computing.

Cloud computing, e.g. Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS), has emerged as a new-generation service-oriented technology to support multiple companies to deploy and manage services for accessing and exploiting over the Internet. Based on Cloud computing, manufacturing companies would provide cost-effective, flexible and scalable solutions to other companies by sharing complex and expensive manufacturing software/hardware with lower support and maintenance costs and much reduced resource consumption. Ultimately, it contributes to the better sustainable manufacturing. The development of the Cloud-based services (or Cloud manufacturing) includes design of four layers [16]:

- *manufacturing resource layer*, such as manufacturing equipment, sensors, servers, etc.;
- *manufacturing virtual service layer*, in which manufacturing resources are identified, virtualised, and packaged as available services. Identification and communication technologies have been researched, including wireless sensor network, RFID, Internet of Things, MTConnect [17], etc.;
- *global service layer*, which relies on a suite of Cloud computing technologies such as PaaS to take global service computing and supporting for various demands and requirements; and
- *application layer*, which is the interface for users to invoke services for various sustainable manufacturing applications.

Cloud manufacturing serves as the vehicle toward better sustainable manufacturing via a modular approach. Wherever relevant, modules with sophisticated technologies for online tracking of resource utilization, multi-objective decision support for process planning and simulation, and on-board manufacturing execution control can be activated by a common Cloud manufacturing platform to enhance responsiveness, adaptability, reliability, and optimality in achieving first-time-right yet sustainable operations on factory floors. Thus, a portable solution at low cost can be offered to the pragmatic mind of SMEs without losing the depth where needed. As shown in Fig. 8, the common services platform supports the service modules of machine availability monitoring (S-1), collaborative process planning (S-2), adaptive setup planning (S-3), and process simulation (S-4) are built into the platform. These technical modules, realized as *decision-support services*, are further tested and integrated with the common Cloud platform via web interfaces. S-2 and S-3 are essential manufacturing services in that they provide collaborative and adaptive solutions, having real-time access to the availability and utilization information of resources. In parallel to these, two more technical modules are designed for better sustainability: (1) an estimation service to help designers at early product design stage to check manufacturability and sustainability, and (2) an eco-friendly service to help customers to reduce energy and resource consumption. This convergent manufacturing approach ensures that the application view of industrial users is converging with the development view of the system components (services). For this purpose, an iterative process of joint specification, design and feedback is possible between engineers and customers via the Cloud manufacturing platform.

Within the context, S-2, S-3 and S-4 can be regarded as a set of Software as a Service (SaaS), S-1 provides real-time information service, and S-5 enables Machining as a Service (MaaS) and Assembly as a Service (AaaS). In addition to cost, time and quality concerns, the challenges of sustainable manufacturing to

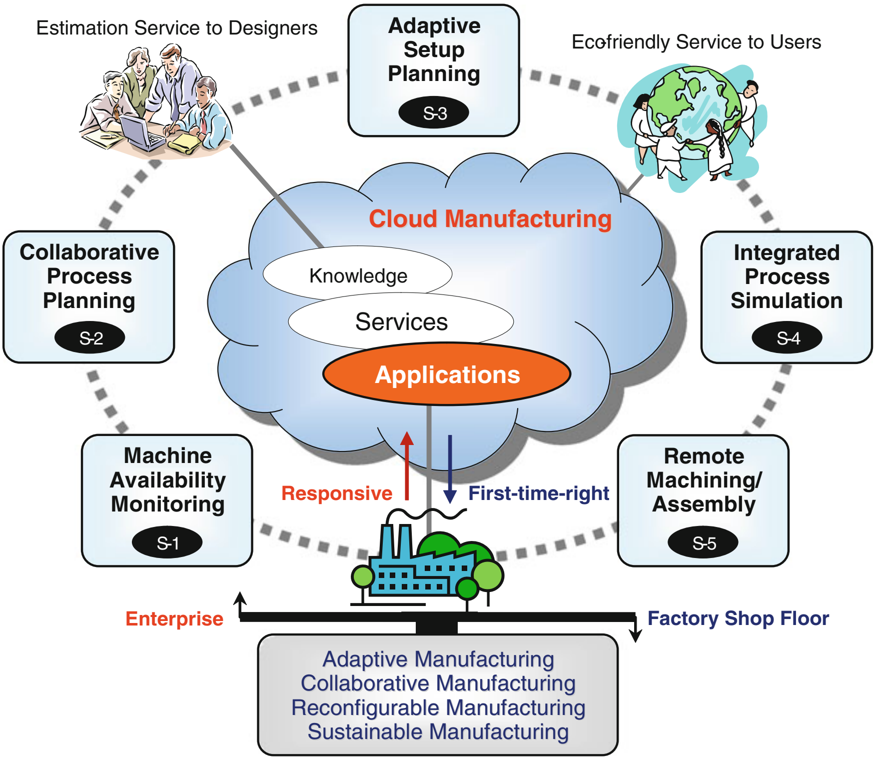


**Fig. 8** A cloud platform for better sustainable manufacturing

environment, society and economy are taken into consideration during process planning and optimization.

## 6 Conclusions and Future Work

Requirements of sustainable manufacturing are ubiquitous. Existing manufacturing systems are usually optimized based on the requirements of cost, quality, time, and product personalization. No system paradigm exists to meet the requirements of sustainable manufacturing. Based on the literature survey and our analysis, the next-generation system paradigm is likely a hybrid of various manufacturing systems—sustainable manufacturing facilitated by Cloud-based services. However, there is unlikely a totally new sustainable manufacturing paradigm. In sustainable manufacturing, it is necessary to bridge manufacturing processes with sustainability in design and optimization, and some quantifiable models for waste and energy measurement are essentials. It is the time for us to re-examine the limitations of existing system paradigms, and explore the means to evolve them into sustainable manufacturing.

As future work, the suggested aspects of endeavors to further increase the sustainability of manufacturing systems are summarized as follows.

- Real-time resource and energy consumption monitoring for better utilization
- Situation-aware and energy-efficient optimization of energy and wastes
- Sustainable manufacturing processes for energy consumption reduction
- Process-oriented dynamics-based energy modeling for process planning and machine/robot control
- Implementation of Cloud-based services for better sustainable manufacturing.

Finally, it is worth of mentioning that Cloud-based approach is not a replacement of sustainable manufacturing but instead a vehicle to realize much better sustainability of future manufacturing activities in a distributed and dynamic environment. Better sustainable manufacturing also needs to address the societal challenges.

## References

1. Kramer BM (2010) Support for sustainable manufacturing at the NSF. web.mit.edu/lmp/news/summit2010/kramer.pdf
2. Anityasarl M (2011) Inserting the concepts of sustainable manufacturing into industrial engineering curriculum. www.its.ac.id/personal/files/pub/3065-mariaanityasaristme-Final%20Paper_Maria%20Anityasari.pdf
3. Suh NP (2001) Axiomatic design—advances and applications. Oxford University Press, New York. ISBN 9780195134667
4. Koren Y (2010) Globalization and manufacturing paradigms. The global manufacturing revolution: product-process- business integration and reconfigurable systems. Wiley, Hoboken
5. Bi ZM, Lang SYT, Shen W, Wang L (2008) Reconfigurable manufacturing: the state of the art. Int J Prod Res 46(4):967–992
6. U.S. Department of Commerce (2004) Manufacturing in America. https://www.armysbir.army.mil/docs/pdf/sbir/manuam0104final.pdf
7. Jayal AD, Badurdeen F, Dillon OW, Jawahir IS (2010) Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels. CIRP J Manuf Sci Technol 2(3):144–152
8. Jayal AD, Balaji AK (2007) On a process modeling framework for sustainable manufacturing: a machining perspective. In: Proceedings of ASME international mechanical engineering congress and exposition, 11–15 Nov s2007, Seattle, IMECE2007-43640
9. Westkamper E, Alting L, Arndt G (2007) Life cycle management and assessment: approaches and visions towards sustainable manufacturing. Proc Inst Mech Eng 215:599–625
10. Reich-Weiser C, Vijayaraghavan A, Dornfeld DA (2008) Metrics for sustainable manufacturing. In: Proceedings of the international manufacturing science and engineering conference. 7–10, Oct 2008, USA
11. Geyer A (2003) The challenge of sustainable manufacturing—four scenarios 2015–2020. Int Summer Acad Technol Stud–Corporate Sustain, http://forera.jrc.ec.europa.eu/documents/eur20705en.pdf

12. Dornfeld D (2010) Green issues in manufacturing. http://lmas.berkeley.edu/public/wp-content/uploads/2010/04/dornfeld-overview-april-2010-1.pdf
13. Kibira D, Jain S, Mclean CR (2009) A system dynamics modeling framework for sustainable manufacturing. http://www.systemdynamics.org/conferences/2009/proceed/papers/P1285.pdf
14. US Department of Commerce (2010) Sustainable manufacturing initiative (SMI) and public-private dialogue. http://trade.gov/competitiveness/sustainablemanufacturing/docs/2010_Next_Steps.pdf
15. Ozel T, Yildiz S (2009) A framework for establishing energy efficiency and ecological footprint metrics for sustainable manufacturing of products. In: Proceedings of ASME international manufacturing science and engineering conference. 4–7 Oct 2009, West Lafayette, MSEC2009-84365
16. Xu X (2012) From cloud computing to cloud manufacturing. Robot Comput-Int Manuf 28(1):75–86
17. Vijayaraghavan A, Sobel W, Fox A, Dornfeld D, Warndorf P (2008) Improving machine tool interoperability using standardized interface protocols: MTConnect. In: Proceedings of 2008 International Symposium on Flexible Automation, Atlanta, 23–26 June 2008

# The Power of Analytical Approaches Towards the Development of Differentiated Supply Chain Strategies: Case Study

**Alexander A. Kharlamov, Luis Miguel D. F. Ferreira and Janet Godsell**

**Abstract** Companies are facing challenging circumstances: markets are evolving; clients are becoming more and more demanding and unpredictable; product variety is rising; time windows are shrinking; and error tolerance is decreasing. Therefore, companies must adapt and improve their supply chains, develop a differentiated supply chain strategy to solve the supply–demand mismatch. So far, the main differentiation approach has been focused on: (a) product; (b) customer; and (c) market characteristics. This paper uses a case based research approach in the context of a business-to-business food company to analyse the use of analytical tools commonly applied in other fields of research to support the identification of product and customer characteristics relevant for supply chain strategy differentiation. Using daily recorded sales data over two operational years we apply the following methods: Principal Component Analysis (PCA) followed by Cluster Analysis (CA). A new differentiator (order corrections) is introduced, in between characteristic correlation is spotted and used to generate a more meaningful attributes (case specific), creating four product segments based on proximate characteristics. Therefore, by reducing a large product portfolio into manageable groups of homogeneous SKU's it is possible to assign a proper set of supply chain tailored practices.

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## 1 Introduction

Supply chains (SCs) are a source of competitive advantage [1], and management of SCs is crucial as SCs compete with others SCs, rather than simply between firms [2, 3]. Over the last decades, it became obvious that one strategy does not fit all situations [3–6]. Moreover, SCs depend on, for example: product characteristics [7], product lifecycle [8], and supply and demand patterns [9, 10].

Facing this growing complexity, management of SCs is a broad and overarching function, extending beyond firm's boundaries [11, 12]. Additionally, the amount of data regarding daily logistic activity is rocketing due to powerful IT systems supporting management. The phenomena of big data present both threats and opportunities [13]. On one hand, without proper approaches business can be overloaded with meaningless data. On the other hand, mining all that data using proper tools can provide managers with useful information. This enable increased SC visibility and valuable knowledge, thus, rational supply chain management (SCM).

Facing the need for differentiated supply chain strategies and growing amount of supply chain data, in this paper we describe a single case based research carried on a business-to-business (B2B) food company. Using a deductive-abductive approach, we rely on daily captured sales data at order level over two years of activity to segment stock keeping units (SKUs) based on demand characteristics.

Previous studies have relied on qualitative approaches [5, 7, 8, 14] and quantitative analysis focused on profiling average demand volume against its coefficient of variation (CV). Additionally, we found none contributions relying on data mining methods for supply chain differentiation. Consequently, this paper's originality is the application of advanced analytical tools to mine supply chain data using a starting pool of classification variables most commonly found in literature (enriched with "Order Corrections Ratio" variable). Although the applied data mining tools are fairly common in other fields such is marketing [15], the value of this paper is its successful introduction into the field of SCM. Consequently, we suggest an alternative approach for supply chain differentiation using quantitative methods.

## 2 Literature Review

SCM is becoming more and more critical to remain competitive in the market [1]. Consequently, the problematic of the "right" SC has been alive for a while and after some decades of research there are already many conceptual models and frameworks [2, 5, 9, 12, 14, 16–18]. One of the first clear references on the problematic (and one of the most cited articles) is Fisher's seminal work "What is the right SC?" [7]. Later, Naylor et al. [19] suggested the integration of the lean/agile paradigms into the total SC strategy. Then, going to a more conceptual level, Lee [20] published the well-known article “Triple-A SC” stating that the SC strategy should be developed in spite of adaptability, agility, and alignment. Thus, these contributions possibly are the best foundation of differentiated (segmented) SC strategies and as further publications suggest, have inspired many researchers to go deeper [5, 21–23].

It is clear that one size does not fit all [6], as well as the importance of the link between the customer value proposition and operations strategy [3] considering the important detail: similar products can have very different demand patterns leading towards demand driven SCs discussed further. One of the bottom-lines in the literature is that matching customer requirement with product characteristics and ensuring delivery should be one of the greatest concerns for the management [8, 9, 24]. Therefore, it is important to align SC strategy and products classification variables accordingly to the target market [9, 14, 25]. SC market orientation is more and more necessary what requires the identification of the classification variables [7, 11, 17]. On this idea, Christopher and Towill [14, 26] created models by considering dominant classification variables using a set of variables such as duration of life-cycle, lead-time, volume, variety, and CV [27, 28] known as DWV[3] [26]. This set of variables is generalizable, although, its relevance and applicability is questionable from case to case. Thus, a form of selection and evaluation is necessary.

SC dependence of product and market characteristics is clear [5, 7, 29]. For example, one way of distinguishing products is regarding its functional or innovative nature [7] best matched by different SC configurations: physically efficient SCs for functional products and market-responsive SCs for the innovative ones. Following the same principle, Lamming [29] expanded the Fisher’s model [7] by considering the product uniqueness and complexity, while Lee [10] focused the analysis on supply and demand uncertainty.

Finally, the concept of differentiation concerns the division into different groups of SKUs/customers sharing similar product/service requirements and demand patterns. Its main purpose is to enable better understanding so the company can best satisfy the clients’ needs. Thus, as SCs (and operations strategy in general) are dependent on customer requirements, market and product characteristics, these may be considered as the three pillars of a SC and may be used to develop a differentiated SC strategy.

In summary, this leads towards differentiated SCs that are based on a number of attributes. Due to the link between SC processes with product life cycles and the business strategy [30], product life-cycle and SC strategy [8], and finally integration of SC strategy and marketing [12]. This outlines the three bodies of literature that should be used to approach SC differentiation and all three must be aligned with the business strategy [31, 32]. Finally, this suggests that SC differentiation is based on (a) SCM, (b) SC processes, and finally (c) marketing [5]. From the SC perspective, conceptually the approach on SC differentiation should start with the context analysis and then, by means of classification variables used as filters, create distinct segments and profiles that must be matched to different operations strategies [5].

## 3 Research Approach

This is a single instrumental case on the organizational level, focused on the demand planning processes. The company produces fruit composites (make to order) on a tailor made basis for the food industry being one of the top European players. Founded more than two decades ago, it supply's the major players in the food industry.

There are several reasons making this case relevant. Food industry, more specifically food SCM has received little attention in the literature despite the fact that food sector holds a major relevance. There are several challenges in this field. For example, SC integration is limited by product and processes specifics [33]. Additionally, maintaining high food quality is demanding, as it depends on environmental conditions, storing, and transport [34]. One of the main drivers for SCM in the food industry is the integration of product quality and logistics, named quality controlled logistics [35]. Consequently, further practical application is beneficial as it covers one of the actual problems in the food SCM: The matching of different SC flows with product and customer characteristics. It has been suggested that products with different attributes and different end customers should be delivered in different distribution channels.

### *3.1 Data Collection and Methods*

The study started with a general meeting for problem identification followed by the data collection. This was considered a critical stage to understand the situation, the main problems and opportunities as SCs are dependent on the context and the needs [36]. The collected data contained demand history logs (two years of orders), enriched attribute for each SKU, specifically the bill of materials, shipping requirements, production process details. Finally, we organized the working data set at a week level for two-year demand volumes for each SKU.

Facing the high variety (more than 1 K different SKUs), it is practically impossible/inefficient to analyse each portfolio element individually. Thus, we looked for a way to reduce the complexity. For that purpose, a relatively young field called data mining and knowledge discovery from data offers many already recognized methods used in other fields of research [15].

The adopted process was the Cross Industry Standard Process for Data Mining (CRIPS-DM) [37], being this paper's focus on the modeling and evaluation phases. The modeling phase take into cluster analysis (CA) after principal component analysis (PCA) using IBM SPSS software, as it is one of the possible ways for segmentation already applied in customer relationship management for customer segmentation [15].

## 4 Data Analysis

The modeling phase began with the classification variables selection. The data availability as well as heterogeneity was the very first selection criteria for the initial set of variables. Constrained by the availability in the historical data-log, we obtained the raw set for almost one thousand SKU's at the order level during two years daily. It was then explored, cleaned, and transformed looking for the maximum number of variables. After obtained the set, we performed some basic descriptive statistics to explore the obtained variables. Consequently, some of the extracted variables revealed total homogeneity, thus they were automatically dropped out, but others remained as described further.

Firstly, variables such as the product life-cycle duration, point of product configuration, profit margin, or reliability of delivery were impossible to obtain given the circumstances and data accessibility (confidentiality). However, variables such as: Time windows for delivery; Demand volume; Product variety; Coefficient of variation; Flexibility; Minimum run size; Change-over times; Frequency of delivery; and Product complexity, were successfully extracted (the weekly measure for frequency was set up due to the companies weekly expenditures practice.) Additionally, based on several discussions of the problem we suggested a new variable: Order Corrections Ratio ($OC_{ratio}$), as being the number of corrected orders divided by the total number of orders for some specific SKU. The ratio between the number of corrected orders and the total orders for a specific SKU gives an indicator of how efficient is the client's inventory management and planning. This regards to the fact that each SKU is exclusive to only one client while one client holds multiple SKUs.

Secondly, descriptive statistics revealed that some of the variables presented equal values for all of the SKU's. Namely, minimum run size and change-over time followed one standard protocol, thus, featured equal values for all the SKU's. Even though complexity was not equal to all of the SKU's, its measure was dubious due to the particularities of different recipes, thus we decided to drop this variable out to avoid further misinterpretation.

Thirdly, following the descriptive statistics and analysis, we selected five variables: Time window for delivery; Order corrections ratio, demand volume, CV, and frequency of delivery (weeks with delivery). Those were simplified by means of PCA and then clustered using the Ward's method on the Euclidean's distance between observations in order to achieve groups of products sharing similar characteristics.

Finally, the model's outputs, namely segments, and its different features were validated and discussed through several meetings with the supply chain manager, production manager, and internal control manager.

## 4.1 Principal Component Analysis

Principal component analysis (PCA) is a method of variable reduction which transforms a vector of observations into a new set of vector observation. It assumes that there are linear correlations among some of the classification variables, thus only suitable for numerical continuous fields (scale variables). It is a way of condensing various dimensions into a small, sometimes more meaningful (and bearable) number of variables when rotation is applied, however, at the expense of some information loss.

PCA with orthogonal rotation is here used to reduce the number of classification variables (simplification) using the linear correlation among the classification variables, producing new, standardized, uncorrelated, and often more meaningful components. This procedure allows better insight on the data structure as well as its visual representation in most of the cases [15]. An examination of the Kaiser–Meyer–Olkin measure of sampling adequacy suggested that the sample was factorable (KMO = 0.630).

As shown in Table 1, in this specific case CV is significantly correlated to the time window for delivery as well as to volume, frequency of delivery (weeks with delivery) is significantly correlated to the time window for delivery, order corrections, volume, and CV. The strongest correlation is between volume and frequency of delivery (weeks with delivery) while the second strongest correlation is between CV and time window for delivery.

Regarding how many dimensions should be extracted, the selected method for this study was the total variance accounted. As those methods are ad-hoc, with no theoretical justification and rely mostly on judgement we set up the rule as being greater than 75 %, so we considered the actual 75,993 % acceptable, extracting three principal components. Orthogonal rotation eases the interpretation of the components, produces uncorrelated components. The rotation method applied for this study was the "varimax" with Kaiser Normalization, which converged in four iterations. After the orthogonal rotation, the total variance is redistributed and each value accounts for the variance of the original variance contained in each component.

**Table 1** Correlation matrix ($\alpha = 0.01$)

| | | Time window for delivery | Order correction | Volume | CV |
|---|---|---|---|---|---|
| Correlation (sig. 1-tailed) | Order correction | −0.030 (0,184) | | | |
| | Volume | −0.086 **(0.004)** | −0.022 (0.255) | | |
| | CV | 0.239 (0.000) | 0.028 (0.200) | −0.150 **(0.000)** | |
| | Weeks with delivery | −0.107 **(0.001)** | −0.185 **(0.000)** | 0.527 (0.000) | −0.159 **(0.000)** |

**Table 2** Rotated component matrix

| Classification variables | Component | | | Communalities | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | Initial | Extraction |
| Volume | 0.888 | | | 1.000 | 0.656 |
| Weeks with delivery | 0.846 | | | 1.000 | 0.972 |
| Time window for delivery | | 0.806 | | 1.000 | 0.802 |
| CV | | 0.761 | | 1.000 | 0.602 |
| Order corrections | | | 0.984 | 1.000 | 0.767 |

As listed in Table 2, the focus is on significant loadings, as it eases component interpretation by improving the readability of the rotated component matrix, hiding loadings lower than 30 %.

- **Component 1** ("Volume + Frequency") represents variances of 89 % for volume and 85 % of weeks with delivery (frequency of delivery) both positively correlated, with 0.527 significant correlation from Table 1 meaning that greater volume represents greater frequency of delivery.
- **Component 2** ("Time window + CV") accounts for 90 % of time window for delivery variance as well as COV variance, both positively correlated (0.237 in Table 1), meaning that longer time window for delivery tends to have greater CV.
- **Component 3** ("Order Corrections") concerns only one classification variable at 98 %, the new proposed order corrections ratio reflecting client's inventory management and planning performance.

Finally, the question is if the derived solution accounts for all the original dimensions. Table 2 lists communalities for each original dimension after the extraction, ranging from 0.602 (the worse) to 0.972 (best). Typically, extractions above 0.500 are considered acceptable [15], suggesting a satisfactory solution, allowing the next step: clustering.

## *4.2 Cluster Analysis: Segmentation*

Cluster analysis is a method used to identify patterns and identify groups (clusters) of objects (individuals, entities, etc.) sharing similarities in an n-dimensional space. Usually those groups are not pre-defined. The advantage of clustering techniques is that it can handle efficiently large number of attributes, which dimensions are many times beyond human capabilities. They are not based on a priori personal concepts, intuitions, and perceptions of business people. Instead, segments are induced by data providing real business meaning and value results.

The preferred method for this study, based on the bearable number of entities and few variables, was hierarchical clustering, namely Ward's method based on the squared Euclidean distance between elements. Additionally, hierarchical clustering methods are slow and old-fashioned, yet, very robust being easy to understand performing well for under 10 K entities. We used the dendrogram as the criteria for the number of clusters to extract.

Figure 1 illustrates all SKU's plotted in space using the three new components (after PCA extraction), where each SKU is marked with its respective segment domain. We characterized each segment (cluster) based on its centroid Table 3. Consequently, the following key characteristics arose for the four segments:

- **Cluster 1**: This cluster is characterized by the fewest order corrections as well as low average monthly volume per SKU.
- **Cluster 2**: The most significant characteristic of this group is the shortest time window for delivery and high frequency of deliveries what is associated with high volume per month and the lowest average CV.
- **Cluster 3**: SKU's delivered rarely and low average monthly demand with the highest order correction ratio.
- **Cluster 4**: It contains SKU's with the longest average time window for delivery as well as highest CV.

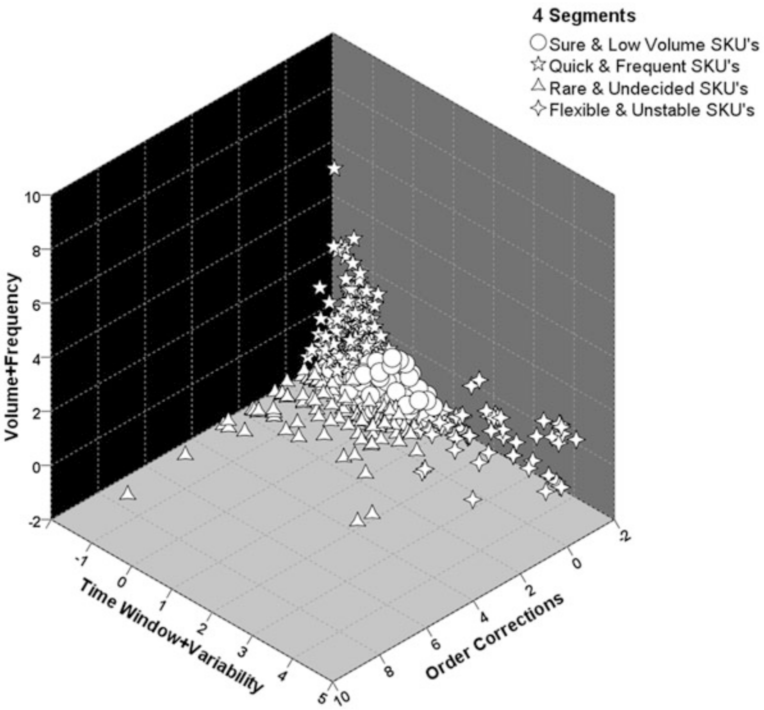


**Fig. 1** SKU's relative position to the extracted components

**Table 3** Segment characteristic

| Classification variables | Segments | | | |
|---|---|---|---|---|
| | Cluster 1: sure and low-volume SKU's | Cluster 2: quick and frequent SKU's | Cluster 3: rare and undecided SKU's | Cluster 4: Flexible and unstable SKU's |
| Revenue (segment sum) | 26 % | 63 % | 8 % | 3 % |
| Variety (number of SKUs) | 498 | 188 | 168 | 63 |
| Volume (mean tons) | 1,702 | 13,235 | 1,517 | 1,449 |
| Weeks with delivery (mean) | 9 | 37 | 4 | 10 |
| Time window delivery (average num. of days) | 33 | 24 | 36 | 196 |
| CV (mean) | 0.61 | 0.37 | 0.59 | 1.28 |
| Order corrections ratio (mean) | 0.29 | 0.45 | 1.72 | 0.36 |

## 5 Discussion and Implications

The need for differentiated SC strategies is eminent. However, most of the differentiation is so far based on pure intuition and managers experience. It should move from this emotional and subjective "system one" thinking toward a more objective and systematized "system two" thinking [38], enabled by data mining methods combined with managers expertise gets the best of both worlds [15]. Moreover, machines are most of the times able to undercover data patterns which even the most talented and experienced human can miss and vice versa: human reasoning and critical pattern recognition is so far unmatched by any machine concerning some cases.

Supply chain strategy is part of a more general, company's competitive strategy composed by a set of practices that must fit together [1, 39]. The current company's strategy intends to fulfil all requests of his industrial customer (B2B), allowing total customization on a pure make-to-order basis. The actual extra manufacturing capacity is able to buffer all the demand volatility; however, with the expected business growth this strategy will soon become obsolete.

Segmentation is a compromise between "one size fits all" strategy and the individual, in most cases topic, least complex approach when each entity of the system is managed separately with "the unique best" strategy. Thus, looking for SC specific classification variables to finding similarities in large number of entities, allow complexity reduction and better demand understanding.

Therefore, the advantage of reducing the product portfolio into few groups is that it enables the differentiated strategy matching. As each group features a distinct profile, it can be matched to a proper set of tailored practices [39] as well as KPI's target adjustment. For example, a simple principle of collaborative forecasting and planning is best match for segments with high order corrections

**Table 4** Matching segments with SC practices and principles

| Segment | Key features | Managerial recommendations |
|---|---|---|
| Sure and low-volume SKU's | High variety; low volume | S&OP; minimize wasted resources; reduce variety; and postponement |
| Quick and frequent SKU's | Predictable; frequent deliveries; stable demand; and high volume | MTF; forecast base demand statistically; forecast surge demand manually (if any) |
| Rare and undecided SKU's | Rare deliveries; unreliable orders; and short time windows | Collaborative forecasting and planning; improve visibility and SC transparency; VMI |
| Flexible and unstable SKU's | Unpredictable; long time windows | MTO; reduce variety by allowing less customization; postponement |

ratio, as it accounts for client's inventory management and planning. As a result, Table 4 shows each segment key features and the best matched SC practices and principles.

## 6 Conclusion

Organizations must be adaptable [1, 20], namely its SCs which works like a vessel system providing what is necessary to keep it alive (and growing). SC differentiation might well be one of the essentials for adaptability and its advantages are various. For example, on one hand it might provide ground for SC risk management, revealing high risk segments, enabling the development of mitigation strategies and on the other hand, highly predictable and easily managed segments allowing more efficient and effortless management. In addition, facing the growing complexity, segmentation is one of the best countermeasures, allowing a differentiated view on the SC entities. Conceptually, this notion naturally grew out of several decades of research and practically SC differentiation possibilities are limitless because despite the fact that segmentation methods might be common, its outcomes will be unique for each company.

Firstly, there are no doubts on the need for differentiation and adaptability to the context and needs. Seeking for that adaptability and differentiation, practitioners have been relying mostly on their "intuition" and domain expertise to develop SC strategies. Data mining models cannot substitute or replace the significant role of domain experts and their business knowledge being useless without active support of business experts. However, such techniques can spot patterns that even the most experienced expert may have missed. Thus, these techniques complemented with human business expertise constitute a very powerful mean of developing a more successful and robust SC strategies. To be clear: human expertise is critical, no matter how sophisticated a tool can be.

Secondly, feeding SC segmentation models provided with data-mining methods is no longer a problem because modern ERPs generate numerous records every day. The data is there, the Big Data [13], what turns the old problem of “no data” into “too much data”. Therefore, managers need the right frameworks and proper tools to extract useful knowledge for SCM, namely SC segmentation must be fed with actual data and not mere beliefs or personal assumptions, enhancing model’s adaptability.

Thirdly, an objective and data driven approach enable the fine-tuning of the existing strategies, as well as to automate, enrich, and standardize manager’s work, which so far, is mostly based on personal perceptions and views. This lowers the decision subjectivity, simplifying time-consuming processes. By learning from real data, practitioners can spot natural groups sharing similar characteristics, grouping entities into clusters (segments) lowers the complexity (variety) which allows better match between supply and demand.

Additionally, following the need for adaptability to the constant change of customer behavior and SC requirements, re-segmentation (real-time monitoring) keeps managers aware of the market dynamics, allowing the organization to react having solid arguments about what is going on, which ultimately might be automatized into an intelligent system defining the best matching SC strategy “on the fly”.

In conclusion, the contributions of this research are not only the successful application of data mining techniques on SC differentiation, as well as the suggestion of a new classification variable, the order changeability ratio. This new classification variable is based on standard measures (order change, date, type of change, and other related properties) usually present in most of order log systems and is used for quality management.

## References


1. Gattorna J, Walters D (1996) Managing the supply chain: a strategic perspective. MacMillan Press, London
2. Christopher M, Towill DR, Aitken J, Childerhouse P (2009) Value stream classification. J Manuf Technol Manage 20(4):460–474
3. Simchi-Levi D (2010) Operations rules: delivering customer value through flexible operations. The MIT Press, Cambridge
4. Christopher M (2011) Logistics and supply chain management, 4th edn. Prentice Hall, Harlow
5. Godsell J, Diefenbach T, Clemmow C, Towill D, Christopher M (2011) Enabling supply chain segmentation through demand profiling. Int J Phys Distrib Log Manage 41(3):296–314
6. Shewchuck P (1998) Agile manufacturing: one size does not fit all. Proc Int Conf Manuf Value Chain
7. Fisher M (1997) What is the right SC for your product? Harvard Bus Rev 75(2):105–116
8. Aitken J, Childerhouse P, Towill D (2003) The impact of product life cycle on supply chain strategy. Int J Prod Econ 85(2):127–140

9. Payne T, Peters JM (2004) What is the right supply chain for your products? Int J Log Manage 15(2):77–92
10. Lee H (2002) Aligning SC strategies with product uncertainties. California Manage Rev 44(3):105–119
11. Frohlich M, Westbrook R (2001) Arcs of integration: an international study of supply chain strategies. J Oper Manage 19(2):185–200
12. Jüttner U, Christopher M, Godsell J (2010) A strategic framework for integrating marketing and supply chain strategies. Int J Log Manages 21(1):104–126
13. White T (2009) Hadoop: the definitive guide. O'Reilly, Sebastopol
14. Christopher M, Towill D (2002) Developing market specific supply chain strategies. Int J Log Manage 31(1):1–14
15. Tsiptsis K, Chorianopoulos A (2009) Data mining techniques in CRM: inside customer segmentation. Wiley, Wiltshire
16. Mason-Jones R, Naylor B, Towill DR (2000) Lean, agile or leagile? matching your supply chain to the marketplace. Int J Prod Res 38(17):4061–4070
17. Schnetzler M, Sennheiser A, Schonsleben P (2007) A decomposition-based approach for the development of a supply chain strategy. Int J Prod Econ 105(1):21–42
18. Christopher M, Towill D (2001) An integrated model for the design of agile supply chains. Int J Phys Distrib Log Manage 31(4):435–246
19. Naylor D, Naim M, Derry D (1999) Leagility: integrating the lean and agile manufacturing paradigms in the total supply chain. Int J Prod Econ 62(1):107–118
20. Lee H (2004) The triple—a supply chain. Harvard Bus Rev 82(10):102–112
21. Selldin E, Olhager J (2007) Linking products with supply chains: testing fisher's model, supply chain management. Int J 12(1):42–51
22. Whitten GD, Green KW Jr, Zelbst P (2012) Triple-a supply chain performance. Int J Oper Prod Manage 32(1):28–48
23. Qi Y, Zhao X, Sheu C (2011) The impact of competitive strategy and supply chain strategy on business performance: the role of environmental uncertainty. Decis Sci 42(2):371–389
24. Li D, O'Brien C (2001) A quantitative analysis between product types and SC strategies. Int J Prod Econ 73(1):29–39
25. Qi Y, Boyer KK, Zhao X (2009) Supply chain strategy, product characteristics, and performance impact: evidence from Chinese manufacturers. Decis Sci 40(4):667–695
26. Christopher M, Towill D (2000) Marrying lean and agile paradigms. In: Proceedings of 7th international annual EUROMA conference, Ghent
27. Childerhouse P, Aitken J, Towill D (2002) Analysis and design of focused demand chains. J Oper Manage 20(6):675–689
28. Vitasek K, Manrodt K, Kelly M (2003) Solving the supply-demand mismatch. Supply Chain Manage Rev 58–64
29. Lamming R, Johnsen T, Zheng J, Harland C (2000) An initial classification of supply networks. Int J Oper Prod Manage 20(6):675–691
30. Hayes RH, Wheelwright SC (1979) Link manufacturing process and product life cycles. Harvard Bus Rev 57(1):133–140
31. Oliver R, Webber M (1982) Supply-chain management: logistics catches up with strategy. In: Logistics: the strategic issues, Chapman Hall, , London, pp 63–75
32. Porter ME (1985) Competitive advantage. The Free Press, New York
33. Ronga A, Akkermanc R, Grunowc M (2011) An optimization approach for managing fresh food quality throughout the supply chain. Int J Prod Econ 131(1):421–429
34. Labuza T (1982) Shelf-life dating of foods, 1st edn. Food and Nutrition Press, Westport
35. Vad Der Vorst JGAJ, Van Kooten O, Marcelis W, Luning P, Beulens A (2007) Quality controlled logistics in food supply chain networks: integrated decision-making on quality and logistics to meet advanced customer demands. In: Proceedings of 14th international annual EUROMA conference, Ankara
36. Parnaby J (1995) System engineering for better engineering. IEE Eng Manage J 5(6):256–266

37. Shearer C (2000) The CRISP-DM model: The new blueprint for data mining. J Data Warehouse 5(4):13–22
38. Stanovich KE, West RF (2000) Individual differences in reasoning: Implications for the rationality debate? Behav Brain Sci 23:645–665
39. Lapide L (2006) MIT's SC2020 project: the essence of excellence. Supply Chain Manage Rev 10(3):18

# Technology Policy for Promoting Environmental Sustainability in SMEs: Issues and Considerations for Effective Implementation

**David A. Wyrick, Ganapathy Natarajan and Chinweike I. Eseonu**

**Abstract** Small and medium enterprises (SMEs) represent over 90 % of the companies in the world. As well, the vast majority of persons employed work in SMEs. Most laws, regulations, and standards are targeted toward and implemented by larger firms. In order to promote global sustainability, policies need to be adapted for smaller entities. This work summarizes an assessment on environmental sustainability in SMEs in a rural region of the United States, which identified barriers to and promoters of environmental sustainability, including how sustainability and green initiatives are interpreted by small business owners. This work also summarizes a model for effectively adapting technology policy and practices to promote (or impede) particular technical practices and policies. A discussion of how this assessment and model can be integrated in the context of promoting sustainability among SMEs in a developing country of Morocco is presented. Finally, the implications for promoting the effective management and perception of sustainability in the world's SMEs are presented and discussed.

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## 1 Introduction

To sustain globally competitive manufacturing, organizations must do many things well. These activities include design, sourcing, manufacturing, quality, service, business processes, and being a good corporate citizen. Lean manufacturing is an effective tool in these activities. Another key element is the concept of environmental sustainability, where the activities of an organization do not decrease the resources available for future generations.

Governments establish policies to promote or deter particular activities or outcomes within their jurisdictions. For instance, a policy of low corporate tax rates is frequently argued to promote job growth in the United States. Policies that facilitate desirable outcomes are frequently adopted by governments. An example of this is the adoption of technology policies similar to the Bayh-Dole Act in the United States by other countries; the Bayh-Dole Act promotes commercialization of technologies developed by university researchers.

Generally speaking, government policies tend to focus on organizations of some critical mass. The logic is that undue regulation will make it very difficult for small companies to understand which laws apply and how to comply with them. In the case of the environment, very small companies often produce significantly more impact relative to their size as compared to larger firms.

Recent research on the environmentally sustainable practices in manufacturing small and medium enterprises (SMEs) in the rural west Texas region of the United States has made interesting findings that relate to understanding, practice, and attitudes of SME owners and managers. In many instances, the SMEs rarely change their historic practices until required to do so, either by governmental regulation or by their customer demands.

These findings have several important implications. How can environmentally sustainable practices in SMEs be improved through changing attitudes, enacting appropriate policies, and sharing best practices?

This paper summarizes research on how heat transfer concepts can apply to the flow of technology policy so that best practices can be encouraged. It also provides more detail on the findings of environmental sustainability in the manufacturing SME's of West Texas. A case study that merges the two concepts in the context of how policy aimed to enhance the practice of environmental sustainability practices can be applied in a developing country, citing developments in Morocco. The implications from this study can benefit both practitioners and academics, and further research is outlined.

## 2 Engineering Policy Change

The effect of national government policy on organizational competitiveness is an increasingly apparent challenge of globalization. Competition is intensified by shorter product life cycles, increasingly sophisticated client requirements, and the pace and ease of knowledge acquisition. Government positions on data protection, biomedical research, and sustainability initiatives are examples of policy areas that affect organizational attractiveness with today's sophisticated client base. Global interactions notwithstanding, organizational culture and policy remain ultimate determinants of competitiveness of any given firm, and thus under the control of the organization's executives and managers.

Timely and effective policy diffusion combats this potential problem, but rarely do technical professionals and managers directly or substantially participate in a government's policy making process [1]. The literature describes policy diffusion as adoption of a policy deemed successful in another organization or political jurisdiction [2, 3]. The ability to identify and effectively manage the factors (called levers) that promote or impede adoption of new ideas or policies is the challenge faced in national and organizational policy circles [4]. The ongoing search for the levers and lever interactions that provide a better understanding of social diffusion systems is of great interest to both policy makers and academics.

The ability to design diffusion within a physical system is learned by engineers from centuries of material science and heat transfer research. To achieve desired properties of a building, for example, an engineer can specify a building shape, site orientation, layout, construction materials, and HVAC system. In recent engineering management contributions, concepts from thermal diffusion in the physical sciences have been applied to explain the effect of lever interactions on policy diffusion and overall change management in social systems [5, 6]. Table 1 summarizes the conceptual similarities between diffusion in physical and social systems and illustrates the application of this identification to managing policy levers.

**Table 1** Conceptual similarities between physical and social diffusion (adapted from Eseonu [5])

| Heat transfer | | Policy transfer | |
|---|---|---|---|
| Occurs across a negative temperature gradient: Heat transmitted from a high to a relatively lower temperature region | | Occurs across a negative policy gradient: Policy transmitted from a high to a relatively lower policy region | |
| Successful heat transfer depends on the degree to which conductivity "outweighs" volumetric heat capacity | | Successful diffusion depends on the degree to which facilitators outweigh barriers to diffusion | |
| **HT term** | **HT definition** | **PT term** | **PT definition** |
| **Diffusivity, $\alpha$** | The rate of change of heat level | **Diffusivity, $\alpha$** | The rate of change of policy level |
| **Conductivity, $k$** | The capacity to transfer heat | **Institutional capacity, $I$** | The capacity to transfer policy |
| **Volumetric heat capacity, $\rho Cp$** | The capacity to resist heat transfer | **Affluence capacity, $A$** | The capacity to resist policy transfer |
| **Temperature, T** | Measure of heat deviation from a reference point ($H_2O$ freeze point for celsius) | **Policy level** | Measure of policy deviation from a reference point (policy absence) |

In heat transfer through conduction, diffusivity of a material is the ratio of capacity to transfer heat (conductivity) to the capacity to resist heat transfer (volumetric heat capacity), described as $\alpha = k/\rho Cp$. On a national scale, the literature identifies institutions and affluence as two major levers [3, 7, 8]. The capacity for diffusion (social learning) increases with increasing difference in the quality of institutions. This is also true of the capacity to resist diffusion.

The goal of this, and similar, attempts in policy modeling, is to understand policy levers for more effective management of lever interactions. However, Eseonu [5] applied this ratio to the diffusion of policies across the United States and compared the accuracy of the modified heat transfer model (conduction only) to the moving average approach used by Walker [3] and Boehmke and Skinner [8] to evaluate the effectiveness of the modified heat transfer model. The modified heat transfer model was 27 % accurate in comparison with a 37 % accuracy of the existing moving average model using similar data. It is important to note that the modified heat transfer model considered only the analog of conduction and was purposely simplified to not consider convection and radiation analogs; these modes of heat transfer are currently being investigated for modeling technology policy diffusion.

This result underlines the complexity of social systems and the challenge we face in attempts to model and design decision tools in this realm. Dennis [9] and Rogers [10] explain the effect of culture—an elusive variable—on diffusion through social systems. It is important that engineering managers think of organizational or national policy diffusion in terms of supports and impediments within cultural realities, and work toward bolstering supports for cultural and policy change, or maintenance of the status quo where this is necessary.

Applying the heat transfer model for policy diffusion may represent a paradigm shift. Philosophically, it represents a move from forecast based on historical trends to an actual design to meet particular specifications. The results using only an analog of conduction compared to the existing model indicate that further academic work is worth pursuing [7]. From a practical standpoint, managers and policy makers may think of finding and adopting best practices in terms of maximizing heat transfer by conduction (contacting the best-in-class organizations or attending specific professional development activities) or by convection (environmental scanning to assess future changes). When implementing lean, we want to maximize flow and minimize resistance, which is the same as maximizing conductive heat transfer through a material.

For policy makers who would like to promote sustainable practices among organizations, the question of how to transfer understanding is important. As described in the next section, the perception of the owners and managers of SMEs plays an important role.

## 3 Environmental Sustainability in Rural West Texas Manufacturing SMEs

Small and Medium Enterprises (SMEs) constitute 80 % of all enterprises globally. In the United States, the number is more than 85 % and more than 90 % in the European Union. In the United Kingdom, the numbers are even higher, with 99 % of the country's enterprises being SMEs. There are two million SMEs in Canada, and they contribute 50 % of the pollution from all the industries in the nation. SMEs are 91 % of all industries in Venezuela and such is the trend throughout South America. In New Zealand, SMEs constitute 98 % of all enterprises [11, 12].

Worldwide, most of the pollution is contributed by SMEs due to the sheer number of SMEs in each country and lax environmental regulations. The cumulative pollution generated by SMEs is substantial [13]. As a result, studying sustainability strategies of SMEs is important to alleviate pollution with sustainable initiatives. SMEs face problems in implementing sustainable practices that include adequate capital, appropriate technology, required knowledge, organizational culture, and internal motivation [14–16].

Barriers that impede and motivators that enhance SMEs move toward environmental sustainability were studied. A review of global literature indicated commonalities in barriers and motivators across different regions of the world [17]. A consolidated list of barriers and motivators, separated as internal and external, is tabulated in Table 2.

In order to study the effect of barriers and motivators on environmental performance, environmental performance had to be defined. With the vast variety of definitions and standards for environmental performance, a performance indicator was developed based on literature. The indicator closely followed the ISO 14001 regulations. The new indicator proposed [17, 18] was called Environmental Sustainability Index (EnvSI). EnvSI is a composite index that quantifies an SME's conscious effort to measure energy and water usage, to measure amount of waste released, to recycle water, and to recycle other materials.

A set of approximately 860 manufacturing SMEs in the rural West Texas region were invited to participate in a survey that studied the barriers, motivators, and

**Table 2** Factors affecting environmental sustainability in SMEs

| Factors | Internal | External |
|---|---|---|
| Barriers | Finance | Information |
| | Expertise | Government stability |
| | Time | |
| | Resources | |
| | Culture | |
| Motivators | Internal drive | Local interests |
| | Cost reduction | Customer demands |
| | Lower liability | Legislation |
| | | Strategic leadership |
| | | Competitor performance |

factors that make up the EnvSI. A total of 155 SMEs participated in the survey and provided interesting insights into their perception of environmental sustainability. The relationship between the factors and EnvSI was weak. In other words, higher motivating factors did not improve the EnvSI score, nor did more barriers relate to a lower EnvSI score. A follow-up phone interview was arranged to study the manufacturing SMEs in depth.

The results of the follow-up study showed some stark characteristic differences of the geographical region. Their political views mostly govern their view toward environmentally sustainable practices. Most companies want to be environmentally friendly as they consider themselves moral citizens. As one respondent said, "Don't try to legislate morality" is the general view with most companies. A combination of customer requirement, economic viability, and ownership to the legislation is what will push SMEs in West Texas toward better environmentally sustainable practices [17].

Finance is regarded by the SMEs in this study as the biggest barrier to implementing environmentally sustainable manufacturing practices, similar to other studies. In terms of external barriers, information is not a high one; rather, companies perceive political intervention and the credibility of enforcing agencies as larger barriers. Any improvement in the sustainable performance of companies can only be achieved with a combination of economic viability and improved political climate. Failure to improve the bitter political climate and partisan legislative practices now in the United States may change the perception of SMEs of government policy from legislation into enforcement, a change of perception from largely positive to negative. When companies perceive legislation as enforcement, their motivation to actively pursue environmentally sustainable practices is lower; an increase in enforcement may actually decrease EnvSI, instead of the intent of the legislation to increase EnvSI, an interesting consideration in light of the previous discussion on policy levers and interactions.

This study showed that there are some perceptions that exist in SMEs that have to align in order for them to move toward environmentally sustainable practices. The most important perceptions that SMEs consider are: culture perception, internal flexibility (resources and expertise), information availability, cost perception, political perception, and community perception. These are the major perceptions that SMEs have when considering the move towards environmentally sustainable practices. These perceptions and the way SMEs look at them are different from how bigger organizations view them. This was made clear from the study of West Texas SMEs. A glimpse of some common differences in perceptions is shown in Table 3.

An index to explain the perceptions of the companies even before measuring the EnvSI will be useful. This new index will be developed to measure the perceptions of the SMEs toward environmental sustainable practices. The index will provide the readiness of SMEs in taking up environmental sustainable practices. Environmental sustainable projects require SMEs to have resources, culture, flexibility, and cost perception from inside the organization, and legislation, stakeholder perception, political climate, collaboration with agencies, and

**Table 3** Perceptions toward environmental sustainability

| Bigger companies/common perceptions | SMEs terminology/perception |
|---|---|
| Environmental management system (EMS) | ISO 14,000 |
| Legislation | Enforcement |
| Government collaboration | Political intervention |
| Environmental investment | Financial burden |
| Long term economic and social gain | Short term economic gain is more important |
| Green manufacturing | Recycling/staying under EPA or other environmental agency established numbers |
| Environmental reporting | Reporting numbers to an enforcement agency |

information from the outside. Only when companies perceive these factors to be suitable will they voluntarily move toward implementing environmental practices. The increase in the Environmental Sustainability Perception Index (ESPI) will then initiate a change in the EnvSI. Therefore, a critical step forward is establishing the Environmental Sustainability Perception Index (ESPI) [17].

Small and medium enterprises comprise a majority of the world's industries and are therefore, important for global economic development and sustainability. The situation of sustainable behavior in manufacturing SMEs in West Texas raises interesting insights and challenges. The results come from a developed country and the largest national economy in the world, so to find that SME owners and managers have a widely varying understanding of the meaning, goals, and importance of sustainability may indicate that policymakers and society as a whole have much more challenging work to do than previously assumed. It is important for policy makers, especially, to understand the reluctance on the part of many SMEs to trust them so that they can design the policies and policy levers in such a way that trust is established, common understanding is developed, and best practices can be encouraged and put into place; the heat transfer model developed in Sect. 2 could help.

The next section will present the case of sustainability efforts, technology policy, and SMEs taking place in a developing country with respect to the concepts presented in this paper.

## 4 Case Study: Morocco

Morocco is a developing country. It is situated on the northwestern coast of Africa and has ports on the Mediterranean Sea and Atlantic Ocean. It has longstanding historical and cultural ties to North Africa, Europe, sub-Saharan Africa, the Middle East, and the Americas. Due to its location, it has been a center of trade from at least the time of the Phoenicians. Today, agriculture and tourism are major industries. Renewable energies and telecommunications are developing industries and play a major part in increasing and diversifying Morocco's economy.

Morocco does not have significant reserves of fossil fuels. The government is trying to establish policies that simultaneously promote renewable energies, increase international ties, develop the nation's higher educational system, and provide economic development to the kingdom's citizens. One program is called IRESEN, *Institut de Recherche en Energie Solaire et en Energies Nouvelles*. It was created by the Moroccan government to build the R&D capacity of the country's universities, fund pilot projects for sustainable energy technologies by industrial or university partners, and help secure funding for continuation and commercialization of projects [19]. Related to this is a series of research and development activities in cooperation with the European Union, in part through international partnerships. Clearly, it is in the best interests of Morocco to design and implement the systems for technology policies and sustainability practices within the firms and organizations working within its borders.

The policy transfer model that is based on heat transfer described in Sect. 2 can be used to describe the developments in Morocco with respect to renewable energies. Technology policy in the country is rapidly evolving to encourage both the transfer of beneficial technologies into the country as well as to develop the *savoir faire* in the nation's universities, which indicates a high diffusivity, $\alpha$, or the rate of change of policy. The institutional capacity, $I$, represents the ability to transfer policy, and varies widely in Morocco's various governmental ministries and private organizations; it could be described as moderately low due to its high bureaucratic level but systems are developing rapidly with respect to solar and renewable energy. The affluence capacity $A$, is the ability to resist policy transfer; this is rather low because there are no entrenched policies or stakeholders to resist the change (due to the absence of major oil and gas players, for example). The policy level, or analog to temperature, is rather low due to the relative low number of laws, regulations, and political involvement. As Morocco develops, more laws and regulations regarding solar and renewable energies are likely to come about quickly in order to standardize practices, enhance safety, and promote their use in the kingdom. Implementing lean practices into the bureaucratic systems will have the effect of increasing institutional capacity and lowering the resistance to transfer policy (or knowledge).

In Morocco, SMEs constitute approximately 95 % of all private firms and about 50 % of employment. SMEs are responsible for about 20 % of the nation's added value, 30 % of the exports, 40 % of production, and 50 % of investment [20]. "Informal" SMEs are firms that do not report figures to the government and are in addition to the official numbers cited. Informal SMEs may not be reported because they are located in remote parts of the country, the owners are not aware of reporting requirements, or because they simply choose to not be official. The challenges of developing, communicating, promoting, and enforcing appropriate technology policies for Moroccan SMEs are significant and numerous and include location (most of Morocco is rural), education and literacy level, and language

(Arabic, Darija, indigenous Berber languages, French, and occasional Spanish are all spoken).

The findings in west Texas are likely present in Morocco as well. SME owners are likely using many practices because that is what they have done in the past, which may sometimes be quite harmful to the environment (burning wood and plastic for heat, for example, can lead to forest degradation and releasing carcinogens into the air). Lack of awareness, lack of expertise, and expense of investing in environmentally friendly technologies are likely problems. For SMEs that work with solar and renewable energy projects that are coming about from projects sponsored by IRESEN and others, environmental sustainability actions and perception should improve and change faster than in other industry sectors due to external forces such as reporting requirements associated with funding from the European Union.

It would be very interesting to replicate the study conducted of the manufacturing SMEs in west Texas again in Morocco to better understand the barriers and motivators of sustainable practices, as well as the attitudes and perceptions of the owners and managers. Additionally, it would be interesting to more closely analyze the heat transfer model for policy diffusion in a setting like Morocco.

## 5 Implications for Promoting Effective Management and Perception of Sustainability

From the work that is summarized in this paper, important implications for promoting effective management and perception of sustainability in SMEs can be made. Several of these include:

A common language of sustainability needs to be spoken. The language used by researchers is very different than the language spoken by SME owners, managers, and employees. The word "green" may be interpreted to mean something that is produced using no fossil fuels, or is intended to an urban market in different SMEs, or is literally the color green to different persons. It is useful to have examples of what is actually meant by a word or phrase.

Larger entities can influence and educate SMEs. Large companies can provide valuable assistance via requirements to SMEs. Universities can sponsor education or training programs for SMEs and their employees.

The perceptions of the SME owners, managers, and employees have of environmental sustainability can positively or negatively affect environmental performance. If people see value in being environmentally sustainable as being more cost-effective, quicker to respond to customers, and paying less in overhead for power and water, they are more likely to have better performance in environmental sustainability (as well as lean).

Applying the concepts of heat transfer to design policy or technology transfer can be powerfully effective. Decision makers can design policies to easily transfer knowledge and best practices (a high heat flow). Business owners can also design their internal policies and practices to transfer knowledge (conduct heat) or to protect intellectual property (in a well-insulated system).

Governments can assist with the knowledge acquisition and competitiveness of industries and SMEs by policy. The case of IRESEN in Morocco is one example of governmental efforts to develop and transform the solar and renewable energy industry and the knowledge infrastructure to support it. In the United States, the Small Business Development Centers provide assistance and know-how and know-why to SMEs.

SMEs represent the majority of private firms in the world. Assisting them and diffusing effective technology policies and practices to become more sustainable is in the best interests of everyone.

## 6 Summary and Conclusions

Sustaining global competitiveness is a multi-faceted problem facing organizations, and it can be especially challenging for small and medium-sized enterprises. Governments can assist the SMEs in their jurisdiction by promoting policies that help firms compete, which is very important due to the number of SMEs in any economy, the number of persons employed in SMEs, and the significant contribution to the economy by the SMEs.

This paper is based on two Ph.D. dissertations that deal with environmental sustainability in manufacturing SMEs and the adaptation of heat transfer to be applied to policy transfer. It has introduced how the heat transfer model can be applied to policy transfer, which is important as policy makers try to “design” the appropriate flow of technology, resources, or practices to the best benefit of its citizens. The issues of how environmental sustainability can be measured and assessed were presented in the case of the west Texas region of the United States; some of the difficulties that were found in that mature and well-educated region indicate that the understanding and perception of persons in less well-developed locations will likely need to be enhanced to promote environmentally sustainable actions and attitudes. Current developments in Morocco in relation to technology policy, sustainability, and SMEs have been introduced as a short case study.

The role of SMEs is very important in the world’s economy, but they tend to be under-regulated, which infers that a good deal of environmentally sustainable actions could be introduced and facilitated by a variety of methods. The heat transfer model for policy transfer can be used to design appropriate methods and policies for SMEs.

The unique contributions made by this paper are the integration of a new model of designing technology policy diffusion (as compared to modeling based on historical data) with findings of a survey of the barriers and motivators of SMEs with respect to sustainable practices. What sustainability actually means and how it is perceived in SMEs varies widely and cannot be assumed by researchers or practitioners. Providing effective policies and practices to SMEs promises significant improvements in sustainability to both the SMEs and to the world, and using the heat transfer model to design these policies and policy levers could enhance the speed of adopting best practices.

The limitations of the work presented are the limited data available to date, although both studies had enough data for statistical treatment [5, 17]. This will be addressed by future work.

There are several very important implications to this work. On the theoretical side, using heat transfer as a model for policy transfer is an important contribution in engineering management; it allows a well understood principle from the physical sciences to be applied to social sciences. Regarding SMEs, it is important to understand that particular words have a common meaning and understanding to researchers, but may mean widely different things to the owners and managers of SMEs. On the managerial side, applying the concepts of heat transfer can help implement lean manufacturing (to maximize heat flow, increase conductivity and reduce resistance) or to protect intellectual property (how to insulate that knowledge to prevent its transfer). For working with SMEs, there is significant room for decreasing pollution and increasing sustainability, but there is a significant amount of trust that needs to be in place before external opportunities are understood to be opportunities or assistance. Working with SMEs is very different than working with large companies, whether as a manager, supplier or customer, contractor, or policy maker, and the differences need to be understood and respected.

Further research has been identified from the work to date, and some of this continuing research is in progress. The heat transfer model for policy transfer is being expanded to include both convection and radiation effects at the theoretical level. In addition, particular technical policies will be identified for modeling. The study of sustainability in the west Texas SMEs will be replicated in other geographic areas. An Environmental Sustainability Perceptions Index (ESPI) is being developed and will soon be evaluated. Further work will be done in Morocco as well as the United States.

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## References

1. Dennis WJ (2011) Entrepreneurship, small business and public policy levers. J Small Bus Manage 49(1):92–106
2. Gray V (1973) Innovation in the states: a diffusion study. Am Polit Sci Rev 67(4):1174–1185

3. Walker JL (1969) The diffusion of innovations among American states. Am Polit Sci Rev 63(3):880–899
4. Berry FS, Berry WD (1992) Tax innovation in the states: capitalizing on political opportunity. Am J Polit Sci 36(3):715–742
5. Eseonu CI (2012) Applying concepts from heat transfer to explain policy diffusion. PhD dissertation, Graduate School, Texas Tech University, Lubbock
6. Eseonu CI, Wyrick DA (2013) Applying thermal diffusion concepts to policy diffusion and change management. Eng Manage J
7. Berry FS, Berry WD (1990) State lottery adoptions as policy innovations: an event history analysis. Am Polit Sci Rev 84(2):395–415
8. Boehmke FJ, Skinner P (2012) State policy innovativeness revisited. State Politics Policy Q 12(2):303–329
9. Dennis WJ (2011) Entrepreneurship, small business and public policy levers. J Small Bus Manage 49(2):149–162
10. Rogers EM (2003) Diffusion of innovations. Free Press, New York
11. Natarajan GS, Wyrick DA (2010) Sustainable practices in small and medium-sized enterprises (SMEs): a comparison between Europe and the United States. In: Proceedings of the American society for engineering management thirty-first annual conference, Rogers
12. Natarajan GS, Wyrick DA (2011) Sustainable practices in small and medium-sized enterprises (SMEs): a world view. In: Proceedings of the American society for engineering management 2011 international annual conference, Lubbock
13. Hitchens D, Thankappan S, Trainor M, Clausen J, de Marchi B (2005) Environmental performance, competitiveness, and management of small businesses in Europe. Tijdschrift voor Economische en Sociale Geografie 96(5):541–557
14. Biondi V, Iraldo F, Meredith S (2002) Achieving sustainability through environmental innovation: the role of SMEs. Int J Technol Manage 24(5/6):612–626
15. van Hamel C, Cramer J (2002) Barriers and stimuli for ecodesign in SMEs. J Cleaner Prod 10(5):439–453
16. Pimenova P, van der Vorst R (2004) The role of support programmes and policies in improving SMEs environmental performance in developed and transition economies. J Cleaner Prod 12(6):549–559
17. Natarajan GS (2012) Developing an environmental sustainability index (EnvSI) for small and medium-sized enterprises (SMEs) in the United States: the case of west Texas. PhD dissertation, Graduate School, Texas Tech University, Lubbock
18. Natarajan GS, Wyrick DA (2012) Environmental sustainability in manufacturing SMEs in west Texas. In: Proceedings of the 2012 international annual conference of the American society for engineering management, Virginia Beach, pp 856–861
19. Institut de Récherche en Energie Solaire et en Energies Nouvelles (2013) Bienvenue sur le site d'IRESEN! http://www.iresen.org/index.php. Accessed 21 Jan 2013
20. La Vie Eco (2013) Maroc: 95% des entreprises sont des PME. http://www.lavieeco.com/actualite/maroc-95-des-entreprises-sont-des-pme-5549.html. Accessed 10 Jan 2013

# Proposal of a Deliberate Discovery-Learning Approach to Building Exploration Capabilities in a Manufacturing Organization

**Yuji Yamamoto**

**Abstract** Many manufacturing organizations in developed countries need to be proficient in not only incremental improvements but also radical innovations. Radical innovations largely depend on exploration capabilities, in other words capabilities of searching, discovering, and developing radically new systems, processes, and operational practices. Since many manufacturing organizations are proficient in incremental improvements, an important challenge for them is to develop the exploration capabilities across the organizations. However, little knowledge has been accumulated as to how to develop such capabilities in practice. The main purpose of this paper is to propose an approach to building organization's exploration capabilities. In the approach, the capabilities are built through leaders iteratively and deliberately creating situations where groups in an organization have to or can be more explorative. The approach is made by analogy from how organizational changes toward lean manufacturing were driven by an experienced lean consultant. In addition, this paper presents a model of how to practically apply the approach at companies. The model is developed firstly based on existing theories then modified through employing the model at a manufacturing company.

## 1 Introduction

Manufacturing organizations especially in developed countries have to be highly competitive in order to provide value for the companies. If the organizations develop manufacturing operations only by emulating competitors' solutions or importing solutions externally available, these organizations may soon risk their

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survival. The organizations have to be active in creating new knowledge and constantly develop new manufacturing systems, processes, and technologies, and operational practices. For such organizations, it is essential to develop organization's innovation capabilities.

Organization's innovation capabilities derive less from specific technologies and manufacturing facilities. Rather, they are largely embedded in the collective skills and knowledge of people and procedures in the organization [1]. Innovation capabilities mostly consist of capabilities of exploiting existing concepts, systems, and processes through modification and refinement, and capabilities of exploring new possibilities, for instance new technologies, systems, processes, and operational practices, through search, discovery, and development. The well-known terms ‘exploitation’ and ‘exploration’ [2] have been often associated with incremental and radical innovation respectively. Traditionally many manufacturing organizations have developed exploitation capabilities since these organizations have been focusing on incremental innovations to maintain their operational competitiveness. However, exploration capabilities tend to be less developed at those organizations. Although it is an important challenge for the organizations to develop the exploration capabilities, little knowledge has been accumulated in literature as to how to build these capabilities across a manufacturing organization in practice.

The main purpose of this paper is to propose a specific approach to building exploration capabilities across a manufacturing organization in practice. In the approach, the capabilities are built through leaders iteratively and deliberately creating situations where groups in an organization have to or can be more explorative. The approach is made by analogy from how organizational changes toward lean manufacturing were driven by an experienced lean consultant. Later in this paper, the proposed approach is explained more and it is discussed why the approach can be a possible approach to building exploration capabilities in an organization. Furthermore, there is little guidance as to how to practically apply the mentioned approach at companies. In this paper, a model describing how to apply the approach in practice is presented. The model was firstly made based on existing theories and then was modified through employing the model at a manufacturing company.

This paper is organized as follows. In the next section, theoretical backgrounds of this paper are presented. Then the specific approach to building exploration capabilities is proposed and its possible advantages are discussed. Later a model of how to apply the approach is presented. Finally, discussions and conclusions are made.

## 2 Theoretical Backgrounds

In this section, theories related to organization's innovation capabilities and building exploration capabilities are introduced and discussed.

### 2.1 Organization's Innovation Capabilities

In the fields of management and innovation, researchers have described organization's innovation capabilities in various ways. In this paper, it is considered that the capabilities largely consist of exploitation and exploration capabilities. Exploitation can be captured by the terms such as modifying, refinement, choice, efficiency, implementation, and execution, while exploration includes the notions such as search, variation, risk-taking, experimentation, play, flexibility, and discovery [2]. As many management researchers suggest, organization's capabilities can be described by bundles of organizational routines [3]. Organizational routines are the way things are done or patterns of activities. These routines encompass both standard formal procedures as well as patterns of behaviors not explicitly guided by written rules and policies [4]. Understanding capabilities as bundle of organizational routines implies that capabilities can not be acquired by an individual or a group exercises certain procedures once. These procedures have to be repeated in the organization until they become routines. It is generally hard to specify exactly what routines are closely related to exploitation or exploration capabilities. Instead, researchers have identified characteristics of organizations (i.e., a high level of bundles of organizational routines) that are proficient in exploitation and exploration. These characteristics are shown in Table 1.

In literature, it has been frequently argued that incremental innovations, or more often called incremental improvements, largely depend on the exploitation capabilities, while radical innovations, which involve development of new systems and processes that are distinctly different from the existing ones, require the exploration capabilities [5]. However, the exploration capabilities also influence the effectiveness of incremental innovations, and vice versa. In this paper, influence of exploitation and exploration capabilities on incremental and radical innovations is understood as illustrated in Fig. 1. An organization with well-developed capabilities for exploitation does not mean that it excels at exploration. Rather, these capabilities tend to inhibit exploration [6]. Because of the inherit tension between exploitation and exploration, researchers have suggested to develop the exploitation and exploration capabilities at different parts of an organizations, for instance,

**Table 1** Characteristics of organizations proficient in exploitation and exploration, based on McLaughlin et al. [9]

| Exploitation | Exploration |
|---|---|
| Formalized | Contingent |
| Centralized | Decentralized |
| Systematic | Loosely structured |
| Efficiency oriented | Supporting experimentation |
| Homogeneous | Heterogeneous |
| Older and experienced | Younger and entrepreneurial |
| High inertia | Focus on discovery |
| Risk-avoiding | Risk-taking |
| Managing and controlling | Autonomous and high trust |

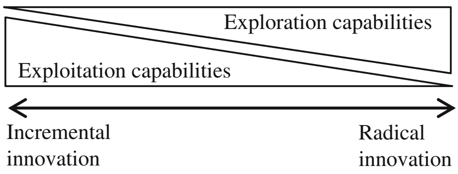


**Fig. 1** Influence of exploitation and exploration capabilities on incremental and radical innovation

the former capabilities at operating departments and the latter at a R&D department [7]. However, there is a growing argument in literature that any departments and groups in an organization should excel at both exploitation and exploration and be able to shift between them as needed depending on the situation that the departments and groups are facing [8]. Traditionally manufacturing organizations are more configured to exploitation because they have a long history of exercising incremental improvements. In a perspective that manufacturing organizations need to achieve a higher level of innovation capabilities, an important challenge for them is to proactively build exploration capabilities across the organizations.

## *2.2 Building Organization's Exploration Capabilities*

In literature, researchers have identified the characteristics of organizations that excel at exploration [9]. However, few guidelines and discussions have been made on how to develop exploration capabilities and achieve such organizations in practice. At a general level, it has been commonly discussed that capability-building can not be achieved overnight. Its process is essentially one of organizational learning, in which what are often unfamiliar routines are first articulated and then reinforced over time [10]. Organizational capability-building resembles becoming an athlete that requires to go through a process of gradual training [10].

Managerial interventions to develop exploration capabilities have been suggested by a few researchers. Crossan and Apaydin [11] have identified five managerial levers: establishing an explicit innovation strategy, allocating resources to development activities, building appropriate organization structures, creating learning environment and knowledge and idea management systems, and establishing organization culture that promote risk-taking and autonomy. McLaughlin et al. [9] also have suggested 16 interventions that are similar to the mentioned levers. These managerial levers and interventions seem to be helpful to create organization settings that are supportive to building exploration capabilities. However, these authors provide little information on how and when to implement those levers and interventions in reality. Moreover, those levers and interventions may change structures and formal procedures in an organization but may not affect changes of behavioral routines at an individual and group level.

Hallgren [12] has practiced a more bottom-up approach to building innovation capabilities in his action research at a case company. Under the support from the top management of the company, Hallgren [12] created an innovation steering group in the company and taught the members of the group various creative problem-solving techniques. The members were expected to eventually disseminate the learned techniques to their colleagues. As a result, some degree of employees' behavioral changes occurred at the company. Hallgren's bottom-up approach can bring about changes of behavioral routines at an individual and group level. However, in this approach effective capability-building may not occur since the effectiveness largely depends on the abilities of the members to disseminate new behaviors.

## 3 Proposing an Alternative Approach to Building Exploration Capabilities

In the previous section, the managerial and bottom-up approaches to building exploration capabilities have been discussed. This paper proposes an alternative approach that can be positioned between these two approaches. The approach is described as follows:

> Organization's exploration capabilities are built through leaders iteratively and deliberately creating situations where groups in an organization have to or can be more explorative. By creating such situations iteratively at different parts of the organization, people in the organization become more trained to think and act in explorative ways, organizational settings (e.g., organization's strategies, formal structures, systems, and processes) supportive to exploration are eventually identified and installed based on the needs, and at the same time new concepts and solutions are created, tested, and/or implemented.

In the subsequent subsections, foundations of the proposed approach and possible advantages of the approach compared to the mentioned managerial and bottom-up approaches are discussed.

### *3.1 Foundations of the Proposed Approach*

The proposed approach is mainly inspired by how organizational changes toward learn manufacturing were driven by an experienced Japanese lean consultant. The consultant had been practiced Toyota Production System (TPS) for more than 20 years and has instructed TPS at more than 150 companies and 2,800 persons globally. The author of this paper worked with the consultant and observed how he facilitated implementations of lean manufacturing (hereafter called lean transformations) at two Swedish manufacturing companies for two years [13]. During the lean transformations, the consultant did not much focus on providing solutions nor teaching lean concepts, tools, and techniques to the members of the client companies. Instead, he mainly concerned how to constantly create situations where people at the companies feel the need for improvement. He strongly believed that creating the need for improvement was the central driver of lean transformation. The belief was based on one of the conclusions made by Ohno, one of the founders of TPS. Ohno states that every improvement starts from the needs and improvements without feeling the need of them tend to have low sustainability or to fail to yield benefits proportional to the investment made for the improvements. The consultant's way of driving lean transformation can be described as; *occasionally by force, he creates situations where people in an organization have little choice but to feel the need for improvement. The situations are created by setting requirements that bring up different problems up to surface. Through letting people in the organization to discover solutions to the surfaced problems in a learning-by-doing manner, the operational performances are improved and at the same time people learn skills, knowledge, techniques, and thinking necessary to achieve lean manufacturing*. Examples of how the consultant acted based on his way of driving lean transformation at the mentioned client companies are shown in below [13].

*Example A* At a section of a factory, the consultant thought that there was too much buffer stock. It was because the products were produced with one-week batches. After a quick investigation, he found that it was possible to produce with daily batches, the consultant suggested to remove the buffer stock completely except the amount needed for the daily batches. The shop floor supervisor and the operators showed confusion and unwillingness to the removal. The consultant however, insisted them to do it anyway, saying that they would somehow find a way to manage the reduced amount of buffer stock.

*Example B* The consultant estimated that the manufacturing lead time at one of the factories could be much shorter. He instructed the members of the company to reduce the lead time registered in the manufacturing planning system by 30–50 % and to start manufacturing orders later in accordance with the shortened lead time. He showed strong confidence that people in the shop floor would certainly find ways to manage the changes made in the planning system.

The underlying principles of the consultant's way of driving learn transformation can be summarized as follows.

- Without people feel the need for improvement with some degree of sense of urgency, the improvement does not occur effectively.
- Constantly creating the need for improvement is the central driver for organizational changes toward lean manufacturing.
- By encouraging and supporting people to discover solutions though experiments, that is *discovery learning* termed by Buckler [14], people can collectively build capabilities necessary to achieve lean manufacturing.

The proposed approach to building exploration capabilities is based on the same principles, except that the words 'improvement' and 'lean manufacturing' in the above principles need to be replaced by 'exploration' and 'innovative organization' respectively.

### 3.2 Potential of the Proposed Approach

A natural question about the approach proposed in the previous subsection is why it can be an alternative approach to building exploration capabilities. Little empirical evidence has been accumulated enough to verify the effectiveness of the approach. However, potential of the approach can be discussed by comparing other approaches to the exploration capability-building. In this paper, the comparison is made by contrasting different approaches to lean transformation. Lean transformation comes again into the discussion, because the transformation and the capability-building share one thing in common; both involve cultural changes in an organization. Although characteristics of an organization desired to be achieved in the transformation and the capability-building may different, cultural changes are considered critical factors for both of the transformation and the capability-building. Lean transformations have been conducted at many manufacturing companies, and thus the knowledge of the transformation has been developed more than the one of the capability-building. Comparison of different approaches to lean transformation and building exploration capabilities are shown in Table 2.

As for lean transformation, there are generally three kinds of approaches, namely deliberate, emergent, and deliberate-emergent approaches. The deliberate approach involves a top-down way of implementing lean manufacturing. Clear separation between plan and implementation tends to be apparent. Solutions tend to be prescribed and implementations are done by following systematic processes. However, many scholars and practitioners have claimed that a prescriptive approach to lean transformation gives little room for employees to learn and thus is less likely to bring about cultural changes in an organization [15]. The emergent approach includes teaching change agents or other employees lean concepts, methods, and techniques, expecting that they are disseminated across the organization. This approach tends to bring about improvements at a local level (e.g. at a section of the shop floor). However, major changes that influence a large part of the organization may not take place because such changes tend to cause conflicts of interest among different groups in the organization. In this approach, use of lean methods and tools may not be sustainable since it largely depends on the employees' interest. In the deliberate-emergent approach, a lean transformation is initiated and general directions for improvements are set by the management, but how to achieve the goal of the transformation is largely left to employees to find through learning by doing. Many researchers advocate this approach because it embraces organizational learning through which cultural changes tend to occur [16]. However, less knowledge has been developed as to how to practically apply this approach. The way of driving lean transformation practiced by the lean consultant mentioned previously in this paper is a variation of the approach.

As for different approaches to build exploration capabilities, the managerial-intervention focused approach discussed in the previous subsection can correspond to a deliberate approach. The intervention focused approach can bring about changes of organization structures, formal procedures, and systems. However, a

**Table 2** Different approaches to lean transformation and building exploration capabilities

| | Lean transformation | Building exploration capabilities |
|---|---|---|
| Deliberate approach | Top down way of implementing lean manufacturing | Managerial-intervention focus<br>Changes of structures and formal processes in the organization |
| | Prescribed solutions and systematic process of implementation | Articulation of strategy |
| | Less likelihood of bringing about organizational cultural changes | Uncertain if cultural changes occur |
| Emergent approach | Teaching employees lean concepts and techniques expecting that the employees use them eventually | Teaching employees methods and techniques (e.g., creative problem-solving techniques) |
| | Local improvements | Local improvements |
| | Stagnation of progress with loss of interest | Stagnation of progress with loss of interest |
| Deliberate-emergent approach | Direction being set by management but solutions being found by employees | Little knowledge of how to do |
| | Organizational learning | The approach proposed in this paper (followings are expecting effects of the proposed approach) |
| | Higher chance of cultural changes | Capability-building by doing organizational learning |
| | Less knowledge of how to practically do | Less risk of stagnation of progress |
| | The consultant's way of driving lean transformation mentioned in this paper | |

generic difficulty of a deliberate approach is that it is less likely to bring about cultural changes. A risk of the intervention focused approach is that even though an innovation slogan is stated and idea and knowledge management systems are installed in an organization, they may affect little cultural changes of the organization. An emergent or bottom-up approach can be applied to the capability-building as Hallgren [12] did in his action research. The concepts, techniques, and tools supportive to explorative ways of thinking and acting (e.g. creative problem-solving techniques) are taught to employees anticipating the dissemination of them. Some behavioral changes of employees may occur, but similar to the emergent approach to lean transformation, a risk is that employees may become interested in trying out the techniques and tools at first but the employees may lose their interest unless there is sufficient and constant need for using them. As for deliberate-emergent approach to building exploration capabilities, little knowledge has been accumulated in literature as to how to perform this approach. The approach proposed in this paper is a variant of the deliberate-emergent approach. In the proposed approach, cultural changes may occur through constantly triggering and embracing discovery learning at different parts of the organization. Necessary managerial interventions become clearer by iterating discovery learning, and they are implemented based on the needs. Progress of the capability-building is less likely to stagnate as far as the need for exploration is constantly created. It can be said that the proposed approach can compensate shortcomings of the deliberate and emergent approaches.

## 4 A Model of How to Apply the Proposed Approach in Practice

Little guidance has been made for how to practically apply the proposed approach at companies. In this section, a model of how to apply the approach in practice is presented. Before the presentation, how the model was developed is briefly explained. After the presentation of the model, results of applying the model at a manufacturing company are presented.

### *4.1 Development of the Model*

The model was first developed based on the existing theories. As discussed earlier in this paper, building organization's capabilities resembles training that requires repetition. A process of the capability-building should be less linear but rather emergent consisting of a series of learning cycles. Therefore, models of learning cycle such as Kolb's experiential learning cycle [17] and PDCA cycle influenced the development of the model proposed in this paper. The characteristics of organizations that are proficient in exploration [9] and the managerial interventions to develop such organizations [9, 11] were also considered in the development of the model. Since managers, leaders, or change facilitator should be the drivers of the proposed approach, the model was made in their perspective.

The model was further modified through applying the model at a manufacturing organization of a Swedish company. The company was a medium sized company developing, manufacturing, and selling electrical products for industrial use. The author of this paper acted as the facilitator of applying the model at the company. The model was applied since the summer 2012 and the application is still ongoing. At the time, when this paper was written in December 2012, approximately 40 managers and employees had been involved in the application. The model presented in the next subsection is based on the application from the summer 2012 to the end of the same year. The period of application is still too short to fully analyze the effect of the application on exploration capability-building. Therefore, the model in the next subsection is still an intermediate state.

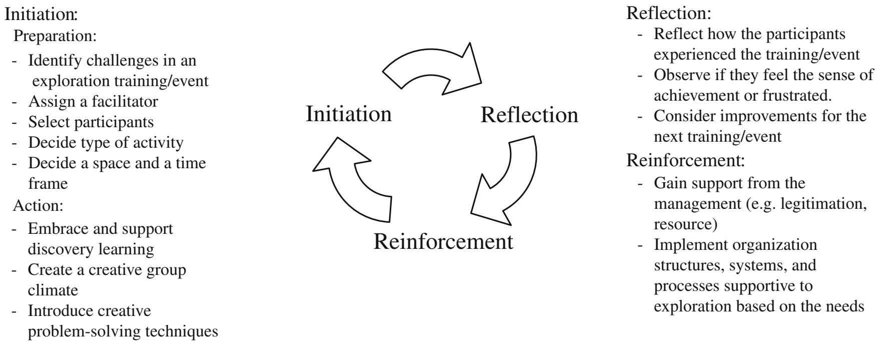


**Fig. 2** A model of how to apply the proposed approach in practice (a perspective of leaders and facilitators)

## *4.2 The Model of How to Apply the Proposed Approach in Practice*

The model of how to apply the proposed approach in practice is shown in Fig. 2. In the model, a deliberately created situation where a certain group in an organization has to or can be more explorative is called an exploration training/event. The model is a cycle of initiating an exploration training/event, reflecting the training/event, and reinforcing the exploration capability-building by identifying and implementing organization settings supportive to exploration. Continuous iteration of the cycle creates an evolutional development of the organization's exploration capabilities; people in the organization gradually become more trained in explorative ways of thinking and acting, organization structures, systems, and procedures supportive to exploration are successively implemented based on the needs, and the management gradually gains more confidence in building exploration capabilities and provides more support to it.

At the initiation step in the model, an exploration training/event is prepared and conducted. Before initiating a training/event for the first time, it is preferable for the management of the company to understand the underlying principles of the model at least to some degree. It is also desirable to decide who is responsible for driving the cycles in the model. The initiation step includes two substeps namely, preparation and action. The preparation substep starts with identifying challenges to be dealt with in the training/event. Investigation of the present situations may be necessary in order to identify the challenges. The challenges should be bold enough to create the need for exploration with some sense of urgency. At least there are two ways to trigger exploration:

- Increasing constraints (e.g., setting requirements such as doubling productivity and eliminating forklifts from the factory, or creating paradoxes such as making smaller but more flexible machines)

- Removing constraints (e.g., designing pieces of equipment from a clean sheet of paper, designing manufacturing processes by conceiving an ideal state).

In the preparation substep, a facilitator and participants of the training/event need to be selected. As many innovation researchers suggest, formulation of a multi-disciplinary group is desirable. The training/event can include idea generation, prototyping, implementation of solutions, or combination of them. Which activities the training/event includes needs to be decided. Furthermore, a space for and a time frame of the training/event should be determined. At the action substep, the participants generate or realize solutions to the challenges posed in the training/event under an autonomous work environment. At the beginning of the action, a facilitator of the training/event can explain the background or the reason of the challenges to the participants. During the action, the facilitator should emulate an explorative organization at a group level. He or she should create an atmosphere of playfulness, openness, respect, and trust, encourage risk-taking and experiment, and embrace less liner and more emergent work procedures. The facilitator can also introduce various techniques and tools for creative problem-solving.

At the reflection step, the facilitator and the participants reflect how they experienced the training/event. Interviews and observations can be made to see if the participants or other members of the organization understand more the meaning of the training/event, if they have obtained sense of achievement and become motivated for further challenges, or if they feel frustrated for some reasons. Improvements for the next training/event can be considered based on the reflection.

At the reinforcement step organization settings supportive to building exploration capabilities are identified and gradually installed. The management of the organization may gain more confidence in the exploration capability-building, and provide more recognition, legitimation, and financial and human resources to activities related to the capability-building. Necessary organization structures, systems, and processes, for instance idea sharing and storing systems, knowledge management systems, reward mechanisms, and a steering group, are identified and implemented.

## 4.3 Preliminary Results of the Application of the Model

During the development of the model at the mentioned company, the author of this paper initiated exploration training/events four times, in other words, the cycle in the model was iterated four times. The contents of the training/events and their results in terms of the exploration capability-building are shown in Table 3.

The training/events were new to the most of the participants. Therefore, the effects of the training/events in terms of the capability-building were limited to increasing the basic understanding of and the motivation for the training/events. In order for the participants to be trained in explorative ways of thinking and acting,

**Table 3** The exploration training/events exercised at the case company

| Challenge in the exploration training/event | Type of activity | Participants | Results in terms of the exploration capability-building |
|---|---|---|---|
| How to package the products with persons or machines touching the products and the packaging materials as little as possible? | Idea generation | 10 persons mostly from the packaging operations | The participants understood the meaning of the training/event<br>They learned how to purposefully think different |
| How to assemble the interface components of the products with persons or machines touching the components as little as possible? | Prototyping | 6 persons mostly from the component assembly operations | The participants understood the importance of risk-taking and experiment |
| How to reduce the amount of walking to one third? | Idea generation | 10 persons mostly from the electric component assembly operations | The participants understood the meaning of the training/event<br>They learned how to purposefully think different |
| How to double the productivity of the assembly operations for the interface components? | Idea generation | 16 engineers from production and product development | The participants understood the meaning of the training/event<br>They became motivated for further executions of exploration training/events |

they need to experience training/events at least several times. Since the cycle in the model was iterated only a few times, the need of formal systems and procedures supportive to the exploration capability-building had not been emerged yet. Nevertheless, the recognition of the training/events among the managers and employees was increased as the cycle was iterated. One of the notable effects of the model application was that the production manager understood the potential of the model and started to initiate exploration training/events by himself. The above described results are still preliminary ones. In order to examine the effectiveness of the model, the cycle in the model needs to be iterated more.

## 5 Discussions and Conclusions

The main purpose of this paper has been to propose a specific approach to building organization's exploration capabilities. Deliberately and iteratively creating the need for exploration and supporting discovery learning are the central principles of the approach. The approach is derived from the knowledge of how to drive lean transformations. Applying the knowledge of lean transformation to exploration capability-building can be a unique contribution of this paper to the innovation management research. At a glance, the lean transformation and the capability-building appear to be different kind of activities. However, they are the same in a way that both entails cultural changes of an organization and continuously creating the need for change is a key driver to achieve the cultural changes. At a R&D or a product development organization, there is naturally more need for exploration than in a manufacturing organization. Therefore, it can be particularly important for a manufacturing organization to deliberately create the need for exploration, if it wants to develop exploration capabilities. Nonetheless, discussions of the proposed approach remain theoretical since there is little empirical evidence that verifies the effectiveness of the proposed approach. The lack of empirical evidence motivated to develop a model of how to apply the proposed approach in practice. The model was applied at a manufacturing company and some positive effects were observed. However, the period of the application was too short to fully evaluate the usefulness of the model. The application of model at the company is still continuing. More results of the application will be obtained in the future.

## References

1. Hayes RH, Pisano GP (1994) Beyond world-class: the new manufacturing strategy. Harvard Bus Rev 72(1):77–85
2. March JG (1991) Exploration and exploitation in organizational learning. Organ Sci 2(1):71–87
3. Peng DX, Schroeder RG, Shah R (2008) Linking routines to operations capabilities: a new perspective. J Oper Manage 26(6):730–748

4. Ketokivi M, Schroeder R (2004) Manufacturing practices, strategic fit and performance—a routine-based view. Int J Oper Prod Manage 24(1-2):171–191
5. Benner MJ, Tushman ML (2003) Exploitation, exploration, and process management: the productivity dilemma revisited. Acad Manage Rev 28(2):238–256
6. Dougherty D, Hardy C (1996) Sustained product innovation in large, mature organizations: overcoming innovation-to-organization problems. Acad Manage J 5:1120–1153
7. Tushman ML, O'Reilly CA III (1997) Winning through innovation: a practical guide to leading organizational change and renewal. Harvard Business School Press, Boston
8. Boer H, Gertsen F (2003) From continuous improvement to continuous innovation: a retro perspective. Int J Technol Manage 26(8):805–827
9. McLaughlin P, Bessant J, Smart P (2008) Developing an organisation culture to facilitate radical innovation. Int J Technol Manage 44(3):298–323
10. Bessant JR (2003) High-involvement innovation: building and sustaining competitive advantage through continuous change. Wiley, Chichester
11. Crossan MM, Apaydin M (2010) A multi-dimensional framework of organizational innovation: a systematic review of the literature. J Manage Stud 47(6):1154–1191
12. Hallgren EW (2008) Employee driven innovation; a case of implementing high-involvement innovation. PhD dissertation, Department of Management Engineering, Technical University of Denmark
13. Yamamoto Y, Bellgran M (2010) Fundamental mindset that drives improvements towards lean production. Assembly Autom 30(2):124–130
14. Buckler B (1996) A learning process model to achieve continuous improvement and innovation. Learn Organ Int J 3(3):31–39
15. Drew J, McCallum B, Roggenhofer S (2004) Journey to lean: making operational change stick. Palgrave Macmillan, New York
16. Riis JO, Hildebrandt S, Andreasen MM, Johansen J (2001) Implementing change: lessons from five development projects. Int J Technol Manage 22(1-2/3):13–27
17. Kolb DA (1984) Experiential learning: experience as the source of learning and development. Prentice-Hall, Englewood Cliffs

# Design of Multi-Stage Manufacturing Networks for Personalized Products Using Metaheuristics

**D. Mourtzis, M. Doukas, F. Psarommatis and N. Panopoulos**

**Abstract** Manufacturers are nowadays highly affected by the ever-increasing number of product variants, under the product personalization trend. The large number of cooperating manufacturing network partners leads to enormous search spaces of alternative manufacturing network configurations. This obstructs effective decision-making towards configuring efficient network structures, a nonetheless crucial decision for a company. Exact methods guarantee that the identified solution is the optimum, with regards to the objectives set in the specified problem. However, in real life cases the magnitude of the solution space is such that these methods cannot be utilized due to computational constraints. For tackling such NP-hard problems, meta-heuristics can be utilized that provide a trade-off between the quality of solution and the computation time. This research work describes the modeling and solving of a manufacturing network design problem using the metaheuristic methods of simulated annealing and tabu search. The quality of the results identified by these methods is compared with the results obtained from an intelligent search algorithm and an exhaustive enumerative method, which are implemented into a web-based platform for the design and planning of manufacturing networks. The approach is validated through its application to a real life case study with data acquired from the automotive industry.

**Keywords** Simulated annealing · Tabu search · Manufacturing network design · Decision-making · Metaheuristics

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## 1 Introduction

The introduced number of product variants under the trend of market's personalization needs constitutes the identification of effective and efficient manufacturing network structures an utterly challenging issue. In this personalization environment, manufacturers are called to materialise, customer unique requests [1]. The vast amount of alternative configurations especially for a newly introduced personalized variant requires immediate feedback from the production system and intelligent methods capable to suggest optimal ways of configuring the manufacturing resources [2]. Toward this end, this research work focuses to provide strategic level decision-support for the design of manufacturing networks in order to handle high product variety and demand volatility.

## 2 State of the Art

The increased complexity, the ever-existing competitiveness and the dynamic character in today's manufacturing landscape generates a series of difficulties in supply chain management [3]. Supply chain design, planning and continuous optimization is nevertheless a critical decision for modern enterprises and at the same time a flourishing research area. As most of the optimization problems and predominantly cases under uncertainty will be of large scale, the need for developing efficient and intelligent procedures is evident [4].

Optimization methods have been extensively utilized for the manufacturing network design. One of the most prominent family of techniques are metaheuristics, which use parallel and non-independent solution constructions [5]. Metaheuristics have been applied to the majority of manufacturing network design and planning problems, aiming at multi or single objective optimization [6]. Commonly used metaheuristics include the methods of simulated annealing [7], tabu search [8], cross-entropy [9] as well as nature-inspired methods like genetic algorithms [10], evolution strategies [11] and, more recently, ant colony optimization [12] and particle swarm optimization [13]. Other metaheuristics such as greedy randomized adaptive search procedures (Grasp) [14] and ant colony optimization (ACO) employ repeated probabilistic solution constructions. Moreover, approximate and non-deterministic tree search procedures (ANTS) [15] and probabilistic beam search derivate like Beam-ACO can be found [16].

Tabu Search is among the most effective approaches for solving hard combinatorial optimization problems, with high applicability in discrete search spaces [5]. Tabu search was preferred by Keskin and Ülster (2007) because it offered both high solution quality and computational time advantages [17]. A tabu search with path relinking was proposed in [18], and was used for the identification of the indicative number of parts to be produced. It also proposed the quantity of each item to be delivered to the customers. Melo et al., proposed a tabu search method for the redesign of a multi-echelon supply network [19]. The study tackled a number of manufacturing network related issues, such as facility relocation scenarios and multi-period design horizons. Tabu search was utilized in a Markov chain bootstrapping procedure, in order to search through the exploding number of alternative scenarios [20].

Moreover, simulated annealing has been extensively applied for the design of manufacturing networks. A simulated annealing methodology that addressed the distribution network design and management problem was proposed in [21]. The study focused on the determination of the optimal set of warehouses and cross-docks to operate while minimizing the cost to operate such open warehouses and cross-docks, costs to transport multiple shipments of products from warehouses to cross-docks and costs to supply products based on customer demands. A simulated annealing approach was proposed to a bi-criteria sequencing problem in two-stage supply chain to coordinate required set-ups between the two successive stages [22]. Mansouri [6] also proposed a bi-criteria simulated annealing approach for a two-stage manufacturing network for the coordination required set-ups between two successive stages of a supply chain in a flow shop pattern. Furthermore, a recent study incorporated environmental objectives into the decision-making procedure for the design and planning of supply chains [23]. Finally, the authors in [24] focused on manufacturing network design for a single-product, single-period problem with constant demand and uncertainty in returns, incorporating also environmental impact factors. A comprehensive comparison among the methods of Tabu Search, Simulated Annealing and Genetic Algorithms is provided by Arostegui et al. [25].

The type of the problem tackled in this paper is a multi-objective decision-making problem that aims at the simultaneous optimization of multiple cost and benefit criteria. The problem is NP-hard [26] and the magnitude of the search space for the specific investigated model is in the order of millions of alternatives. The aim is the timely identification of high quality feasible alternative multi-stage manufacturing networks that support the production and transportation of heavily customized products.

This design of multi-stage manufacturing networks for personalized products problem is tackled using exhaustive, intelligent and metaheuristic techniques. The developed framework includes the following search methods: Exhaustive Search, Intelligent Search Algorithm, Simulated Annealing and Tabu Search. The performance of these methods is calculated in terms of solution quality and computational requirements. The solution quality takes into consideration classical indicators such as cost, lead time and quality, along with parameters of environmental impact and manufacturing network reliability. Finally, the approach is validated through a real life case study utilising data acquired from the automotive industry.

# 3 Manufacturing Network and Personalized Product Models

The evolution of manufacturing resources and the establishment of Key Enabling Technologies (KETs) has allowed the realization of highly complex products cost-effectively. Moreover, innovative production concepts such as Flexible Manufacturing Systems grant capabilities for producing larger number of different parts using the same machines [27]. Apart from OEMs, who already implement such technologies, their cooperating pool of suppliers and dealers are forced to do the same. They are driven by the needs of maintaining their competitiveness, or they are imposed to reform their production system by the OEM they supply. Therefore, manufacturing tasks, such as assemblies and/or special personalization tasks can be outsourced to suppliers and dealers closer to the final customers [28]. This concept of decentralized manufacturing that has already been implemented in practice, is utilized in the presented research work for modeling the manufacturing networks.

The modeling of the personalized product structure includes a number of commonly shared parts by all variants and a series of customer-personalized components and accessories. The product personalization is carried out by the customer through a web-based three-dimensional configurator. The customer can select an accessory and modify its characteristics, ranging from simple colour and texture modifications up to more elaborate geometrical alteration. The system is checking in real-time the manufacturability of the customer preferences and in case the design is feasible, the order is forward to the production system, which is the starting point of the presented study.

# 4 Methods for the Design of Manufacturing Networks

The decision-making methods used for the identification of manufacturing network alternatives and their evaluation is performed using the following four methods: Exhaustive Search, Intelligent Search Algorithm, and Simulated Annealing and Tabu Search.

## *4.1 Exhaustive Search*

The Exhaustive Search (EXS) is an exact enumerative method [27, 29]. During an EXS, the entire search space of the manufacturing network configuration alternatives is generated and evaluated. Therefore, EXS is capable of identifying the best alternative with respect to the selected criteria, as defined by the design and planning objectives. However, the EXS can be very time-consuming in realistic cases, due to the enormous size of the search space. In real-life manufacturing cases, when the Total Number of Alternatives (TNA) is in the order of billions, EXS is non-executable in conventional workstations in real time, therefore, it is impractical for manufacturing needs.

### 4.2 Intelligent Search Algorithm

The ISA used for the digital experimentation is described in [29–32]. ISA is an artificial intelligence search method that utilizes three adjustable control parameters. The depth of the search is defined by the Decision Horizon (DH), the breadth of the search by the Selected Number of Alternatives (SNA) and the Sampling Rate (SR) guides the search towards paths of high quality. The algorithm's performance is investigated in [29, 32].

### 4.3 Simulated Annealing

In the Simulated Annealing (SA) method, an initial solution *S* is fed to the algorithm. *S* is randomly generated obeying the constraints of the manufacturing capabilities of the supply chain partners. This *S* is changed following a hill climbing notion. However, the difference with simple hill climbing is that when SA makes the decision on when to replace *S* with *R*, its newly tweaked offspring. More specifically, if *R* is better than *S*, SA will always replace *S* with *R*. But if *R* is worse than *S*, it may still replace *S* with a certain probability *P(t, R, S)*:

$$R(t,R,S) = e\frac{UtilityValue(R) - UtilityValue(S)}{t}, \text{where } t \geq 0$$

Thus, the algorithm sometimes goes down hills. The fraction in the exponent is negative because *R* has a lower utility values than *S*. First, if R is much worse than S, the fraction is larger, and so the probability is close to 0. If *R* is very close to *S*, the probability is close to 1. Thus, if R isn't much worse than S, SA will still select R with a reasonable probability. Second, the tuneable parameter *t*, if close to 0, the fraction is again a large number, and so the probability is close to 0. If *t* is a large number, the probability is close to 1. Initially *t* is set to a high number, which causes the algorithm to move to explore new neighborhoods by adopting every newly-created solution regardless of how good it is. Afterwards, *t* decreases slowly, eventually becoming 0, at which point the algorithm is doing nothing more than plain hill-climbing. The rate at which *t* is decreased is called the algorithm's schedule. The longer *t* is stretched out the schedule, the longer the algorithm resembles a random walk and the more exploration it does. The pseudo-code of the SA implemented in this research work is a follows:

$t \leftarrow$ temperature (initially a high number)
$S \leftarrow$ initially generated candidate solution
*Best* $\leftarrow S$
**repeat**
$R \leftarrow$ Tweak(Copy($S$))
**if** Utility($R$) > Utility($S$) **or** if a random number chosen in [0, 1] $< e^{\frac{UtilityValue(R) - UtilityValue(S)}{t}}$ **then**
$S \leftarrow R$
Decrease $t$
**if** Utility($S$) > Utility(*Best*) **then**
*Best* $\leftarrow S$
**until** *Best* is the optimum solution **or** $t = 0$ **or** another termination condition is met
**return** Best

## *4.4 Tabu Search*

TS employs a different approach to doing exploration, by exploiting a memory feature. TS stores a history of recently considered candidate solutions (known as the tabu list) and refuses to return to those solutions until they're sufficiently far in the past, i.e. removed from the list of taboos. Thus, if a hill climb is carried out, the algorithm will cause a back down walk on the other side because it is not permitted to stay at or return to the top of the hill. During TS, a tabu list $L$, of some maximum length $l$, of candidate solutions that have been searched so far is stored. Whenever a new candidate solution is adopted, it goes in the tabu list. If the number of rows of the tabu list exceed $l$, the oldest candidate solution is removed and it's no longer taboo to reconsider. The implemented TS algorithm is based on the following pseudo-code:

$l \leftarrow$ desired maximum tabu list length
$n \leftarrow$ number of tweaks desired to sample the gradient
$S \leftarrow$ initially generated candidate solution
*Best* $\leftarrow S$
$L \leftarrow \{\}$ a tabu list of maximum length $l$
Enqueue $S$ into $L$
**repeat**
**if** Length($L$) > $l$ **then**
Remove oldest element from $L$
$R \leftarrow$ Tweak(Copy($S$))
**for** $n - 1$ times **do**
$W \leftarrow$ Tweak(Copy($S$))
**if** $W \notin L$ **and** (UtilityValue($W$) > UtilityValue($R$) **or** $R \in L$) **then**
$R \leftarrow W$

**if** $R \notin L$ **and** Quality($R$) > Quality($S$) **then**
$S \leftarrow R$
Enqueue $R$ into $L$
**if** UtilityValue($S$) > UtilityValue($Best$) **then**
$Best \leftarrow S$
**until** *Best* is the optimum solution **or** another termination condition is met
**return** *Best*

### *4.5 Decision-Making Method*

The underlying decision theory is based on five steps: (1) form a set of alternatives according to the selected method (EXS, ISA, SA and TS), (2) determine a set of decision-making criteria, (3) normalise the calculated criteria values, (4) calculate the utility value, and (5) select the best or a good alternative. The alternatives are selected according to their utility value, which is the weighted sum of the normalized criteria values multiplied by their corresponding weight factors. The weight factors are defined according to the specific design and planning objectives.

The normalization of the criteria values is necessary due to the fact that the considered criteria may be conflicting and have different units of measurement. Some of the criteria need to be maximized (quality and reliability) and others need to be minimized (e.g., production cost, lead time, $CO_2$ emissions, and energy consumption). The normalization of the benefit criteria is performed using Eq. (1) and for the cost criteria using Eq. (2) [29, 33]. The utility value is calculated using Eq. (3) [29, 30].

$$\hat{C}_{ij} = \frac{C_{ij} - C_j^{min}}{C_j^{max} - C_j^{min}} \tag{1}$$

$$\hat{C}_{ij} = \frac{C_j^{max} - C_{ij}}{C_j^{max} - C_j^{min}} \tag{2}$$

$$U_i = \sum_{j=1}^{n} W_c \hat{C}_{ij} \tag{3}$$

## 5 Mathematical Modeling of the Problem

The problem faced is expressed through the optimization of the following objectives (decision-making criteria). The weighted sum of these criteria is expressed through the utility values which must be maximized in the range [0, 1]:

***Production and Transportation Cost (PTC):*** sum of production cost (*PC*) for partner *i* to perform task *k* and of transportation cost (*TC*) from partner *i* to *j*, where $i, j, k \in \mathbb{N}$, $i = 0,1\ldots I$, $j = 0,1\ldots J$, $k = 0,1\ldots K$ [29, 34].

| | |
|---|---|
| $\min PTC = \sum_{i}^{I}\sum_{k}^{K} PC_{ik} + \sum_{i}^{I}\sum_{j}^{J} TC_{ij}$ | (€) |

***Lead Time (LT):*** sum of processing and setup times (*PT*) for partner *i* to perform task *k* and of transportation time (*TT*) from partner *i* to partner *j* [34].

| | |
|---|---|
| $\min LT = \sum_{i}^{I}\sum_{k}^{K} PT_{ik} + \sum_{i}^{I}\sum_{j}^{J} TT_{ij}$ | (days) |

***Energy Consumption (EC):*** sum of energy consumption (*EP*) for partner *i* to perform task *k* and of the transportation energy (*ET*) required from partner *i* to partner *j* [28, 35].

| | |
|---|---|
| $\min EC = \sum_{i}^{I}\sum_{k}^{K} EP_{ik} + \sum_{i}^{I}\sum_{j}^{J} ET_{ij}$ | (Joules) |

***$CO_2$ Emissions (CO):*** the $CO_2$ tonnes for the transportation (*CE*) of parts from partner *i* to partner *j* [28, 35].

| | |
|---|---|
| $\min CO = \sum_{i}^{I}\sum_{j}^{J} CE_{ij}$ | (tonnes $CO_2$) |

***Quality (Q):*** the mean quality of the partners of an alternative manufacturing network configuration [27].

$$\max Q = \frac{\sum_{i}^{I} QL_i}{I}$$

***Reliability (R):*** total reliability, where *s* represents serial and *p* parallel resources, $s,p \in \mathbb{N}$, $s = 0,1\ldots S$, $p = 0,1\ldots P$ [36].

| | |
|---|---|
| $\max R_{stot} = \prod_{s}^{S} R_s$ | For serial resources |
| $\max R_{ptot} = 1 - \prod_{r}^{R} (1 - R_p)$ | For parallel resources |

## 6 Software Tool Implementation

The digital experimentation was executed into a web-based software tool, where the ISA and EXS algorithms are coded using JAVA™, contained in the Apache Tomcat web-server and stored in a MySQL database. The SA and TS engines were executed in the Matlab® environment. Graphical interfaces are shared among the four methods and are used for performing the required data entry (resources, tasks, materials etc.) and adjusting the parameters of the ISA, SA and TS methods. The user is capable to select the preferred decision-making method, execute the experiments and visualise the results, comparisons as well as the selected manufacturing network configurations within a web-browser.

## 7 Industrial Pilot Case

The dataset used in the experiments are obtained from an automotive manufacturer and includes the manufacturing resource characteristics (processing time, setup time, energy consumption, quality etc.), the armrest Bill of Materials (BoM) structure, the Bill of Processes (BoP), and the mapping between these three (Fig. 1).

Moreover, the locations of the production plants are entered to the system, in order for the integrated GoogleMaps™ API to automatically calculate the distances between them, which are utilized for the accurate calculation of the transportation related impact. The distances are used for the calculation of transportation cost and time, $CO_2$ emissions and energy consumption. The armrest can be produced in 3 variants upon customer request. The basic non-customized armrest (A1 variant) is comprised by the compartment, the external covering, the closing covering, the bushing, the hinge support and the screw. The other variants are extensions to this A1 and feature the addition of an inner light kit and an inner cooling kit (A2 variant) an internal covering (A3 variant) (Fig. 2). These components can be produced and assembled by a set of suppliers, dealers and OEM plants, at different cost, time, and quality. The final stage of this value-adding chain is the delivery of the customized product to the customer.

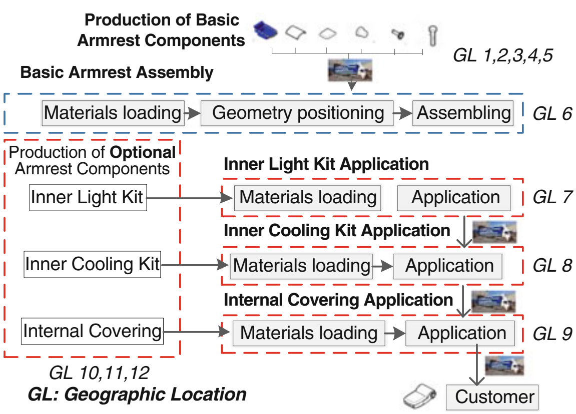


**Fig. 1** BoP of the customized armrest

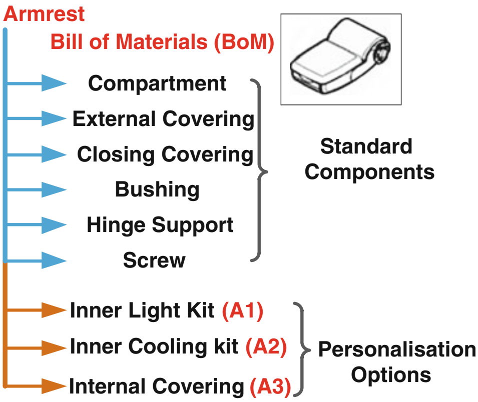


**Fig. 2** BoM of the customized armrest

## 8 Results and Discussion

The digital experiments conducted are: one execution of the EXS and ten executions for each of the ISA, SA, and TS, due to the inherent randomness of these methods. The adjustable parameters of the ISA method were obtained through a Statistical Design of Experiments, and were SNA = 1,000, DH = 6, and SR = 20 [37]. The cooling schedule ($t$) for the SA was 0.99 and the initial temperature was 1. Moreover, the tabu list was a matrix with dimensions maintained at [150 × $l$], where $l$ the number of stages in an alternative manufacturing network configuration. Other termination conditions jointly applied in these two algorithms were the maximum number of iterations (*MI)*, which was set at 65,000 and the maximum number of accepts (*MA*) for a solution, which was set at 1,500. The *MA* for SA represents the number of occurrences for a tweaked solution to replace the parent solution. In the case of TS, *MA* counts the times when the newly created solution is not contained in the tabu list and therefore, replaces a current taboo solution. The obtained criteria values of the best alternatives as provided by each of the 4 methods are collectively depicted in Fig. 3.

The EXS values were superior when compared to the other three methods, as expected. More specifically, regarding the values of the cost criterion the alternative configuration obtained by the ISA is 24.05 % worse than the results of the EXS an 28.43 and 12.88 % better than the result of the SA and TS methods respectively. The value of the cost criterion obtained from the TS is 32.71 % higher than the value obtained from the EXS. Furthermore, the same trend is observed for the values of the $CO_2$ emissions quality and reliability. More specifically, the relative difference for the $CO_2$ Emission values between the EXS and the other three methods is 29.31 % from ISA, 54.82 % from SA and 46.92 % from TS. Additionally, the relative difference in the quality value of EXS is 0.12, 1.28 and 0.58 % higher than the ISA, SA and TS. Finally, the difference between the EXS and the other three methods for the Reliability criterion is 3.57 % for the ISA, 10.71 % for the SA and 1.19 % for the TS. The lead time as well as the energy

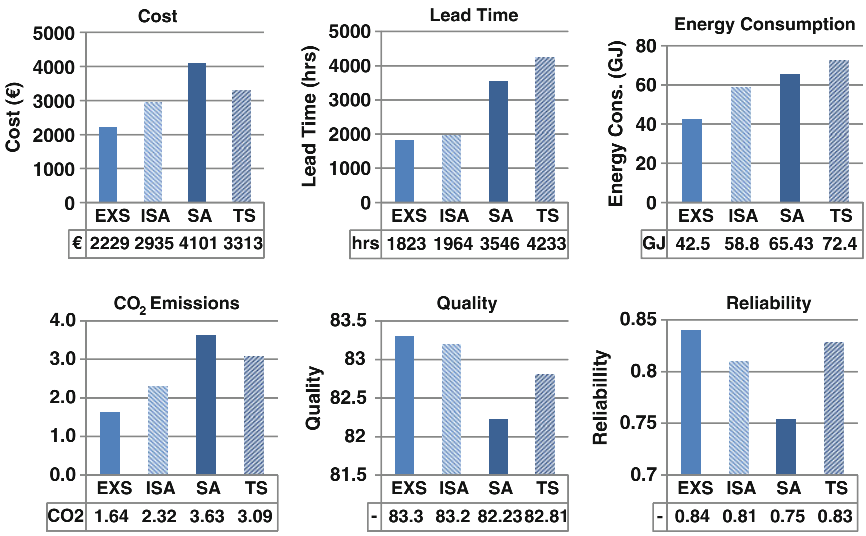


**Fig. 3** Criteria values obtained from ESX, ISA, SA and TS methods

consumption values when comparing the SA and TS results however, are in favor of the first.

Moreover, Fig. 4 below includes a comparison of the utility value of the solutions of the four methods and graphically presents the performance of the methods. The figure on the right hand side includes normalized values for the criteria, utility and computation time indicators. Comparing the utility value with the computation time that each method required in order to solve the problem it becomes obvious that ISA, and TS are superior to the EXS and SA. The relative difference of the utility value obtained from the ISA and the EXS is −5.4 %, however, the computation time required from ISA was calculated at three orders of magnitude less than the respective time required from EXS (Table 1). Furthermore, the difference of the utility value of the EXS and the SA and TS is 20.46 and 14.52 % correspondingly. The difference in the computation times between the methods of ISA, SA and TS is relatively small. Thus, the trade-off between the

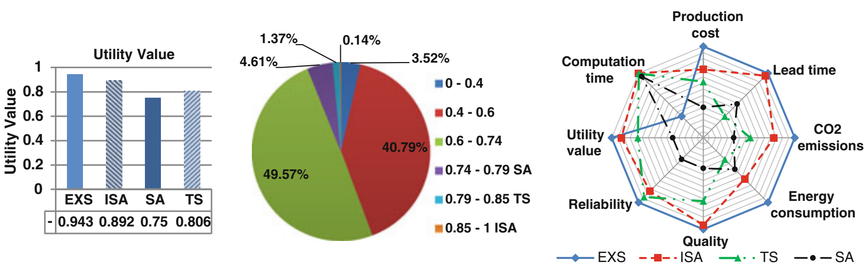


**Fig. 4** Utility and criteria values as obtained from the four methods

**Table 1** Criteria values and required computation time for the four methods

| Method | Production cost (€) | Lead time (hrs) | $CO_2$ emis. (tonnes $CO_2$) | Energy cons. (GJ) | Quality | Reliability | Computation time (sec) | No. of alternatives |
|---|---|---|---|---|---|---|---|---|
| EXS | 2229.7 | 1822.6 | 1.6396 | 42.5027 | 83.3 | 0.84 | 1,719 | 12,266,496 |
| ISA | 2935.5 | 1964.3 | 2.3168 | 58.7606 | 83.2 | 0.81 | 1.7 | 20,000 |
| TS | 3313.3 | 4233.3 | 3.0879 | 72.4214 | 82.8 | 0.82 | 12.6 | 1,626 |
| SA | 4101.8 | 3546.1 | 3.6308 | 65.4279 | 82.2 | 0.75 | 131.5 | 135,419 |

quality of the solution and the computation time is in favor of these methods as opposed to the EXS computationally intensive procedure. Moreover, the solutions identified by the ISA belonged to the top 0.14 % of the best alternatives of the solution space, the TS results to the 1.41 % and the SA to the top 6.12 %.

## 9 Conclusion and Future Work

The presented research work focused on the design of manufacturing networks that aim on the production of personalized products. The methods of Exhaustive Search, Intelligent Search Algorithm, and Simulated Annealing and Tabu Search were implemented in a software framework and compared based on the results they yielded. The comparison depicted that the solutions identified by the ISA are of high quality when compared to the results obtained by TS and SA, the latter yielding the lower performance of all examined methods. The deviation of the ISA, TS and SA solutions from the best solution acquired by the EXS is nevertheless acceptable taking into consideration the required computation time. Moreover, the exploding solution space of realistic manufacturing cases constitutes the use of EXS non-practical due to the computational resource constraints introduced by the magnitude of the solution space. In realistic manufacturing cases, the TNA may be calculated in the order of billions. Thus, a timely and efficient solution can only be then obtained through the utilization of the intelligent search techniques such as the ISA and other well-established metaheuristics, among which the SA and TS presented above. As a result, depending on the design and planning objectives, a trade-off between the time for obtaining the solution and its quality is necessary. Concluding, in case an objective function $n = f(utility\ value,\ computation\ time)$ was to be calculated, this trade-off will become apparent, as the EXS will yield results of lower $n$ values as opposed to intelligent methods [38].

Future work will focus on enhancing the capabilities of the TS and SA methods. For TS, a novel memory feature will be introduced, supported by a knowledge-based repository. A set of rules will effectively aid the exclusion of already visited neighborhoods, enabling the exploration of larger search spaces. For SA, an intelligent procedure will be devised for iteratively adjusting the cooling schedule, in order for the algorithm to decide when to focus on exploring the solution space and when to focus on the exploitation of discovered regions of high quality. Moreover, the developed TS and SA methods will be coded into a web-based design and planning software platform as components, under the Software as a service (SaaS) pattern. Finally, the wide applicability of the proposed framework will be depicted through its application in other industrial sectors, such as the CNC and robot building industries.

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## References

1. Fogliatto FS, Da Silveira GJC, Borenstein D (2012) The mass customization decade: an updated review of the literature. Int J Prod Econ 138(1):14–25
2. Yao J, Liu L (2009) Optimization analysis of supply chain scheduling in mass customization. Int J Prod Econ 117(1):197–211
3. Papakostas N, Efthymiou K, Georgoulias K, Chryssolouris G (2012) On the configuration and planning of dynamic manufacturing networks. Logistics Res 5(3–4) 105–111, Springer
4. Papageorgiou LG (2009) Supply chain optimisation for the process industries: advances and opportunities. Comput Chem Eng 56(4):1205–1215
5. Mastrolilli M, Blum C (2010) On the use of different types of knowledge in metaheuristics based on constructing solutions. J Eng Appl Artif Intell 23(5):650–659
6. Mansouri AS (2006) A simulated annealing approach to a bi-criteria sequencing problem in a two-stage supply chain. Comput Ind Eng 50(1–2):105–119
7. Kirkpatrick S, Gelatt CD, Vecchi MP (1983) Optimization by simulated annealing. Science 220(4598):671–680
8. Glover F (1989) Tabu search. INFORMS J Comput Summer 1(3):190–206
9. De Boer PT, Kroese DP, Mannor S, Rubinstein RY (2005) A tutorial on the cross-entropy method. Ann Oper Res 134(1):19–67
10. Holland J (1975) Adaptation in natural and artificial systems. The University of Michigan Press, Ann Arbor
11. Beyr HG, Schwefel HP (2002) Evolution strategies. Nat Comput 1:3–52
12. Colorni A, Dorigo M, Maniezzo V (1992) Distributed optimization by ant colonies. Elsevier Publishing, Paris, pp 134–142
13. Kennedy J (1995) Particle swarm optimization. In: Proceedings of the IEEE international conference on neural networks, vol 4. pp 1942–1948
14. Feo TA, Resende MGC (1995) Greedy randomized adaptive search procedures. J Global Optim 6:109–133
15. Maniezzo V, Carbonaro A (1999) An ANT heuristic for the frequency assignment problem. Future Generation Comput Syst 16(8):927–935
16. Blum C (2005) Beam-ACO: hybridizing ant colony optimization with beam search: an application to open shop scheduling. J Comput Oper Res 32(6):1565–1591
17. Keskin BB, Ulster H (2007) Meta-heuristic approaches with memory and evolution for a multi-product production/distribution system design problem. Eur J Oper Res 182:663–682
18. Armentano VA, Shiguemoto AL, Løkketangen A (2011) Tabu search with path relinking for an integrated production–distribution problem. Comput Oper Res 38(8):1199–1209

19. Melo MT, Nickel S, Saldanha-da-Gama F (2012) A tabu search heuristic for redesigning a multi-echelon supply chain network over a planning horizon. Int J Prod Econ 136(1):218–230
20. Cerqueti R, Falbo P, Guastaroba G, Pelizzari C (2012) A Tabu search heuristic procedure in markov chain bootstrapping. Eur J Oper Res. Available online 26 Nov 2012
21. Jayaraman V, Ross A (2003) A simulated annealing methodology to distribution network design and management. Eur J Oper Res 144(3):629–645
22. Taheri J, Zomaya AY (2005) A simulated annealing approach for mobile location management. In: Proceedings of the 19th IEEE international symposium on parallel and distributed processing, p 194
23. Martins C, Pinto-Varela T, Barbósa-Póvoa AP, Novais AQ (2012) A simulated annealing algorithm for the design and planning of supply chains with economic and environmental objectives. Comput Aided Chem Eng 30:21–25
24. Subramanian P, Ramkumar N, Narendran TT, Ganesh K (2013) PRISM: PRIority based SiMulated annealing for a closed loop supply chain network design problem. Appl Soft Comput 13(2):1121–1135
25. Arostegui MA Jr, Kadipasaoglu SN, Khumawala BM (2006) An empirical comparison of Tabu search, simulated annealing, and genetic algorithms for facilities location problems. Int J Prod Econ 103:742–754
26. Zhou G, Min H, Gen M (2002) The balanced allocation of customers to multiple distribution centers in the supply chain network: a genetic algorithm approach. Comput Ind Eng 43(1–2):251–261
27. Chryssolouris G (2006) Manufacturing systems: theory and practice, 2nd edn. Springer, New York
28. Mourtzis D, Doukas M, Psarommatis F (2013) Environmental impact of centralised and decentralised production networks in the era of personalisation. In: Windt K (ed) Robust manufacturing control. Springer, Berlin, ISBN 978-3-642-30748-5, Chapter 27, DOI: http://dx.doi.10.1007/978-3-642-30749-2_26
29. Mourtzis D, Doukas M, Psarommatis F (2012) A multi-criteria evaluation of centralized and decentralized production networks in a highly customer-driven environment. CIRP Ann-Manuf Technol 61(1):427–430
30. Chryssolouris G, Dicke K, Lee M (1992) On the resources allocation problem. Int J Prod Res 30(12):2773–2795
31. Michalos G, Makris S, Mourtzis D (2012) An intelligent search algorithm-based method to derive assembly line design alternatives. Int J Comput Integr Manuf 25(3):211–229
32. Michalos G, Makris S, Mourtzis D (2011) A web based tool for dynamic job rotation scheduling using multiple criteria. CIRP Ann-Manuf Technol 60(1):453–456
33. Milani A, Shanian A, Madoliat R, Nemes J (2005) The effect of normalisation norms in multiple attribute decision making models: a case study in gear material selection. Struct Multi Optim 29:312–318
34. Mourtzis D, Doukas M, Psarommatis F (2012) Design and planning of decentralised production networks under high product variety demand. In: Proceedings of Procedia CIRP, 45th CIRP conference on manufacturing systems 2012, vol 3. pp 293–298, 2012
35. EPA (2010) URL: www.epa.gov
36. Evans JR (1993) Applied production and operations management, 4th edn. West Publishing Company, St. Paul
37. Phadke MS (1989) Quality engineering using robust design, 1st edn. Englewood Cliffs, Prentice Hall
38. Mourtzis D, Doukas M, Psarommatis F (2012) An intelligent multi criteria method for the design of manufacturing networks in a mass customisation environment. Int J Prod Res Under Review
39. Blum C, Roli A (2003) Metaheuristics in combinatorial optimization: overview and conceptual comparison. ACM Comput Surv (CSUR) 35(3):268–308

# New Business Models Elements Oriented to Product-Service Machinery Industry

**Américo Azevedo and Henrique Ribeiro**

**Abstract** Nowadays, business models play a key role in competitiveness. Each industry has specific needs regarding the customization of their business models. Through a personalized business model, organizations can enjoy a customized mapping of all the business activities. In the machinery industry domain and specifically producers of integrated Products and Services, the need for a customized business model has been growing due to the specifications of the industry. The existing business models do not satisfy the capital goods companies' needs, therefore a study was conducted to analyze and understand companies' specifications, the existing supporting business frameworks to further proceed with the creation of a new methodology and framework that supports the businesses of this specific industry.

## 1 Introduction

The evolution of the world, economy, technology and industry has created some gaps in the manner that the traditional businesses were made and by that, the relations between costumer and supplier have also suffered significant changes [1]. Thus, in order to stay competitive, companies, in every fields of industry, have been improving the manner of doing businesses. In this context, the business model concept has been discussed and improved by several authors.

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Several studies point the business model innovations as a strong source of the organizations long-term success. This successful dynamic of evolution passes through the business model progress, connecting products and services in the value offer and adding value through the relations between customers and technology users [2]. The growth and development of the organization's business model has been reaching a new stage of importance among the differentiating factors of an organization.

This new role of importance has been even more significant in technological product based companies, because, the relations created between the company, customers, suppliers and other business partners last longer, which allow a stronger and competitive position for the organization in the market. The competitive position implies that the partnership development and sustainability should be aligned with the new business model for a more efficient innovation system [3]. A shift of paradigm has to be made in order to create cooperation models that can connect the product's development with the service development since, most of the cases they are not performed together [4] therefore, this two should be done simultaneously and incorporated into one another. With the goal of increasing company's competitiveness, the business model has to be enhanced and constantly reviewed, accordingly to the specificity of the industry where a certain company is inserted [5].

The companies addressing Product/Service Systems (PSS) paradigm (e.g. machinery industries) have specific and distinguishable characteristics [6, 7] that have to be taken into consideration when thinking in the Business Model. Each specific characteristic has an impact on the competitiveness and value creation of the company for its customers. Furthermore, there are some specific business models elements of the PSS business industry that have to be considered when designing their Business Model, namely: the production process based on partner's network as a source of competitiveness advantage and increase of performance.

With our Research we intend to study the suitability of the Business Model Canvas framework, proposed by Osterwalder [8], to the domain of machinery industry addressing the PSS paradigm. Aligned with this main research goal, two main research questions arise: (1) "Does the Business Model Canvas fit the PSS business industry?" and "Does the Product and Service development alignment can be mapped into the Business Model Canvas?" Specifically, given the importance of innovation on the business model, this paper aims at identifying key business model elements necessary to build a business model for Product/services Systems (PSS) oriented business. It features an in-depth literature study spanning various definitions and concepts about the business model and product/services themes.

The remainder of paper is organized as follows. After this introduction, Sect. 2 reviews the literature about business model definition, Product/services characteristics in order to build a theoretical background that supports the identified business model elements. Section 3 presents our proposal for new business model elements to consider in PSS oriented business models. Finally, Sect. 4 concludes the paper.

## 2 Literature Review

Current business trends determined a move from vertically integrated companies towards flexible network organizations, where the ability to quickly and efficiently set-up, maintain, develop, and dissolve partnerships with business partners is a critical success factor and also generate more complexity. In addition to the complexity factor, there is still one problem existing for today's companies, which is the business strategy. This has to be shaped along the lifecycle of the organization, in order to be adapted to the external competitive environment.

Managing the external environment complexity and uncertainty, is one of the most difficult management challenges to perform by an organization, so in this manner, business models, can help in the creation of several scenarios simulation in order to diminish the gap between what is and what it will possibly be. The degree of variety and new organization formats created are increasing, with the intention to elevate productivity, raise the offering bundle and improve the company processes, creating even more complexity within a certain company [9, 10].

### *2.1 Origins and Evolution of Business Model*

In the year 2000, Hamel [11], defined a business model as a spectrum of modules interconnected between them in a way that the shared assets, responsibilities and competencies could support the market strategy adopted by the company. The four modules described by Hamel were: Customer Interface, Value Network, Core Strategy, and Strategic resources.

Amit and Zott, made an important addiction to the previous definition, in 2001, when they saw a business model as the configuration of the architecture of the actors, assets and transactions as the core of the business model, defining the product, service, information, and competencies that were part of the process of doing business [11]. According to Osterwalder and Pigneur, the words business model have a meaning themselves that are important to be considered, because when this two words are combined they can express a range of possibilities that exist, in literature, for the application and understanding of this concept [11].

In 2002, Osterwalder and Pigneur defined a business model as a tool, able to conceptualize a bundle of elements and the relations between them, which allow communicating the logic of a specific business [12]. In several ways, the different authors mentioned above, added some explanation to what a business model is, what represents and what value does it have inside a company. However, there were some divergences in the understanding of the concept and its implementation. To ease the mind of the researchers and industry in general, in 2002, a model was proposed by Osterwalder and Pigneur. This pillars represented the "what", "who" and "how" a business is made and the authors considered that, in addition to these pillars a new one could be added, the "how much". Basically, the pillars have a function of defining the several views of a company, expressing what is the market offering proposed by the company, who is the customer target that the organization is aimed to, how can the company create and/or produce and/or distribute their offering and finally how much is the profit with this whole process. The framework created, supported the definition of the business logic of a company under four categories, and supported also the relations and objects between them [12].

A literature review, made in 2005, by Osterwalder and Pigneur has revealed some advances in the field of business models. In 2005, a new hierarchy to classify several instances of the business models concept were proposed, in order to clarify the numerous literatures produced until then [13]. The business model ontology was proposed and it referred to three levels of business models, each one concerning and focusing on different concepts, models and implementation degrees.

In 2010, Business Model was described as a "rationale of how an organization creates, delivers and captures value" [8] and the nine building blocks ontology was refined. Osterwalder and Pigneur created this Business Model ontology in 2004 [10] and sophisticated it in 2010.

The ontology presented is commonly called the Nine Building Blocks and his concept was successfully applied in several companies around the world as IBM, Ericson, Deloitte, and others [8]. Other possible definition, for business model, and a more recent one, created by Clark with the collaboration of Osterwalder and Pigneur, in 2012, defines business model as "the logic by which an enterprise sustains itself financially. Put simply, it's the logic by which an enterprise earns its livelihood" [14]. A central part of any business model is the bundle of offerings that the company can provide to its customers. Although the value proposition offered by much companies are still centred in the process of buying and selling products, the exchange of ownership of some artefact, there is a new tendency in the market, the service logic, which is as important part of the offering.

## 2.2 Product and Service Evolution

In the end of the 80s and the beginning of the 90s, there was a shift in the mind of the product producers; they have started to recognize the importance of the service aspect in the value proposition that they present to their customers. This move from the product to the service was named by the literature as "Servitization" [15]. The Servitization definition can be simply explained as "the innovation of an organizations capabilities and processes to better create mutual value through a shift from selling product to selling PSS" or "recognized as the process of creating value by adding services to products" [16]. This kind of environment has made a big impact on the machine industry: innovative offers had to be though to fight this environment in order to maintain a long relation with their clients, collect new ones and generate customer loyalty [2]. A possible definition of the junction (product and service) can be called as PSS—Product/Service System and can be defined as a "tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs" [17]. This junction has the ability to join product with services, creating a big breakthrough in the industry and leading to a new source of innovation [2] and value. According to Azarenko [18] a Product/Service System can be defined as "a system of products, services, network partners and supporting infrastructure that is economically feasible, competitive and satisfies customer needs. It offers dematerialized solutions that minimise the environmental impact of consumption".

In 2004, Tukker [19], and later in 2006, Cook [20] talked about a division in three categories of the PSS, according to the level of product or service that each of the PSS package contains. The three main categories are:

*Product-Oriented* The ownership rights of the product (physical asses), like in traditional commercial trades, are transferred to the costumer, although the supplier (manufacturer) adds new and improving services to support the product created.

*Use-Oriented* The property of ownership mainly remain in the possession of the manufacturer company and to fulfil the commercial arrangement the company sells the right of use of the machinery in systems like leasing, sharing and pooling.

*Result-Oriented* The PSS is an approach based on the end result of the production made by the sold physical asset, focusing on the production service and disregarding the physical aspect of the commercial agreement [2, 18]. Figure 1, shows the three PSS categories, stated above, and place them along the path from pure good to pure service, Fig. 1 also marks the shift from the value offering in the three categories, starting from the most added value, in the product and finishing with the most value added, in the service.

The findings of the literature review reveal the evolution in terms of existing models to support a company's business. Even though some specific work in the PSS field has already been done, such as main classifications of the PSS, there is still a need to create a supporting and generic framework dedicated to this industry type, so some research opportunities come to place in order to improve the existing models frameworks.

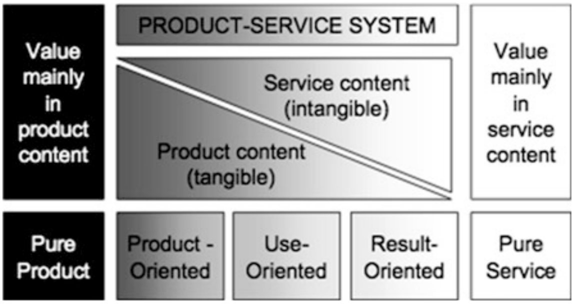


**Fig. 1** Main classification of PSS [21]

### *2.3 Improvement Opportunities*

Our research allowed us to conclude that the concept of “value network” is not properly considered. We can look to “value network” as a set of organizations that have very specific roles and value interactions, oriented toward the achievement of a particular task or outcome. The purpose of this network is to share resources, competencies, skills and knowledge with the other active agents of the network. These agents are real people and/or organizations that participate in the network by playing particular roles in which they convert both tangible and intangible assets into negotiable offerings and fulfil different functions. Therefore the inclusion of some value’s network specification in the business model could be leveraged in competitiveness and value creation.

Other opportunity arises from the success and value addition activities performed by the company, these activities depends directly of certain suppliers/partners and their activities, in order to have the necessary offering so the organization can play his role in the network to create and add more value to the offering that is going to be delivered to the customer along the chain of production and development. The activities or main processes of the key partners are, sometimes, a *touchpoint* between companies in a certain network. That led us to think that the mapping and integration of the partners key activities may play an important role in the construction of value, creating an opportunity to improve the organizations business models.

Equally important is the fact that in traditional business models, usually the value created stopped at the moment of the sale, although in Product/Service System oriented industries the value creation process continues throughout the product’s life time [21]. Thus, usually, in the traditional industries only the life-cycle of the product was considered. However, to address the Product/Service System paradigm, we have two life cycles to be considered, the development of the Product/Service System and the Supporting Services Activities throughout the product life cycle [21]. With the use of the two life cycles, the customer and supplier have to be connected to the company’s business model. The service needed by the customer and the element needed by the manufacturer to satisfy his client, are a constant presence in the second participant cycle. Therefore, the business development and implementation processes are crucial actors. Considering the different lifecycles and developing processes of the product and service component, a need for integration of the development processes is a point that could bring competitiveness differentiation, namely concerning costs, quality, performance and customer satisfaction.

Thus, there is a need to develop strategies and action plans that can sustain competitive advantage. In that context, the product and service paradigm is a new concept that has being increasingly explored to support innovative business’s strategies. The need for innovation in the Business Model is thus justifiable in organizations that intends to develop and delivery Product/Service Systems.

## 3 New Business Model Elements

Grounded in the opportunities, identified previously and complemented by the purpose and scope of Business Model Canvas (BMC) framework, companies that intend to address the PSS paradigm should integrate some new elements (new building blocks) in their business models.

In addition to BMC framework building blocks, we are proposing the inclusion of three news building blocks to completely satisfy the company's orientations towards PSS paradigm, namely: (1) Value Network Configuration, (2) Key Partners Activities, and (3) Key Development Processes. Nowadays organizations are more often organized like a business network than a traditional company, where employees of several levels can cooperate virtually such as the organization itself with its partners [22].

The business networks, composed by organizations, have the purpose to exploit emerging business opportunities [23] and create value by generating synergies in order to construct a value proposition appealing for the customer. The activity networks, where several companies work together leveraging from each other can be a win-win situation for all the companies involved. According to the new production environment, a single company may not own all resources, knowledge and skills to place competitive solutions in the market. Therefore, such enterprises become part of networks in order to produce products/services leveraging from the business network [24].

These business networks can be considered and named as value networks, according to Kindstrom [25]. Each company, participant of the value network has a specific role to play in the value interactions in order to successfully achieve a particular outcome. The network participants transform both tangible and intangible resources into negotiable offerings and value propositions with the purpose of performing different value adding activities along the network [26]. The inclusion of the Value Network Configuration into the Business Model Canvas is very important in order for the company to establish its network of partners and the value that each one of the participants creates and passes along the chain.

Creating a value network will allow the company to: (1) map its own value network, (2) identify network participants, (3) define the value that each participant produces, (4) identify the most crucial and influent network partners, and (5) constantly analyse the network in order to expand or retract the number of participant by the value they produce and add to the network.

A company can be in several Value Network Configurations according to the type of Product/Service System model it's applying at a certain customer. The Product- Oriented, Use- Oriented or Result -Oriented models [2] can change the value network of the organization although, several of these types can be performed by one company meaning that a single company.

The selection of partners is usually done by several factors but discarding and important one, the partners core activities [27]. The business partner's activities are deeply connected to the value created that is passed along the value network.

When thinking about the business model of a company, the partners that a company has, their core competences and activities, have to be considered. A new perspective of looking at the partnerships is to choose the partners based on the key activities that the company requires from them. A partner have to be chosen to enter the company value network by the value that himself can add to the network, organizations and the final customer.

The partners and the activities they develop are crucial to the success, quality and satisfaction of the final customer regarding the final Product/Service System (Value Proposition) delivered. In other cases, some key external activities that have an important value to the manufacturing company are not performed by direct partners but by virtual or temporary's partnerships. In both cases, Key Partner Activities or Key External Activities are deeply connected to the value in the offering so, the company business model has to integrate and map these activities. Knowing, analyzing, selecting, and incorporating the Key Partner activities into the organization business model can be a valuable asset. Alongside with the key partners activities and the value network configuration, is the business process thinking that is starting to be an important and very usual way of philosophy in the business fields. A relevant definition was given by Davenport about business processes "…a structured, measured set of activities designed to produce a specific output for a particular customer of market" [28]. The business processes represent the organization way of developing and coordinating its activities to fit the customer requirements: the processes support the organization competencies, changing the inputs into value added outputs.

The implementation of the business processes is very important in several ways: (1) lower costs, because the process organization and structure increase efficiency, due to better use of resources, (2) the process standardization result in the presentation of one face to suppliers, partners and customers, lowering the costs of transactions for the participants involved, and (3) the raise of flexibility, because when there is a process standardization and several business units are utilizing the same process the need for people reassign can be easily done in the case of demand fluctuations [29].

The product and service development is one of the most important processes in a PSS producer company. The new product development and the new service development frameworks alignment is a crucial step to companies that produce and commercialize heavy machinery with associated services, by developing the product and the service at the same time, the development methodology will completely integrate the both of them, creating a unique form of value creation. Therefore, the integration has the objective of merging design tasks that can and should be performed simultaneously [4]. The development of the products and the services can bring a great competitive advantage, so, the mapping of the development process of the product and service integration into the business model is necessary to create a distinguishable and value added feature of the organization.

The diagram presented in Fig. 2 summarizes the proposal extension to Business Model Canvas framework with the inclusion of the proposed three new elements. We named this extended framework as the PSS Business Model Canvas. With this

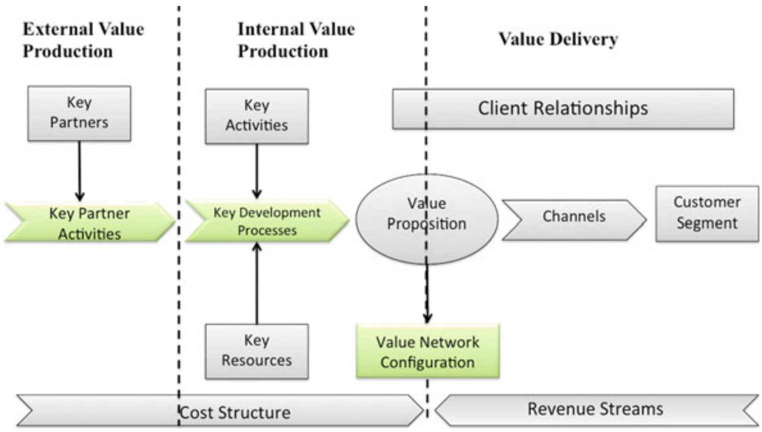


**Fig. 2** PSS business model canvas

proposal extension, we argue that will be more effective to map business models of companies developing and delivering innovative value proposition, namely offers based in machinery equipment together with associated services. The value proposition will be affected by the Value network configuration, the value proposition will no longer be just the product or the service but, with the new business model framework, the value proposition will be built by several intervenient in the value network in witch the company is presented. The outsourcing or the simple fact that a business partner can perform an activity as a core competence that the company does not, will enhance the value and stronger the relations between companies creating a long lasting relations that will leverage from several factor namely: (1) The increase of scale, scope of activities and/or sales volume, (2) Share the cost and risks, (3) Improve the ability to deal with complexity, (4) Enhanced the learning effect, (5) Flexibility, (6) Efficiency, and (7) Speed.

The key activities and key resources of the company will now be aligned in a process manner to conceptualize, create, produce, and develop the product/service system in an integrated methodological approach. The integration of the development processes of the product and the service will create key process that is crucial to the companies, in this industry. The key partner of the companies will, in this new model, be related to the company by their core competencies and core activities. The key partner activities will allow the company to map the crucial partners activities that add value to the firm's proposition, allowing the organization to choose, evaluate, and create stronger relations with their partners based on the key activities that the partners perform and somehow are important to the company and therefore to the delivery of value to the customers.

Below a table is presented, Table 1, describing each one of the new building blocks that compose the PSS Business Model. The mentioned table is an updated and more complete version of table presented by Osterwalder and Pigneur in 2010 [8].

**Table 1** PSS business model elements

| Building block | Question | Description |
|---|---|---|
| Key partner activities | What are the most important activities developed by the company partners? | Describes the core value adding activities performed by the company business partners |
| Value network configuration | What is the value network created between the company and its partners? | Describes the network, or networks in which the company is inserted with their business partners |
| Key development processes | What are the company product and service development processes? | Defines, describe and detail the methodological approach for the product and service development and their integration into one another |

## 4 Conclusions

The business model is, nowadays, one of the most important sources of competitiveness advantage in every industry. The customization of a company business model can bring leverage to the organization and in the way it does business. The commercial activities are no longer the simple act of buying and selling a product, in the current days, performing business activities calls for a stronger and complex interaction of the several participants and activities.

The improved Business Model Canvas framework, named the PSS Business Model, was created to represent a specific type of company business model: the companies delivering as a value proposition Product/Services Systems. With the introduction of the three new Business blocks: (1) Key Partners Activities, (2) Development Key Processes, and (3) Value Network Configuration, the companies can benefit from the power of stronger relations between business partners that already exist or can be created in the future, establishing new and long lasting relationships with suppliers and partners that can provide value addiction. Knowing that the Business Model frameworks that exists today does not support the mapping of the core processes of the company and being the production process one of the most important processes of the companies in the PSS industry, the PSS Business Model will satisfy the companies need in this area.

The PSS Business Model Framework was deployed and tested in two pilot business application cases oriented to PSS paradigm. A structured interview was created to collect data of each company business model regarding the 9 building blocks created by Osterwalder and the three new blocks proposed here proposed. After collecting all building block related data, the framework was tested for two different scenarios. In one of scenarios we address the offer of product-services already available in the market. Basically, the use of the PSS Business Model framework was effective to map 'as-is' situation and namely to identify gaps and business improvement opportunities. Although we tested with only two companies, the results were very promising. In particular in the second application scenario, we could anticipate some of the solutions to problems that later would be more difficult to solve (e.g. product features to support remote maintenance services).

Through the development of two pilot case studies we were able to collect evidence, that the proposed extension to Business Model Canvas Framework was effective. However, further research is needed to validate these new elements in others Product-Service Systems business environments.

## References

1. Teece DJ (2010) Business models, business strategy and innovation. Long Range Plan 43(2–3):172–194
2. Biege S, Copani G, Lay G (2009) Innovative service-based business concepts for the machine tool building industry. In: Proceedings of the CIRP IPS2 conference, pp 173–179

3. Chesbrough H, Schwartz K (2007) Innovating business models with co-development partnerships. Res Technol Manage 50(1):55
4. Aurich J, Fuchs C, DeVries M (2004) An approach to life cycle oriented technical service design. CIRP Ann—Manuf Technol 53(1):151–154
5. Aurich JC, Fuchs C, Wagenknecht C (2006) Life cycle oriented design of technical product-service systems. J Cleaner Prod 14(17):1480–1494
6. Wu Y, Gao J (2010) A study on the model and characteristics of product-based service supply. In: Logistics systems and intelligent management, 2010 international conference on, pp 1127–1131
7. Neely A, Mcfarlane D, Visnjic I (2011) Complex service systems—identifying drivers, characteristics and success factors complex service systems—identifying drivers, characteristics and success factors. In: 18th European operation management association conference
8. Osterwalder A, Pigneur Y (2010) Business model generation. Wiley, New York, Inc.
9. Hodgson GM (2003) Capitalism, complexity, and inequality. J Econ Issues XXXVII 2:471–478
10. Osterwalder A (2004) The business model ontology a proposition in a design science approach. Harvard Business School Press, Cambridge
11. Schweizer L (2005) Concept and evolution of business models. J Gen Manage 31(2):37
12. Osterwalder A, Pigneur Y (2002) Business models and their elements. BITA B4U workshop, business models, 4–5 Oct 2002
13. Osterwalder A, Pigneur Y, Tucci C (2005) Clarifying business models: origins, present, and future of the concept. Communication of the association for information systems, 15 May 2005
14. Clark T, Osterwalder A, Pigneur Y (2012) Business model you. LLC, US
15. Pawar KS, Beltagui A, Riedel JCKH (2009) The PSO triangle: designing product, service and organisation to create value. Int J Oper Prod Manage 29(5):468–493
16. Baines TS, Lightfoot HW, Benedettini O, Kay JM (2009) The servitization of manufacturing: a review of literature and reflection on future challenges. J Manuf Technol Manage 20(5):547–567
17. Tukker A, Tischner U (2006) Product-services as a research field: past, present and future. reflections from a decade of research. J Cleaner. Prod 14(17):1552–1556
18. Azarenko A, Roy R, Shehab E, Tiwari A (2009) Technical product-service systems: some implications for the machine tool industry. J Manuf Technol Manage 20(5):700–722
19. Tukker A (2004) Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. Bus Strategy Env 13(4):246–260
20. Cook MB, Bhamra TA, Lemon M (2006) The transfer and application of product service systems: from academia to UK manufacturing firms. J Cleaner Prod 14(17):1455–1465
21. Tan AR, Mcaloone TC, Myrup Andreasen M (2006) What happens to integrated product development models with product/service-system approaches? In: 6th integrated product development workshop, IPD2006
22. Alle V (2002) A value network approach for modeling and measuring intangibles. Madrid
23. Rojas E, Barros A, Azevedo A, Batocchio A (2012) Business model development for virtual enterprises. In: Proceedings of PRO-VE 2012 collaborative networks in the internet of services. IFIP advances in information and communication technology, pp 624–634
24. Copani G, Bosani R, Tosatti LM, Azevedo A (2006) A structured methodology for business network design. In: Proceedings of 12th international conference on concurrent enterprising, 2006
25. Kindström D (2010) Towards a service-based business model—key aspects for future competitive advantage. Eur Manage J 28(6):479–490
26. Allee V (2008) Value network analysis and value conversion of tangible and intangible assets. J Intellect Capital 9(1):5–24
27. Lau HCW, Lee WB, Lau PKH (2001) Development of an intelligent decision support system for benchmarking assessment of business partners. Benchmarking: An Int J 8(5):376–395

28. Davenport T (1993) Process innovation: reengineering work through information technology. Harvard Business Press, Boston
29. Hammer M, Stanton S (1999) How process enterprises really work. Harvard Bus Rev 77(6):108

# Reference Model Framework for Production of Small Series of Innovative and Fashionable Goods in Manufacturing Networks

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**Abstract** In fashion business, consumer needs and expectations of specific target groups—such as elderly, obese, disabled, or diabetic persons—are arising as challenging opportunities for European companies that are asked to supply small series of innovative and fashionable goods of high quality, affordable price and eco-compatible. This paper aims at proposing a reference model to support collaborative supply networks in addressing the need for Fashionable and Healthy Clothing and Footwear products. In particular this work describes the implementation of the model in a real case highlighting the developments and changes implied at network level.

## 1 Introduction

Recent years have stressed the need of re-inventing the enterprise concept and the path to achieve competitive advantage. Moreover, the global financial crisis coupled with the remarkable increase of oil and energy prices has forced managers to dramatically change the way they perform business. The flows of money shrank and consequently the flows of products and services have considerably decreased. Enterprise managers are now forced to address market and especially individual customers with augmented care by putting more emphasis on the service levels they provide, by reducing response times and by tackling customers' specific

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needs. This confluence of trends has led managers moving from a traditional functional focus in the way they conduct business into a more holistic approach in addressing the overall supply chain. As a consequence, it is emerging at industrial level the adoption of collaborative strategies for the production of small series of high-customized complex products with increased emphasis in the service levels and the reduction of the response time. Along this vein, consumer needs and expectations of specific target groups—such as elderly, obese, disabled, or diabetic persons—are arising as challenging opportunities for European companies which are asked to supply small series of innovative and fashionable goods of high quality, affordable price and eco-compatible in short time and with high service levels. In order to design, develop, produce and distribute such products, a new framework, and related components for collaborative networking are necessary.

The main objective of this paper is to describe an innovative Reference Model (RM) for manufacturing networks in the fashion sector and its implementation in a real case to support the production of small batches addressing the specific needs of the consumer target groups considered. The aim of the proposed reference model is to support and guide footwear and garments network stakeholders in modeling, designing and configuring the combination of processes, functions, activities, relationships and paths along which products, services, and information flow in and among companies.

The focus of the model is not on cost optimization strategies but on improving the responsiveness of the supply chain (SC) according to the agile paradigm. When dealing with product customization, the modularization of product components bring to split between standards components, where the focus is on cost reduction and which can be produced in advance and stocked, and other more important components, which are customized ones. These components are crucial for the product characterization and have to be realized according to higher quality levels only when the order for a specific product is made: this requires a deep coordination in the production chain between partners and short lead times. For this reason, in order to optimize the management of these components during design and production, it is necessary to apply the agile model for SC. The definition of the decoupling point is important to define how agile should be the SC and to identify the right partners.

In the following chapters it is presented the Reference Model framework highlighting the addressed methodology, the RM peculiarities targeted on company from the TCFI sector and its instantiation in a specific real case.

## 2 Literature Review

Nowadays competition within the fashion sector is among global networks and the key issues are on how to develop and implement innovative managerial models and methods to support collaborative practices, especially among SMEs, which represents the majority of companies in TCFI [1, 2].

A new level of complexity is arising, given the fact that competition as well as collaboration schemes are transitioning from company versus company, to supply network versus supply network. As a consequence, the management of both inter-organizational and inter-supply chain processes and information is becoming even more critical in order to assure rapid responses, eco-sustainability and quality assurance of products and processes.

Recent research in the field of supply networks addressed different forms of business networks. They are distinguished, for example, by the value chain orientation (horizontal, vertical, lateral), life span (long-term vs. short-term), degree of virtualization or hierarchical structure (hierarchical vs. non-hierarchical networks) [3]. The current market asks for flexible organizational structures, which quickly adapt to new business requirements and sustainability challenges. These new demands are forcing business networks to have shorter life-time existence and take advantage of new infrastructure technologies supporting distributed information systems and knowledge.

The paradigm of demand-driven supply networks is emerging in literature as a collaborative approach answering to consumer's needs and expectations [4, 5, 6]. This implies different approaches to market based not only on traditional sales channels (as shops or retailers) but more and more on an Internet mediated contact with consumers both for product conception and for sales.

At the same time, the market increasingly values collaborative networks that endorse the sustainability challenges. Moreover, as Adler [7] effectively discussed, the new enlarged structures, characterized by high cognitive content exchanges, can no longer be coordinated by traditional hierarchy/market instruments as they require trust to share knowledge and leverage on external, updated and complementary competencies.

After a deep analysis of some of the most important supply network reference models in literature—among others the Value reference model, the SCOR model and the Y-Cim model—the SMART model proposed by Filos and Banhan [8] has been selected as the starting point to map practices to be implemented at different levels along the following three main dimensions:

1. **Knowledge**: to map partners' competencies to be shared within the network in terms of products and processes;
2. **Information and Communication Technologies** (ICTs): to support the requirements for the implementation of ICT services at different process levels along the network;
3. **Organizational**: to provide specifications of the organizational changes for SMEs for structuring supply networks in small series production.

For the scope of this study a new dimension, coherent with the eco-efficiency objective, has been added to the model, namely **Sustainability**. This dimension is intended to support companies aiming to create sustainable networks, in developing an eco-compatible approach for their products and processes.

## 3 Footwear Sector Analysis

In order to conceptually build a structure and validate a reference model framework addressing supply networks for fashionable and innovative products, it is necessary to collect and evaluate relevant field data and perform specific industrial case studies in different sectors and scenarios. The research approach selected is based on empirical fieldwork based on cross-case analysis which was chosen due to its suitability in addressing both qualitative and quantitative data and also social and behavioral aspects.

The considered companies from the fashion sector have been selected both among large companies and SMEs to analyse practices that can be transferred and applied to SME networks. The sample was created adopting theoretical sampling [9], and multiple investigators have been used to reduce bias and produce more reliable data [10, 11]. For each selected company an "AS IS" business process analysis was conducted through focused interviews and BPMN (Business Process Modeling Notation) representation to collect and formalize a rich set of data, both qualitative and quantitative. Furthermore, the requirements of each company were pointed out and analyzed in detail to draw the relevant characteristics, procedures, and techniques along their supply network. Cross-case analysis among the different companies of the same sector, allowed to compare companies' behaviors and understand collaboration mechanisms. For each analysis the four main dimensions of the SMART network model (knowledge, ICT, organizational, and sustainability) have been considered to understand which are the main characteristics of the sector (and also the strength and weakness) along all of them.

The fashion sector is characterized by volatile product demand and need of quick planning and production responses. Footwear in particular presents a really fragmented and rigid scenario, constituted by many specialized knowledge intensive companies most of the time grouped in industrial districts. Each phase of their production process is deeply characterized by traditional approaches always oriented to batch quantities and local maximization [6]. Based on the previously defined four dimensions, the cross-case analysis for the fashion footwear companies resulted in the following outcomes:

**Knowledge**: innovation is strongly customer driven, and especially in the latest years companies started to manage smaller production lots with a higher level of customization (based both on aesthetic and functional features) to face competitively the market. Evolving customer needs influence production with requests of personalization and customization affecting components and/or materials, but not the structure of the products, thus according to the "best fit" approach. Design capabilities and an established know-how on production techniques owned by companies represent an important competitive advantage for them.

**ICTs**: manufacturing processes of fashion footwear companies are more and more supported by CAD based design starting from the 2D drafts creation to the 3D development of models and sizes. Other production activities are also supported by IC technologies, for example the laser cutting and leather marking.

However, several other phases, in particular concerning the smallest companies, are still characterized by traditional approaches and a huge effort is necessary to drive improvement towards automation and real-time monitoring along networks.

**Organizational**: Long-term relationships are established and suppliers are involved in the design phase and during product industrialization, since each of them has to develop its own component according to the information received by the shoe producer. Suppliers provide both standard components and exclusive products (i.e. soles and heels can be patented). Several phases of the production processes are commonly outsourced: cutting, stitching and often final assembly. Companies develop a strong relationship with their outsourcers as well to guarantee the highest quality level to their customers, and benefit from their availability and flexibility along the season, according to collected orders variation.

**Sustainability**: large enterprises have started to implement sustainable practices moving to eco-products and eco-processes. Nike, for example, developed an environmental apparel design tool to create eco friendly products; Adidas implemented a test to check the sustainability of raw materials and Timberland developed a Green Index to compare the environmental impact of their products.

## 4 Reference Model Framework for Manufacturing Networks

The proposed Reference Model (RM) Framework aims to support fashion companies in defining collaborative networks for the production of healthy and fashionable products and is based on matching theoretical approaches from literature and emerged needs from the analyzed business cases along three different levels: strategical, tactical, and operative. Figure 1 presents the overall conceptual view of this proposed RM mapping its three decisional levels with the four structural dimensions.

For what concerns the strategic level, the business model framework proposed by Osterwalder [12] and extended by Loss and Crave [13] in combination with the model improved by Romero et al. [14], and integrating also approaches from Plantin [15] to fit to Collaborative Networks, is here applied. This model maps the most important building blocks that influence the definition of the value proposition when working in networks. In Fig. 1 the scheme of the model is represented.

In the RM strategic level, a set of characterizing elements for the adequate definition of the supply chain strategy for fashion SMEs based on the data collected in the cross-case analysis and the related research literature were identified according to the dimensions of the building blocks.

In the tactical level of the RM, the most important processes critical for the implementation of the business model have been identified according to the requirements mapped in the business case analysis. These processes have been formalized according to the Business Process Model Notation (BPMN). At the

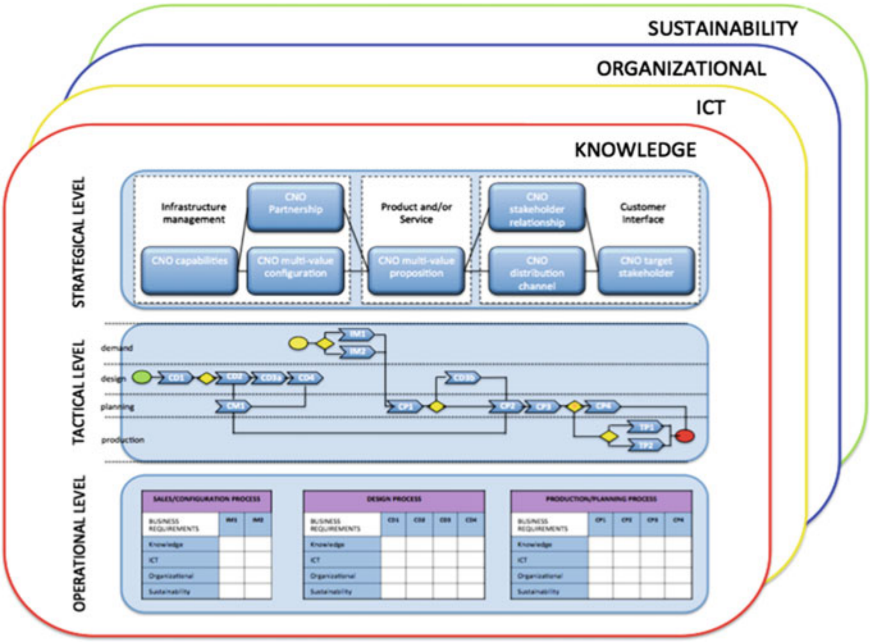


**Fig. 1** Reference model context diagram

tactical level a high level view summarizes the whole process flow, highlighting the sequence and the interrelations between the different sub processes involved in each phase. Moreover a set of tools to support collaboration between the different stakeholders of the network, both from the customer side (B2C) and from the supply chain side (B2B), are also mapped along all the business processes.

The operative level guides companies in the implementation of the business processes with specific practices, KPIs, templates and all information, and materials useful to support the processes considered and the management of all related activities.

## 5 Implementation of the Model: A Case Study

This section presents the implementation in the footwear industry of the RM as an application example. The model can be instantiated to different types of business, both traditional companies, where relationship with customer passes by retailers and distributors, and companies with on online business (B2C), where the direct contact via web gives the possibility to create easily new configuration spaces and to understand customer's needs without intermediaries. The most important features of the reference model are here described for a footwear traditional company.

In order to apply the Reference Model developed and presented in the previous paragraphs it has been chosen a worldwide company operating with own brand in the footwear fashion market, which main products are highly refined shoes for women. This manufacturing firm externalizes some production phases (around 100 partners, both suppliers and outsourcers) maintaining the core competences along the supply network (i.e. design skills for shoes and components, manufacturing skills and distribution channels) and adding the most of the value to the final products. Customization nowadays regards only aesthetical and material configurations. For these reasons it could be considered as the starting point to build up the whole supply network. We will refer to this company as company A in the following sections.

## 5.1 Strategical Level

The work consisted in the definition of the business model of company A network according to the different building blocks identified in the strategic level of the RM and in the identification of the implications on the supply network. In the table below a short summary of the most important characteristics related to the building blocks of the new business model is depicted as a guideline for companies of the fashion sector. For each building block it is shortly described which are the dimensions to be involved in the process to allow a fashion company to enter a market segment to offer innovative and fashionable products for target groups like diabetics, elderly, and obese people (Table 1).

## 5.2 Tactical Level

The tactical level has been instantiated to the footwear scenario according to specific requirements and needs collected and analyzed with the company and all the partners of the collaborative network. Within the whole process flow five different phases have been identified and analyzed, namely Market interaction, Collaborative design, Development and Customization, Network configuration, Supply network co-planning, and coordination and Customized production. Table 2 here below summarizes, as an example, the different processes included and the related four dimensions considered in the model for two of them, highlighting for each process, the actors involved as well as the tools used. An innovative aspect considered in the Reference Model is the capability to consider the interaction with customer (even end-consumer) during product design and configuration and the strict collaboration both with suppliers and technology providers all along the process flow.

**Table 1** Implementation of the strategic level

| Building blocks | Dimensions (organizational, ICT, knowledge, sustainability) |
|---|---|
| Target stakeholder | Target stakeholders are Podiatric centers and retailers already selling orthopaedic shoes. In the long term there can be multi-brand independent retailers selling specific TG shoes together with dedicated shoes.<br>To reach the stakeholders, companies need to focus on improving ICT dimensions with new tools to support customers during the sales process, both in shop (foot measurement, product configuration) and online sales. Moreover knowledge dimension needs to be reinforced with a deep analysis of the target groups requirements |
| Multi-value proposition | Footwear with fashion and functional features specific for each target groups. The multi-value proposition is based on the collaboration of all the stakeholders for the design and realization of the new product concept. The multi value proposition implies the transversal application of new approaches along the four dimensions: knowledge—ICT—organizational—sustainability |
| Distribution channel | Distribution channel can be based on:<br>• existing and new retailers (big/small)<br>• Own shops<br>• Podiatric centers<br>Distribution channels need to be improved both in terms of organization (closer relationship to collect customized orders) and in terms of ICT dimension since it implies the application of new tools for product configuration allowing customer from TGs to have dedicated configuration space taking into consideration the specific requirements both in terms of functional and aesthetic variants of the product |
| Stakeholder relationship | Creation of trusted relationships can be achieved having a clear and updated vision of market needs and building an effective communication channel with customers. This can be done with a set of structured actions able to continuously monitor and take into account customer inputs and needs in the development of new functionalities for the company's products<br>Fidelity card can, for example, be considered a way to improve relationship with customers in shops, it can be used also to collect info about customer behavior. Moreover it is necessary to provide clear and reliable information on products and their characteristics (for example on sustainability aspects)<br>Beside improvements in the Knowledge dimension, the ICT dimension needs to be reinforced along the CNO, and this can be realized through direct electronic communication to end-consumer using internet interface and feedbacks<br>From the sustainability side information on environmental impact of product and processes collected and structured have to be accessible and included in the product data |

(continued)

**Table 1** (continued)

| Building blocks | Dimensions (organizational, ICT, knowledge, sustainability) |
|---|---|
| Capabilities | Capabilities to be created in the CNO are: (1) services to members like brokering, marketing services, market trends analysis (2) provide a common base ICT infrastructure; (3) Support cooperative business rules; (4) Offer assets (especially ICT and knowledge based) that will be shared by members as for example services for supply network management; (5) Evaluation, qualification and certification of members; and (6) Manage the organization and its infrastructure<br>Reinforcement of the Knowledge and ICT dimension of the CNO based on data coming from different partners of the CNO itself, both sales data from retailers and market trends from stylists, and social networks management<br>Capability to measure customer requirements is based on advanced systems for dynamic measurement used at shop level. Knowledge dimension is very important at this stage because it influences the capability of the network. For what concerns sustainability, capabilities are related to network process monitoring and integration of green production practices |
| Multi-value configuration | Configuration of the value can be based on financial, technological, knowledge, and social issues. In this case it is based mainly on technological innovation for the product development and its realization as well as on social value given by the possibility to address target groups with new products improving their life conditions both in terms of health and social inclusion<br>The configuration of the new product value is based on the collaboration along the CNO of many different actors as stylists, designers, production managers, as well as external professionals as medical experts bringing their Knowledge on the TGs. Change the CNO configuration (organizational dimension) involves all the actors of the CNO also for sustainability evaluation |
| Partnerships | Different partners are necessary to cover some phases of the process activities; partners are involved in standard as well as customized production and are selected according to their skills, equipment, reliability, and costs<br>Periodically (at the beginning of the season or yearly), long term relationships should be activated with strategic suppliers and outsourcers. Production of customized components should be based on framework agreements which allows to activate time by time each partner according to customer needs<br>The dimension involved in network formation and coordination is mainly organizational. Also ICT infrastructure (such as integrated software or machinery) is important in order to support network formation and management |

(continued)

**Table 1** (continued)

| Building blocks | Dimensions (organizational, ICT, knowledge, sustainability) |
|---|---|
| Cost | Main costs arising are on the technological innovation of the product (search of new components and new materials) and new processes for the development of customized components. From the ICT point of view companies are not required to install any new tool but to use tools available on a SaaS (Software as a Service) approach<br>Costs definition is based on the organization of the CNO and how partners interact each other<br>Cost will be mainly for improving the ICT base of the network in order to manage the partnership. Each company in the network will pay a fee to use a collaborative platform where many different tools to support the various stages of the design and production will be included |
| Revenues | Revenues for the CNO are both from the sales of the products and from the related services. Putting together competencies, companies can enlarge revenues and the model to be applied can be based on sharing them along the value network<br>Also in this case the organizational dimension is the most important one because it is important to define clearly relationships along the processes and related responsibility in order to allow a proper sharing of revenues along the CNO according to given contributions |

## *5.3 Operative Level*

For what concerns the operative level, as an example, this chapter gives some hints on one of the processes of the tactical level, highlighting how to support the supply chain configuration phase in CM1 (Partner Search) with operative tools like partner profiling based on selection of intelligent indicators. Similar work has been done for all the other business processes developing tools and defining specific practices for each step.

Small series and customized products require new supply network management tools, able to support companies in collaborating with specialized partners, enabling to configure specific networks for each covered market niche, or, even, for each customer order, in case of personalized products. According to that, a company have to face different scenarios characterized by a very large number of small orders, each of them involving different partners, selected on the basis of their availability and capabilities. In this context, the process of partner profiling and monitoring, as well as the collaborative planning process, need to be supported by a partner search service based on easy to retrieve, easy to manage and reliable information. According to the needs of the analyzed companies and literature a set of KPIs have been defined for all the dimensions identified in the framework represented in Fig. 2 to be used for a multi-criteria partner search and selection.

**Table 2** Example of the business processes of the tactical level

| Phase | Organizational | ICT | Knowledge | Sustainability |
|---|---|---|---|---|
| | Processes and actors | | | |
| Network configuration | CM1—*Partner Search and Selection* Supply chain manager identifies best suppliers and outsourcers to assign them production phases and materials | Network configuration service | Standard (technical) selection criteria, e.g., capability and capacity as also quality, flexibility, reliability, and costs | Cooperation with customer to implement pollution preventive technologies |
| Supply network co-planning and coordination | CP1—*Customer order processing* Sales department validate orders and administrative info are sent to accounting department; then they are aggregated by production department | Workflow management | Analysis and translation of the product configuration information into the production data; Orders aggregation rules | Acquisition of supplier availability |
| | CP2—*Collaborative process planning* Production manager assures the delivery of business documents integrating standard product data and specific order info to suppliers and outsourcers | Workflow management | Fixed product and process data (already stored in the PDM system as generic BOM and working cycles) and "customer order" specific data which must be provided coherently structured | Collaboration/integration with partner to implement pollution preventive technologies |
| | CP3—*Collaborative production planning* Production manager negotiate production order schedule with suppliers and outsourcers to minimize costs and times | Collaborative planning service | Assessment of the availability of partner with the possibility for quick adaptations. Knowledge is also needed for handling exceptions | Sustainability based KPIs in the evaluation of partners |
| | CP4—*Partner monitoring and control* Production manager assures suppliers and outsourcers monitoring | Quality monitoring service | Set of KPIs (ontology, vocabulary, etc…) that define different aspects related to quality and sustainability | Implementation of environmental performance indicators |

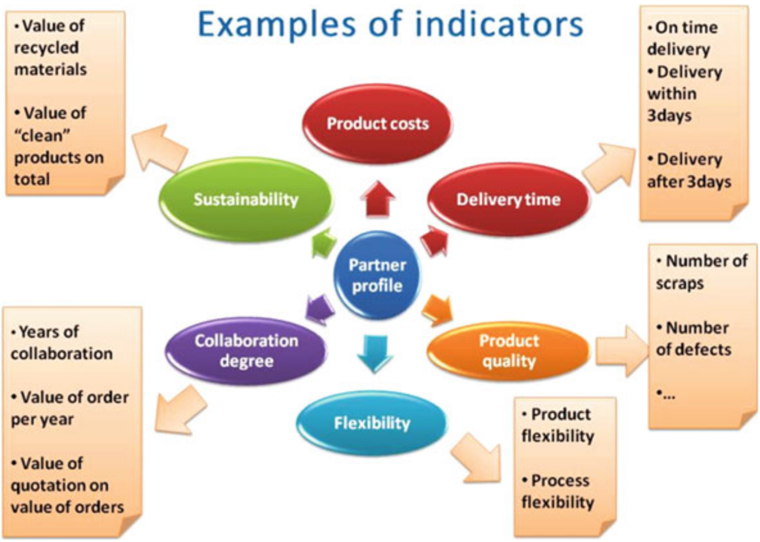


**Fig. 2** Example of framework for the definition of partner profile

## 6 Conclusions

This work proposes a RM framework to create innovative collaborative environments enabling European fashion companies to produce and deliver small series of specialized and customized high value added products. The industrial and empirical nature of the RM framework guarantees full applicability of its guidelines.

In particular, the RM represents a formalization of a methodology that can be applied to companies with the support of methods and tools for product design, planning, production activities, and rapid manufacturing technologies. The RM aims to facilitate supply networks in managing consumers' data to understand their needs, involve consumers in product design and configuration, exchange consumers' data through adequate data models and secure systems, collaborate with suppliers, implement innovative manufacturing machines, monitor quality, and sustainability of products. The model has been applied to a real case of a fashion company willing to enter a new niche market. The instantiation made according to the three different levels of the RM started with the definition of the new Business Model and the description of the most relevant dimensions involved in its application concerned with the strategic level. Then the model enabled a revision and a formalization of the main business processes at the tactical level and provided operative support to this processes. In particular, the case of the partner profiling process is reported as an example to show how specific practices and guidelines can support the proper process implementation. Feedbacks collected from companies allowed to make a refinement of different aspects of the RM.

For what concerns the specific implementation in the considered business case, even if the collaboration processes are still under revision, some improvements have already been reported by the network companies: the capability to increase the level of coordination among partners, the capacity to involve consumers through specific requirements included in product design and configuration all over the supply chain and the increased ability to monitor quality and eco-sustainability of products in the network (in terms of amount of information available on materials, production process, and practices along the network).

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## References

1. Dyer JH, Singh H (1998) The relational view: cooperative strategy and source of interorganizational competitive advantage. Acad Manage Rev 23(4):660–679
2. Camarinha-Matos LM, Boucher X, Afsarmanesh H (2010) Collaborative networks for a sustainable world. In: Proceedings of the 11th IFIP WG 5.5 working conference on virtual enterprises
3. Grefen P et al (2009) Dynamic business network process management in instant virtual enterprise. Comput Ind 60:86–103
4. Childerhouse P, Aitken J, Towill DR (2002) Analysis and design of focused demand chains. J Oper Manage 20(6):675–689
5. De Treville S, Shapiro RD, Roy D, Hameri AP (2004) From supply chain to demand chain: the role of lead time reduction in improving demand chain performance. J Oper Manage 21(6):613–627
6. Piller F, Tseng M (2003) New directions for mass customization. The customer centric enterprise. Advances in mass customisation. Springer, New York
7. Adler PS (2001) Market, hierarchy and trust: the knowledge economy and the future of capitalism. Organ Sci 12(2):215–234
8. Filos E, Banahan E (2001) Towards the smart organization: an emerging organizational paradigm and the contribution of the European RTD programs. In: Journal of Intelligent Manufacturing, vol 12(2). Springer Netherlands, pp 101–11
9. Glaser B, Strauss A (1967) Grounded theory: the discovery of grounded theory. Aldine, Chicago
10. Eisenhardt KM (1989) Building theories from case study research. Acad Manag Rev 14(4):532–550
11. Yin RK (1994) Case study research. Design and methods. Sage, Thousand Oaks
12. Osterwalder A (2004) The business model ontology a proposition in a design science approach. PhD-Thesis, Lausanne University, Switzerland
13. Loss L, Crave S (2011) Agile business models: an approach to support collaborative networks. Prod Plan Control Manage Oper 22(5–6):571–580
14. Romero D, Galeano N et al (2006) Towards the definition of business models and governance rules for virtual breeding environments network-centric collaboration and supporting frameworks, vol 224. Springer, Boston, pp 103–110
15. Plantin S (2008) Orange labs R&D internal methodology for building business models

# Customer Service in Supply Chain Management: A Case Study

**Fatiha Naoui**

**Abstract** ***Purpose*** The purpose of this paper is to present a case study to assess the customer service concept within the internal supply chain management (SCM) approach. In particular, the paper emphasizes an interest in an integrated approach to considering customer service performance in an efficient way. Indeed, information systems as technical support play an essential role in the SCM of small and medium-sized enterprises (SMEs). The customers are the first concern of any firm that seeks to be competitive. ***Design/methodology/approach*** A qualitative research methodology is used based on semi-directed interviews with SME telecommunications professionals and direct observation as part of a telecommunications network SME in France. ***Findings*** In total, the objective of this empirical case study is to delineate the concept dimensions (background). These dimensions allow the drawing up of a framework of actions to improve SME customer service performance evaluations in the supply chain management. ***Practical implications*** This proposal will help to the picture regarding services for improving the relationship with the customers (by commercial and Project Manager reporting on customer follow-ups); improve operational reporting (internal indicators, quality reports); improve invoice control and indicator follow-ups with the Project Manager; and improve cost management. ***Originality/value*** The paper adds a new case study—that of Alpha—which is focused on the engineering and telecommunications network. As such, it offers a new perspective that customers are among the major actors in the telecommunications market, along with the corporate customers and administrations involved in implementation or service quality follow-up and telecommunications use.

**Keywords** Supply chain management · Customer service · Performance antecedents and measurement

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For confidentiality reasons, the SME will be referred to as "Alpha".

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# 1 Introduction

Changes in worldwide market behavior require an agile answer from a company and its partners in a supply chain. Nowadays, companies' campaigns in the various markets are concerned with services which integrate fast delivery and friendly contact with their customers. The cost strategies have become options which are easily imitable by competitors, so companies do not represent differentiation for the customer [1–3]. From this point of view, observers are increasingly numerous in stressing that products offer few competing advantages in themselves and that, in fact, service provides a major differentiation [4]. The importance attached to customer service also finds justification in strong competitive pressures, which are translated, in particular, by increased customer requirements regarding a company's capacity to coordinate matters and information flows, from raw materials acquisition to its after-guarantee policy, after-sales service and maintenance [5]. Customer service takes its support from logistics. In other words, the capacity of a company to coordinate matters and information flows, from raw materials acquisition to after-sales service. For managers, customer service appears from now on to be one of the main sources of competing advantage which companies can offer; which, moreover, explains its place in the new concerns of the logistic function [6]. Indeed, if the service quality offered to customers has been associated long enough and naturally with the marketing function concerned, it constitutes more and more one of the logistic stake steps [7]. In this way, the role that organizational size plays in determining adoption rates of total quality management is important (Haar and Spell [8]). Two research questions guided this inquiry. The primary question is which are the antecedent variables of customer service performance in a small to medium-sized enterprise (SME) supply chain approach? The secondary question is what are the principal indicators (key performance indicators [KPI]) for evaluating "Alpha" customer service performance? This study provides both theoretical and practical contributions. The article contains four sections. First, the literature is reviewed from the supply chain management (SCM) customer service notion and customer service performance measurement logic. Second, an explanation of the case study methodology is provided. The next section presents the results and offers some recommendations. The final section covers implications for future research and its applicability for practitioners.

# 2 Literature Review

## *2.1 The Supply Chain Management Concept*

Many SCM definitions are presented in the literature. This section is organized as follows. First, clarification is given of the supply chain's strategic and integrating role. Second, the World Class Logistics (WCL) model is presented. The section ends with a brief discussion of the structure of Supply Chain 2000. **The supply chain strategic and integrating role**: Several academic researches highlight the logistics essential role, considered as the origin of the SCM process [9]. There are four mean uses of the term supply chain management. First, the internal supply chain that integrates business functions involved in the flow of materials and information from inbound to outbound ends of the business. Secondly, the management of dyadic or two party relationships with immediate suppliers. Thirdly, the management of a chain of business including a supplier, a supplier's suppliers, a customer and a customer's to customers, and so on. Fourthly, the management of a network of interconnected business involved in the ultimate provision of production and service packages required by end customers [10]. Mentzer [11] defines SCM as a set of three or more companies directly linked by one or more of the upstream and downstream flows of products, services, finance, and information from a source to a customer. Mentzer et al. [12] propose SCM as systemic, strategic coordination and the tactical management of the actions within the departments of a particular organization, as well as business carried out inside the chain for provisioning the organization as a whole. The network of organizations is required, through bonds upstream and downstream and in various processes and activities, to produce value in the products and services held in the hands of the ultimate customer [13]. Added to this approach are three competitive advantage factors: reliability, responsiveness, and relationship [14]. The reliability of an organization is dependent on the need to guarantee a delivery which is complete and on time; responsiveness is an evaluation of the capacity to answer within the shortest possible time, with the greatest flexibility; finally, the relationship factor stresses the importance of partnerships in the implementation of continuous improvement in matters of quality, innovation, reduction of costs and adjustment of the delivery logs. In the same way, every sensitive company must engineer a major reorientation of its management system [15]. Thus, a company must modify its organizational diagram according to three points: (1) to change from a system in terms of functions to logic in respect to process. This means that the company must regard the horizontal character of the structure as a unit of inter-functional processes based on the requirements of the customer; (2) to change from a profit concept to a performance concept. This point underlines the obligation to provide financial and non-financial indicators; (3) to change from product management to customer management. The satisfaction of the customers must be the ultimate objective of any commercial organization, and it is imperative that the structures of management and the systems of measurement are also reflected [15]. **The World Class Logistics model**: The model provides a nomenclature in four key dimensions. Initially, strategic positioning selects the strategic and structural approaches. At the second level, integration establishes what is advisable to do and how to carry it out with reactivity. At the third level, agility is intended, like aptitude, to achieve and maintain competitiveness as well as to obtain the confidence of the customer. The criteria of anticipation, adaptability and flexibility attempt to answer this field of performance. It is a question of remaining aware of customers' unexpected requests, while being able to decrease the response time for such exceptional requests. This highlights the adaptability of a structure to all unexpected circumstances. Finally, at the fourth level, performance measurement evaluates the internal and external logistics chain. A company determines choices of static and dynamic internal indicators, enabling it to refine the process of supply chain evaluation by benchmarking techniques which enrich and diversify the evaluation modes. **The structure of Supply Chain 2000**: This structure proposes a sequential step, since the reasoning proposes the relations and methodologies to apply to reach step-by-step coordination between the individuals and organizations involved in an SCM step [16]. In other words, from a methodological point of view a sample must seek to gather internal and external actors who revolve around the same finality of a product or service design. This structure seeks to clarify the understanding of SCM as a step in strategic management. Other works specify certain features of SCM, such as the role of information systems, confidence and power in inter-organizational exchanges. **Information technologies supporting logistics and SCM**: [17] focuses on three areas. Firstly, the decision-making axis stresses the integrative aspect (operation-tactical and strategic). Secondly, the extended enterprise axis defines the external transversality external impact. Finally, the operational axis emphasizes the internal transversality role. (Table 1)

The essential element in this presentation is the issue of information system interoperability and the role of information technologies in SCM performance evaluation. Moreover, it appears that the SCM approach reinforces the relationship between competitors and partners [18], as well as different modes of cooperation (strategic outsourcing, business networking, joint ventures, and strategic alliances) between stakeholders (Miles and Snow 1989; [19]. Unquestionably, this cooperation is facilitated by efficient and compatible information systems. Nevertheless, the benefits of some areas of enterprise resource planning (ERP), for example, are still to be understood by stakeholders [20]. Indeed, the factors that influence ERP benefit realization fail to differentiate between some factors that may influence the realization of these benefits, such as size and type of company, the ERP system implemented, and the organizational context [21].

**Table 1** SCM: steps and information technologies

| Step | Origins | Tools |
|---|---|---|
| Decisional axis | Consistency and speed of decision-making flow | Decision support technology |
| | | APS (advanced planning system) |
| | Performance measurement | SCM tools, data warehousing databases |
| Extended entreprise axis | Cooperation, communication, partnership, and commitment monitoring | Interface technology, electronic data interchange, the Internet, intra and extranet, efficient consumer response, call centers, and managed inventory |
| Operational axis | Customer and shareholder satisfaction | Monitoring technology, entreprise resource planning, manufacturing, and logistics execution systems |
| | Monitoring, evaluation, and integration of the major processes | |

## 2.2 Customer Service Review

This section is organized as follows. First, a basic definition of customer service is provided. The various customer service components (along a continuum) then follow. **Various definitional approaches**: The customer service definition influences the company performance mode of evaluation [22]. In most companies, customer service is defined in three different ways [23]: as an activity (to manage litigation, invoicing, etc.); as a performance measurement (the capacity to deliver 95 % of the orders in 48 h); and as a philosophy and strategy element of the company. The definition of customer service varies from one company to another. Customer service is a process which takes place between the purchaser, the salesperson, and the intermediaries. This process leads to added value for the produced or exchanged service. This added value can arise in the short run in a simple transaction or in the long term as in a partnership contract. Thus, customer service is the process by which significant advantages are reached in a value chain and in an effective way [23]. The implementation of the marketing concepts involves being able to keep customers by increasing their satisfaction. This makes it possible for a company to invest in the long term in the acquisition of new customers. In this direction, customer service is the capacity of a company to answer a customer's order starting from the stock available. If the order is not fulfilled, a rupture results [24]. It is the supply chain which takes part in the total product definition. **The customer service component**: This continuum relates to a process made up of three activity levels: pre-transaction, transaction, and post-transaction elements [22]. **Pre-transaction elements** concern the means by which a company effectively offers a service to its customers. It is about the structural design and piloting systems which ensure progression in relation to customer service operations. The customer will never be aware of these elements, but a bad proportioning of each one of them can have significant consequences for the two other levels of transaction. The customer service policy statement: this is a written engagement of the customer service policy based on an analysis of needs and a definition of standards; it determines the customer service performance measurement in accordance with which frequency, so that this written engagement can become operational. Diffusion near the customers: a written engagement reduces the probability that customers will expect unrealistic performance; however, it also provides them with the means of communicating with the company if the levels of performance specified are not reached. The organizational structure: although there is no typical organizational structure for each customer service policy statement, the selected structure must facilitate communication and cooperation between the functions involved in written customer service engagement. Moreover, the company should provide its customers with the individual names and telephone numbers of services designated specifically to satisfying their information needs. The people who manage the customer service components must be invested with responsibility and authority (empowerment), and financially compensated in a manner in which they are actively encouraged to manage the interfaces between the various functions of the company (reward system). Flexibility and services: system flexibility is necessary for answering non-anticipated events such as strikes, snowstorms or shortage of supply. Training and meetings will make it possible for a company to improve its integrated management of customer service. The whole of these elements constitute an essential component of the logistics strategy. **The transaction elements** are those which link the exchanges between the customer and the organization. It is on this level that the customer starts to evaluate the company service performance. Normally, these elements are directly associated with the traditional customer service concept. Out-of-stock level: this is a direct measurement of product availability. In the case of a shortage of stock, the satisfaction of the customer can be safeguarded either by offering a substitute product higher in conformity with a very attractive price, or by dispatching the product with the delay compensated by an advantage. The role of strategic stock in the supply chain: strategic stock is the stock which one must maintain in order to satisfy any request higher than the quantity scheduled for a given period. This varies frequently in many situations because the forecasts are rarely right. The inventory control system must face hazards of several natures [24]. Service function: commercial function aims to ensure the customer an immediate delivery. This function is as present in the retail stores as in the factories which deliver standard articles to a distribution network. When the delivery period is shorter than the product production or procurement lead time, it is necessary to anticipate the customer order. Information regarding the order: this is a question of communicating with the customer in a fast and precise way the stock levels, the progress report of the order, the dispatch and delivery dates, and the follow-up of orders. The management of a back order and a total order cycle time constitutes an essential performance measure. Order cycle is the total time necessary between the order initialization and the complete delivery to the customer. The components of the order cycle include order reception, implementation, handling, packing, sending, and information flow. The customer being mainly concerned with the total order cycle time, it is essential to have data-processing follow-up, making it possible to locate any variation in the components defined. Expedition: although the expenses of fast (sending) shipping are higher, it is particularly significant to identify the customers who will profit from this specific service; it is a logistics management role to define a coherent policy to permit customers to contribute to rapid expansion. Systems precision: the precision of the product quantities and categories is as significant as invoicing precision. Errors can be very expensive, in terms of litigation or the quality of customer relations. The gaps must be the subject of a report. Product substitution: substitution can improve customer service. It takes place when a product must be replaced by another in order to bring an equivalent or higher level of satisfaction to the customer. To develop a policy of coherent substitution, the company must maintain good relations with the customers to inform them and gain their consent. The company should keep a trace of the market products involved in the substitution in order to manage performance and try to improve it. The key element of this policy remains good communication with the customer. **Post-transaction elements** relate to the company capacity to support customers once they have bought a product. Installation, guarantee, and repair: these elements can make up a key factor of a purchase; they should be evaluated with the same care as the elements of customer service during a transaction. It is necessary to provide assistance in the following: the installation of a product or, at the very least, to check its correct operation before the consumer uses it; the availability of repairers and replacement parts; documentation and handbooks ensuring the repairers' performance; and an administrative office which manages the guarantees. Complaints and returns: policies and procedures should thus specify how to manage possible requests, complaints and returns. The company should conserve the information relating to these aspects, as it can help develop products and their logistics. Replacement of a product: in certain circumstances, a product can be replaced temporarily while a customer waits for an order delivery; a replacement product can also be provided during repair as an element of customer service. These elements belong to the customer service support after the sale of a product.

## *2.3 Performance Evaluation Review*

Traditionally, performance is considered from a financial point of view where the satisfaction of the shareholders, as recipients, is privileged [25]. However, more and more research conceives of a multi-criterion and multi-dimensional evaluation in which the interests of all the actors are integrated [26]. **Performance piloting: The polysemous concept**: The subjacent assumption of performance piloting approaches the problems of the formulation of operational and strategic measurements according to a multi-dimensional vision (as in [27–30]). The manager must face other groups of actors (in addition to the shareholders) in the organization. These represent the authorities, investors, political groups, customers, suppliers, communities, employees, and the property owners' organization [27]. This relationship is obvious when, for example, customers appreciate products of quality and are ready to guarantee the safeguarding of the ecosystem. In the literature dealing with performance, the presence of a statement of a series of indicators is omnipresent. The indicator can be appreciated from several angles. First, it undergoes a classification. Lynch and Cross [29, 31] refer to financial and non-financial indicators. Financial indicators relate to the countable system of costs and non-financial indicators, putting forward a countable management of the objective and gaining support for decisions relating to strategic actions and training [31]. In addition, indicators are qualitative and quantitative. For example, [32] isolate eight qualitative topics from non-financial indicators which are, respectively: the quality of the product and the processes; satisfaction of the customer; cycle time (lead times, delivery, etc.); human resources; productivity; inventory control; innovation; and flexibility. **Performance measurement: The pyramid model**: Performance measurements are attached to a company's vision. In fact, they are useful primarily for measuring the achievement of the strategy objective in order to concretize the company vision. Each sector of the company, each function and each action must ideally be based on this strategy. Customer service, *a fortiori* by its strategic character, does not escape this rule. It must thus be evaluated from every angle necessary. **Efficiency and effectiveness: The concept of appreciation**: Efficiency and effectiveness appreciation develops the distribution between external effectiveness and internal efficiency. This point takes as its basis of reflection the arguments formulated by the performance pyramid. By preserving the framework proposed by [29], it is possible to propose a group of indicators which covers the multi-dimensional nature of customer service. Accordingly, it is obvious that the customer service quality offered is the result of the quality of service of the actors intervening throughout the logistics chain. By nature, the performance of an organization, or the performance resulting from relations between several organizations, requires evaluation starting from multi-dimensional and multi-criterion measurements able to respond to the expectations of each actor. In the literature review, fortunately, a growing number of models proposes management tools which take this reality into account. It is thus significant that companies can not only measure the quality of their customer service, but can also find in their working procedure an explanation for their performance. In other words, it is a question of operating a judicious reading of the realization of services, justified by the interdependence between all the components of the logistics chain of a company. Recourse to a combination of indicators of process and result is then impossible to circumvent [33]. The inherent advantage in such an approach is, certainly, to make it possible for a company to judge in a relevant way the performance generated by its logistics process and, therefore, to locate this performance compared to that of its competitors and to obtain a means to improve it.

## 3 Methodology Adopted

The methodology is approached through the following points:

### *3.1 Alpha SME's Presentation*

Alpha is an engineering and telecommunications network SME. It was created in 1999 and selected by the Regional Council (organization that creates the conditions for a harmonious growth of the whole territory in France) to perform measurement campaigns accessibility rates and coverage of mobile operators. Alpha thus carried out a number of national and international projects thanks to its real expertise in the radio and transmission fields. Interview extract: "We provide the service to the operators and the manufacturers. This service is radio engineering and transmission. We also perform network quality measurements for the local

**Table 2** Alpha's principal customers

| Operators | Equipment suppliers |
|---|---|
| Bouygues telecom; orange; neuf cegetel; and SFR | Siemens; nokia; and alcatel |
| Administration | Prime contractors |
| RATP; regional council | Sofratev; INEO; and Graniou |

communities. We have two types of services, technical services and set fixed price" (CEO). This case has a role in measuring service quality networks, technical installations, auditing, control, testing, validation, and the receipt and assumption of network evolution responsibility. Alpha's expertise lies in its set price services. These set price services are organized according to project mode, in a "made- to-measure" approach. Alpha defines with its customers the conduct rules of the responsibility limits, information exchange flows, contacts, documents, etc. All these points are formalized in a project quality insurance, which is a specific contractual document (Quality assurance plan). Alpha deals with project realization and engages with the result. Two complementary approaches are used: technical and manual measurements. The technical measurements make it possible to characterize the network performance cover. The manual measurements assess service quality from beginning to end. The following table presents the Alpha customers and partners (operators, equipment suppliers, administration, and prime contractors) (Table 2).

### 3.2 Why Case Study?

A case study is but one of several ways of conducting social science research. In general, case studies are the preferred strategy when "how" or "why" questions are being posed, when the investigator has little control over events, and when the focus is on a contemporary phenomenon within some real-life context. In order to discover certain antecedents of the customer service performance within a supply chain management approach and to propose Alpha's performance measurement indicators, we undertook a qualitative study based on 11 interviews.

### 3.3 The Choice of Interviewees

The staff members questioned have been confronted with many customers (corporate customers) during their professional experience. Those who are no longer in contact with customers have a thorough knowledge of them and are interested in the SCM steps. Finally, Alpha's small size and structure facilitated us in our access to the various interviewees (Table 3).

**Table 3** Sampling and data collection

| Interviewee's post | Number of interviewee |
|---|---|
| Chief executive officer | 1 |
| Project head | 2 |
| Consulting engineer | 1 |
| Network engineer | 1 |
| Salesperson/HRM | 3 |
| Telecom. Engineer | 2 |
| Computer engineer | 1 |

We chose to conduct semi-directed interviews. They were held starting with a flexible interview guide which was defined as a preliminary. Several themes were approached. The use of a tape recorder was necessary to allow transcription of the interviews. The interlocutors were not reticent regarding the use of a tape recorder. We also took notes and transcribed under the 48 h following the interview. The interviews lasted one-and-a-half to two hours. All the interviews started with a general question. We let our respondents approach the questions freely, while endeavouring to allow them to go further in relation to potentially interesting points [34]. The realization of the interview guide was undoubtedly the most delicate phase of the qualitative analysis because it is a question of discovering the antecedent variables of the customer service performance within the Alpha supply chain approach. Finally, the interview guide was composed of supply chain management questions and customer service and performance measurement questions.

### *3.4 Secondary Data Collecting and Content Analysis*

We also collected throughout the study various documents allowing us to increase our analyses. They were mainly newsletters, website information, and informal interviews. This step was inspired by Miles and Huberman's typological analysis [35]. To condense our qualitative data, we carried out a coding of the interviews. The interview analysis was carried out starting from a categorical analysis of a set of themes on the sense units presented in the interview guide. Categorical analysis is a powerful device for data condensation, whose fundamental principle is the regrouping of similar objects under a common title or class [36].

## 4 Results

In this section, we describe the findings regarding Alpha's supply chain management vision in answer to the first interview question: What are we saying when we talk about Alpha's supply chain management? The vision arises from the respondents' comments as mentioned below.

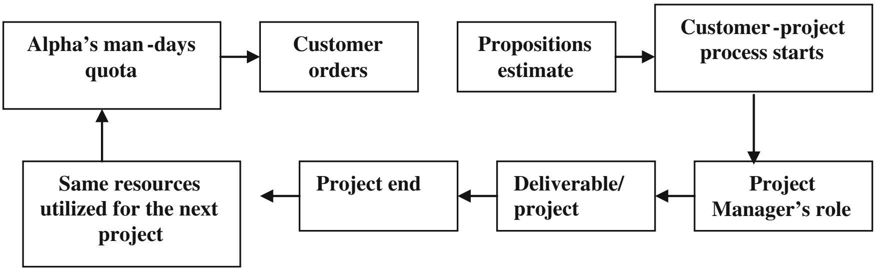


**Fig. 1** The alpha SCM process

### *4.1 SCM as a Transverse Services Process*

Interview extract: "The supply chain which concerns us is more that of services. All other logistics, equipment measurements, analysis and materials treatment are the needs of this service" (CEO). SCM is perceived through transverse service processes where information and financial and physical flows of products make up bridges between each process. In this way, the process is defined as a series of tasks and activities connected with each other, continuous and managed so that they contribute step by step to the achievement of an objective and obtaining a concrete result which can proved (Fig. 1).

Interview extract: "SCM is a process of service supply. This process is well formalized, a process which makes it possible to carry out services in man-days that one runs out month by month, they are the intellectual services of the days sold to our customers, it is a project-customer process" (Engineer network).

### *4.2 SCM as a Relation Between Organization and External Customers*

SCM is perceived through relations which are established between the organization and the customer. There is a wide relation in the energy of the upstream (intellectual engineering services) towards the downstream (customer). Interview extract: "SCM is a process starting from the customer requirements. Turnover is based on the man days sold to our customers. The services which we are able to sell from one month to another" (HRM network). This extract appears to stress the typologies and diversity of the SCM concept. In this case study, SCM acts as a particular service, behaving neither as physical nor financial flows but the provided service is intellectual.

## 4.3 Customer Service Performance Findings

The analysis of the answers to the question: For you, what is the performance of customer service? highlights two complementary elements: the role of the internal and external actors is significant in any reflection engaged in the performance of customer service; and the quality of the collaboration, communication, information, order visibility, confidence, and expertise supports the dynamics of the relations between the internal employees and the customers. Each of these points will be specified briefly below. **The role of Alpha's internal actors**: Interview extract: "In reality, we don't have a Supply Chain Manager. In our SME structure all the members deal and bring the service quality. We take part in the service quality according to our specialities" (CEO). For the respondents, in this type of SCM step, the customer service performance involving the relations between actors will be reinforced gradually. **The Supply Chain Manager's transverse role**: Relations are seen from both an internal and external point of view of an organization. The reinforcement of links is necessary where there are pressing demands on behalf of the customers for the total visibility of the orders and the modes of adjustment in the event of risks. Interview extract: "The Supply Chain Manager's role is to ensure the service provides quality from the beginning to the end. To take care that the service is carried out well in the practice code (good practice), in well-negotiated and contractual conditions. His role is also to bring future service solutions and to evaluate added value. The Supply Chain Manager intervenes before the contract signature. Namely, after the service proposal, the contract signature, the contract transaction and after the transaction" (PDG). **The Project Manager's role**: The Project Manager has an important role in collaboration and communication with customers. Collaboration is achieved via the telephone and mutual assistance. For example, the Project Manager visits the customer's site to take measurements, and to assess the relationship and availability. This also means that SMEs cannot answer a customer's request by explaining that they cannot do it. Interview extract: "With the customers it depends on the contracts. In the fixed price contract, we send weekly files with the services carried out, the number of missed services (…). We do it for the quality and for invoicing but they are not the same files. For invoicing, for each customer operation we did not do well, we will remake it for quality. The follow-up file is sent when the customers ask for it and we carry it out. But customers do not know our technicians' availability. For quality, the customer is informed by email or phone. The Project Manager explains to the customer why such a service was not well carried out and sends a copy to the Director. The Director gives an explanation to the customer" (Chief Executive Officer). **The role of competence, expertise and trust**: In a partnership the bond between confidence and competence is very strong. For Alpha, confidence arises from the company's expertise and competences. Interview extract: "Collaboration is a partnership. We are in close collaboration with our customers. It is a certain confidence, it is necessary to create confidence. If there is no confidence this does not occur very well.

Confidence is created by quality follow-ups. The customer must perceive that we deal in assurance quality and we have a quality preoccupation (example: how to check materials before using? how the technicians are trained (CEO)". Trust reduces contractual rigidity. Contract rigidity is not of interest to anybody in business. The contract is there only for litigation cases. Interview extract: "Yesterday, one customer calls us and asks us, please I need such a thing (…) whereas we do not have the order. We carried out the operation without an order because we let ourselves trust him. Then, the order was sent this morning. There are many things which arrive like that but it needs mutual confidence" (PDG). Interview extract: "Let us imagine that in a contract we specify that any operation cancelled on the same day as the operation is invoiced. The cost of the operation is 1,000 euros for example. The customer invites us to cancel the operation. If we have not sent the technician yet, the invoicing is not taken into account. Then, the contract principle is not applied. It is an agreement and confidence relation" (PDG).

**The role of information systems**: To talk of customer service in an SCM step is by its nature to speak of the role of information systems insofar as the technical support plays an essential part. For certain respondents, success with customers depends on the use and coherence of the technical support. Two points were approached: concerning the tools on the one hand, and the communication with the internal actors and the customer on the other. Interview extract: "Obviously these tools are significant; the success of a project customer process depends on the exchange of information" (Engineer network). In this way, we meet the analytical context: the information system allowing the real connection and sharing of all information necessary among the participants of the SCM. Interview extract: "There are information processing systems, data exchanges by e-mail, telephone, weekly or monthly physical meetings according to the progress report of the project" (Engineer network). Interview extract: "In the SME internal system, we have simple follow-up files. Databases like Excel, Access. These databases are an internal creation and they allow us to follow up service quality. We do not have a dedicated information system. Our own system is shared by everyone in the SME" (Telecom Consultant). In this way, much of the literature propounds the need for integration, leading to extension of the supply chain concept, firms are pursuing IT implementations which are premised solely on internal benefits [37].

## *4.4 Case Study Audit System*

Two principal ideas are analyzed in the case study audit system: corrective and preventive actions and the Project Managers and Directors' audit role. **Corrective and preventive actions**: There are two possibilities in the Alpha audit system when customers have a problem. If the problem can be corrected, the actors proceed initially to corrective actions. If the problem can not be corrected, they proceed to preventive actions to avoid the problem being reproduced in the future and they give an explanation to the customer. Interview extract: "The audit

**Table 4** Customer service performance background and criteria evaluation

| | |
|---|---|
| Service quality | **Service success rate** (period and budget, 100 %); **service failure rate**; availability rate; service rate; realization number (contract number); turnover; service not executed rate; and technician trained equipment verification |
| Customer satisfaction | **Reactivity** (time required to adapt a change, for example: rapid servicing invoicing and error); reply time; time delivery; duration and objectives (contractual on-time rate); and customer satisfaction/survey |
| Confidence and relationship relational | Presence; evaluation meeting and propositions; business lunch (…); results commitment respect, mean commitments respect and; to improve customer service quality (commercial policy and project manager role) |
| Deliverable project adequacy cycle time | **Service extension rate**, missing; physical logistics (machines); first customer-expressed demand; customer-negotiated demand; customer-project delivery (to compare the customer demand and realization dates); **Customer order numbers**; project delivery date respect; and ensure service on time and in good condition (performance) |
| Adequacy between production capacity and order book | **Order numbers; occupation rate**/inter-contract rate and; **sales prices** |

enables us to evaluate added service value, identify the errors and to provide recommendations to make future services corrections. The audits enable us to know customers' complaints, the number of times where a measurement was missed, the number of times a train was late, the customer's problem" (CEO). **The Project Managers and Directors' audit role**: As [38] affirms, without good control of flows of information within a company and between the company and the customers, customer service is generally relegated to a simple statistical level and to the reaction to particular problems. Interview extract: "The Project Managers take care of the service quality. We organize a weekly meeting to guarantee this quality and to define future strategies. The service quality is followed from the lower (technicians, service execution) to the higher level (Project Manager's budget, Managing Director). We discuss together strategic decisions, recruitment, customers' complaints and each one brings proposals. Then, the solutions are formalized and enforced by the Project Manager who normally supplies the instrumental panel" (CEO). So, the Alpha's key performance indicators (KPI) are proposed in the following synthesis: (Table 4).

For the service failure rate performance measurement, SMEs have an internal instrument panel to follow up failures the following day. For example, three interesting measure indicators allow Alpha to know its errors. On one side, these errors can result from technicians' incompetence (Alpha error). The other way, errors can result from an information default (customer error). For example, a customer does not give necessary information like the street number. Finally, Alpha is able to know the service success rate with and without exceeding budget.

The service extension rate is a time surpass service. It is very important to calculate this indicator as it penalizes Alpha and makes invoicing corrections for the customer. The service success rate (100 %) depends upon whether a margin is very limiting because SMEs have many competitors in the telecommunications field. It is, therefore, necessary to have a 100 % service success rate. The success of this rate can be explained by two elements: firstly, Alpha's experience and reactivity; secondly, Alpha counts the corrections among its successes.

## 5 Summary

This case study had the aim of leading a qualitative analysis in relation to internal actors. The summary of the results obtained can be articulated as follows: each project has its own indicators and an exhaustive list of criteria evaluation is not provided. This proposal will help in providing a picture of the services to improve the relationship with the customer (commercial and Project Manager reporting on customer follow-ups); improve operational reporting (internal indicators, quality reports); improve invoice control and indicator follow-ups by the Manager Project; and improve cost management. Alpha must share its intellectual resources and information with its partners under penalty of desynchronizing the rest of the chain and creating bottlenecks. All the actors will be concerned—commercial, technical, data processing, and financial—which will provide indicators to measure performance and the effectiveness of Project Manager, CEO and Human Resources, which will become a true added value. Indeed, a model could be used to predict which SMEs are more likely to become adopters of enterprise systems (ERP, CRM, SCM, and e-procurement) [39]. SCM is thus the search for excellent total performance in a chain made up of companies which are independent but bound by a common objective: the satisfaction of the end customer.

## References

1. Kyj M (1987) Customer service as a competitive tool. Ind Mark Manage 16(3):225–230
2. Quinn JB (1994) L'entreprise intelligente. Dunod, Paris
3. Tixier D, Mathé H, Colin J (1998) La logistique d'entreprise. Dunod, Paris
4. Livingstone G (1992) Measuring customer service in distribution. Int J Phys Distrib Logistics Manage 22(6):4–7
5. Loomba APS (1996) Linkages between product distribution and service support functions. Int J Phys Distrib Logistics Manage 26(4):4–22
6. Brockmann T (1999) Warehousing trends in the 21st century. IIE Solutions 31(7):36–40
7. Tchokogué A, Jobin MH, Beaulieu M (1999) Evaluation du service à la clientèle: enrichir la perspective client par la perspective logistique, Cahier de recherche, pp 99–06
8. Harr JM, Spell CS (2008) Predicting total quality management adoption in New Zealand: the moderating effect of organisational size. J Enterp Inf Manage 21(2):161–178

9. Colin J (2002) De la maîtrise des opérations logistiques au supply chain management, Gestion 2000. Janvier-Février, pp 59–75
10. Harland C (1996) Supply chain management: relationship, chains and networks, British newspaper of management, vol 7(1). Special edition, pp 63–80
11. Mentzer JT (2004) Fundamentals of supply chain management. Sage Publications, Thousand Oaks
12. Mentzer JT, Dewitt W, Keebler JS (2001) Définir le supply chain management. Logistique Manage 9(2):3–18
13. Christopher M (ed) (1992) Logistics: the strategic issues. Chapman & Hall, London
14. Christopher M (1994) New direction in logistics. In: Cooper J (ed) Logistic and distribution planning, 2nd edn. Kogan Page, London, pp 15–24
15. Christopher M (1997) Marketing logistics. Butterworth-Heinemann, Oxford
16. Bowersox DJ, Closs DJ, Stank TP (2000) Ten mega-trends that will revolutionize supply chain logistics. J Bus Logistics 21(2):1–16
17. Fabbe-Costes N (2000) Supply chain management: concepts et pratiques. Conférence-débat à IAE d'Aix en Provence, Avril
18. Joffre P, Koenig G (1992) Gestion stratégique, l'entreprise, ses partenaires adversaires et leurs univers. Editions Litec, Paris
19. Fulconis F (2000) La compétitivité dans les structures en réseau. Méthode d'analyse et perspectives managériales, Thèse de Doctorat en Sciences de Gestion, Université de Nice Sophia-Anti-polis
20. Shahneel B, Shafqat H, Atta B (2008) Analysing the factors responsible for effectiveness of implementation and integration of enterprise resource planning systems in the printing industry. J Enterp Inf Manage 21(2):139–161
21. Esteves J (2009) A benefits realisation road-map framework for ERP usage in small and medium-sized enterprises. J Enterp Inf Manage 22(1/2):25–35
22. Tucker FG (1983) Creative customer service management. Int J Distrib Mater Manage 13(3):34–50
23. Samii AK (2004) Stratégie logistique, supply chain management. Dunod, Paris
24. Baglin G, Bruel O, Carreau A, Greil M, Delft C (2001) Management industriel et logistque, economica. Wiley, Paris
25. Batsch L (1996) Finance et contrôle: à propos de la 'corporate governance', Cahier de recherche du CEREG, No. 9606, Université Paris-Dauphine
26. Kaplan R, Norton D (1996) Using the balanced scorecard as a strategic management system. Harvard Bus Rev 74(1):75–85
27. Atkinson A, Waterhouse J, Wells R (1997) A stakeholder approach to strategic measurement. Sloan Manage Rev 38(3):25–37
28. Cauvin E (1994) Développement et test d'un modèle de compétitivité par activités: une application dans les services, Thèse de Doctorat en Sciences de Gestion, Université de Droit, d'Economie et des Sciences (Aix-Marseille III)
29. Lynch RL, Cross KF (1995) Measure up: how to measure corporate performance, 2nd edn. Blackwell Publishers Ltd, Oxford
30. Malo JL, Mathe JC (1998) L'essentiel du contrôle de gestion. Editions d'Organisation, Paris
31. Nanni A, Dixon J, Vollmann T (1992) Integrated performance measurement: management accounting to support the new manufacturing realities. J Manage Account Res 4:1–19
32. Bughin-Maindiaux C, Finet A (1999) Les mesures non financières de la performance: une information au service de prévention des faillites. Dir et Gestion des Entreprises 175–176:45–55
33. Imai M (1996) Gemba kaizen: a commonsense low-cost management strategy. Kaizen Institute, Japan
34. Demers C (2003) L'entretien, in conduire un projet de recherche, une perspective qualitative, ouvrage coordonné par Y. Giordano, pp 173–210
35. Miles M, Huberman AM (1994) Qualitative data analysis: an expanded sourcebook. Sage, Thousand Oaks, (traduction Française 2003 de Boeck Université)

36. Bardin L (1993) L'analyse de contenu. PUF, Paris
37. Smart A (2008) eBusiness and supply chain integration. J Enterp Inf Manage 21(3):227–246
38. Lamming R (2000) Networking activities in supply networks. J Strateg Mark 8(2):161–181
39. Ramdani B, Kawalek P, Lorenzo O (2009) Predicting SMEs' adoption of enterprise systems. J Enterp Inf Manage 22(1/2):10–24

# Strategic Fit Assessment for Value-Added Networks of Electric Engine Production

**Carsten Nee, Achim Kampker and P. Burggräf**

**Abstract** Disruptive innovation, such as electric vehicles, go along with new requirement in aspects of cost, quality, and scalability while the market environment is considered as risky and dynamic. Many companies form strategic alliances, acquire competencies or participate in new developing value-added networks to cope with the new requirements and to spread the risk. This leads to new opportunities for value-added networks, as they can be designed to perform best in terms of cost and quality, to handle scalability as well as to define a cooperative strategy to align the specific goals of network participants. For companies it remains unsure which value-added network to join, which role to play and whether the cooperative strategy fits the corporate strategy of the company. So far there is no methodology that allows network participants to assess the strategic fit of a value-added network. This paper address the need for action in theory and practice and presents a methodology to assess the strategic fit of value-added networks. Part of the strategic fit assessment are: fit in motives, fit in resources and products, structural fit, and cultural fit. The electric engine production for electric vehicles is chosen as an example for disruptive innovation and serves as the application case for the methodology of the network fit assessment.

## 1 Introduction

The trend toward mega cities, rising mineral oil prices, and the increasing awareness of environmental friendliness attract major interest in electric mobility. However, since electric vehicles are not yet competitive with conventional powered cars, they are not accepted by potential customers [1, 2]. Companies need to build up and acquire new or enhance existing competencies to be able to develop and produce competitive electric vehicles. Since a concentration on either cost or

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quality will not be enough to have sustainable success and to make electric mobility attractive to the consumer, successful electric vehicle manufacturers have to follow a dual strategy, by leading in both: cost and quality [3–5]. In particular with regard to network cooperation, Porter's generic competitive strategy approach of either following differentiation or cost leadership, can be proven wrong [3, 6]. In this context it has to be considered, that due to market trends, electric vehicles are going to be produced in small to medium quantities in the near future. Therefore, new approaches for economic production of small quantities are needed. At the same time, a scalability concept must be implemented to enable a fast ramp-up as soon as demand increases [2, 7]. Also the disruptive innovation of electric vehicles goes along with a large amount of new required competencies, investments and capacity utilization of personal and equipment resources. The requirements concerning knowledge and competency development, cost, quality and scalability cannot be met by companies on their own. Instead, to minimize the business hazard as well as to create a tightened market position within the turbulent environment, companies form value-added networks [4, 6, 8]. However, gaining and sustaining competitive advantage depends on how well the company fits into the chosen network [6, 9].

Companies facing disruptive innovations, such as the electric vehicle production, call for a new approach of designing value-added networks, that takes the specific characteristics of emerging technologies into account. Therefore, this paper introduces an approach to design value-added networks with a strategic fit for the electric engine production.

## *1.1 Purpose*

The approach addresses especially small to medium-sized companies that are not able to follow an in-depth strategic analysis due to restrictions in strategic planning competencies or planning capacity [10]. The main goal is to provide companies with a systematic approach to evaluate the strategic fit of a company towards an existing or prospective new value-added network. The approach shall offer a step-by-step procedure and include all necessary tools and evaluation methods. The fit assessment has to cover the five relevant forms of strategic fit: motives, market and products, resources, structure and culture. Potentials lie in a value-added network design with respect for hybrid strategies and scenario based future scalability. In the following the need for action in practice and theory will be explained in detail.

## *1.2 Need for Action in Practice*

The need for action in practice is based on an increased formation of networks with a significant larger number of partners during disruptive innovations [11, 12].

This increased formation of networks is caused by a lack of know-how of production processes, challenging customer requirements based on the maturity level of the technology as well as scalable productions systems and the need to set standards. Caused by the market dynamics and the pressure to develop new products in a short development period, value-added networks consist of a variety of uncoordinated, company specific strategies which are not in line with a cooperative network strategy [13]. Since there is a lack of monitoring tools to evaluate the strategic fit between the corporate strategy and the cooperative networks strategy, particularly in small and medium-sized companies, strategic decisions are often made by the management's gut feeling [10]. Especially for network formations coping with disruptive innovation, where product prices are too high and customer demanded performance attributes are often not met [11], there is a necessity to follow a hybrid strategy, by addressing both: cost and quality leadership.

### *1.3 Need for Action in Theory*

Existing fit-approaches are unable to assess the strategic fit of value-added networks. Beside models outlining the criteria and variables of strategic fit [14–17], several studies on the relevance of strategic fit have been carried out. Venkatraman and Prescot examined independent business units over a period of four years in an empirical study and showed a significant positive correlation between strategy, environment and business unit performance [18]. Ghoshal's and Nohria's statistical study of 41 multinational companies showed that companies with a fit between inner structures and the market environment are more effective than companies without a fit [19]. A study of Bain & Company presents, that 94 % of American CEOs see the strategic fit as the key success factor for mergers and acquisitions [20]. Zajac et. al. prove the relevance of strategic fit by examining banks over a period of 9 years [21]. Haspenpusch proves that a consistency between business and manufacturing strategy is a requirement for business success [22]. Xu's study to demonstrate the relevance of strategic fit also includes fit criteria within the company [23]. Pothukuche et al. show the relevance of cultural criteria for strategic fit assessments [24].

So far, the strategic fit has mainly been examined by a statistic comparison of past data [19, 21, 22, 25]. There is a need for a methodological validation of the strategic fit using present data to give companies the possibility to respond quickly to market dynamics. Despite the large amount of models and relevance demonstrating statistical studies, none of them concentrates on the strategic fit of networks. Thus, the coherence of value-added networks cannot be proved, although its relevance is verified by several studies [20]. Only Bleicher and Gaus allow a methodological assessment of the strategic fit without relying on statistical data of the past [26, 27]. However, their approaches are also restricted to the fit between a company and its environment and are not transferable to assess the strategic fit of

| Author | | Number of Variables | Fit Assessment of Cooperations | Methods for Analysis | Market dynamics of Disruptive Innovation | Consideration of Dual-Strategies |
|---|---|---|---|---|---|---|
| Ansoff | Models for strategic fit | - | ○ | ○ | ○ | ○ |
| Chandler | | - | ○ | ○ | ○ | ○ |
| Porter | | - | ○ | ○ | ○ | ○ |
| McKinsey | | 7 | ○ | ○ | ○ | ○ |
| Bea und Haas | | 8 | ○ | ○ | ○ | ○ |
| Venkatraman und Prescot | Proof of relevance of strategic fit by evaluation of enterprise data or inquiries in the management | | ○ | ○ | ○ | ○ |
| Ghoshal und Nohria | | | ○ | ○ | ○ | ○ |
| Bain & Company | | | ○ | ○ | ○ | ○ |
| Zajac et al. | | | ○ | ○ | ○ | ○ |
| Milling und Hasenpusch | | | ○ | ○ | ○ | ○ |
| Xu et al. | | | ○ | ○ | ○ | ○ |
| Pothukuche et al. | | | ○ | ○ | ○ | ○ |
| Swoboda et al. | | | ○ | ○ | ○ | ○ |
| Bleicher | Approaches towards analysis of strategic fit | 12 | ○ | ● | ○ | ○ |
| Gaus | | ~40 | ○ | ● | ○ | ○ |
| Child et al. | | 11-12 | ◔ | ○ | ○ | ○ |
| Douma et al. | | 12+x | ◑ | ◑ | ○ | ○ |
| Medcof | | 5 | ● | ○ | ○ | ○ |
| Cummings et al. | | 11+x | ◑ | ● | ○ | ○ |
| Haupt | | 6 | ● | ○ | ○ | ○ |
| Knop | | - | ◑ | ○ | ○ | ○ |
| Own Approach | | >30 | ● | ● | ● | ● |

○ Not fulfilled
◔ Fulfilled to minor extend
◑ Not completely fulfilled
● Fulfilled

**Fig. 1** Comparison of strategic fit approaches

value-added networks. Bleicher's approach is based on a tool, illustrating the current state of a company's strategic programs and helping to identify misfits to improve the overall strategic fit [26]. The approach distinguishes between two directions of modification for companies. On the one hand, there are stabilizing strategies and on the other hand there are modifying strategies. With regard to an extremely dynamic market environment and the need for change to cope with disruptive innovations, Bleicher's stabilizing strategies do not have any relevance to the electric vehicle production industry. Therefore, the approach is reduced to modifying strategies and therewith to only one expedient direction of development for twelve company-internal dichotomies. In Bleicher's approach a relation to the cooperative strategy of value-added networks does not exist. Another aspect is the universality of the approach, it covers all industry sectors, resulting in a very general und unspecific fit assessment. In contrast to Bleicher's approach, Gaus' approach can't be used universally. Instead the methodological approach can only be applied for the established industry of tool and die manufacturing. Thus, it is only partly transferable to other industry sectors, also the Gaus' approach is not taking into account the dynamic network environment after disruptive innovations. The method offers no opportunity to assess a fit between companies or the fit within a network (Fig. 1) [27].

## *1.4 Interim Conclusion*

Derived from the mentioned need for action, a methodology has to be developed that allows companies to improve both the position of the company in a value-added network and the position of the whole network toward the market environment. So far, there is no approach that allows for an assessment of the strategic fit of value-added networks especially considering the market dynamics of disruptive innovations.

## 2 Methodology

The approach for strategic fit assessment in value-added networks is based on the methodologies of "disruptive innovations", "cooperative strategy" and "strategic fit".

### *2.1 Disruptive Innovation*

Govindarajan and Kopalle describe disruptive innovation as an introduction of "a different set of features, performance, and price attributes relative to the existing product, an unattractive combination for mainstream customers at the time of product introduction because of inferior performance on the attributes these customers value and/or a high price—although a different customer segment may value the new attributes" [11]. Disruptive innovation are often characterized by a lack of know-how of the overall production process. In this situation missing skills are acquired through cooperation with specialists in the prospective field [28]. Besides, network formation is increasing due to uncertainty of production quantity development and the business hazard of the sustainability of the innovation [2, 7, 12].

### *2.2 Cooperative Strategy*

Cooperative strategies gain importance in a dynamic market environment [6]. A cooperative strategy describes an aligned strategy of at least two companies in order to gain competitive advantage [6, 29]. By establishing a cooperative strategy companies can proactively influence the dynamic market environment and create stability. Astley and Fombrun first used the term "collective strategy" (syn: cooperative strategy) in 1983 to describe a lack of existing strategic management concepts: So far management concepts anticipated the environment as given and unswayable, Astley and Fombrun state that the impact of cooperation can influence the market environment proactively [30, 31]. Contractor defines general dimension of cooperative strategies for joint ventures based on Astley's and Fombrun's idea of cooperative strategies. A cooperative strategy should define the following aspects: Risk management, economies of scale, synergies in technology and knowledge, impact on the competitive environment and access to new markets [32]. Cuplan introduced a framework for the development of cooperative strategies. Driven by the dynamics in the market environment motives for a cooperation

| Cooperative Strategy Dimensions | Contractor | Cuplan | Rugman and Cruz | Dyer and Singh | Kothandaraman and Wilson | Haupt | Synthesis | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Markets | Business Segment | Markets | - | - | Business Segment | Market | Market and Products | Corporate Strategy | Cooperative Strategy |
| | - | Product and service offerings | Product and service offerings | - | Product value-added | - | Products | Market and Products | Corporate Strategy | Cooperative Strategy |
| | Economies of scale, Technology acquisition | Resources, Investments | Investments, Technology acquisition | Investments, Resources, Technologies | - | Resources | Value Chain | Value Creation | Corporate Strategy | Cooperative Strategy |
| | Knowledge | - | Knowledge | Knowledge | Process value-added | - | Knowledge and Competencies | Value Creation | Corporate Strategy | Cooperative Strategy |
| | Competitive Advantage, Risk Spreading | Motive, Expected Results, Targets | Image | - | Customer Value | Motive and Vision | Motives and Targets | Motives and Targets | | Cooperative Strategy |
| | - | Organizational Structure | Structure | Organization and Structure | - | Network Structure | Organizational Structure | Struc-ture | | Cooperative Strategy |
| | - | - | - | - | Ability to cooperate | Degree of Partner Integration | Culture | Culture | | Cooperative Strategy |

**Fig. 2** Comparison of cooperative strategy definitions

shall be defined and agreed on. A cooperative strategy can be defined by stating the aspects, organizational form, expected results and timeframe of a cooperation [33]. Rugman and D'Cruz developed a framework model for cooperation. In their opinion a "flagship company" develops a cooperative strategy. Furthermore the flagship company establishes and maintains relationships to partners, it also controls the compliance to the cooperative strategy [34]. Dyer und Singh define 4 dimensions of a cooperative strategy: Definition of investments directly related to the cooperation, knowledge exchange, synergies in resources and competencies, aspects to control and maintain the cooperation [35]. Kothandaraman and Wilson define cooperative strategies by the motive to create extraordinary customer value and to acquire new core competencies through network partners, both lead to potential product and process value-added. Kothandaraman and Wilson also mention that cultural aspects are part of the cooperative strategy, such as the ability to cooperate [9]. Haupt's approach states that a cooperative strategy has to define a business segment, network structure, resources, vision and motive, as well as a degree of partner integration [29].

A synthesis of the definitions of cooperative strategy shows that the following dimensions have to be taken into account (Fig. 2): In addition to the dimensions market, products, value chain, and knowledge/core competencies which are also dimensions of corporate strategies [27, 36, 37], a cooperative strategy has to define motives and targets, the organizational structure, and cultural aspects of the cooperation.

## 2.3 Strategic Fit

The concept of the strategic fit belongs to the fundamental ideas of strategic research and organizational studies and is considered as one of the most important approaches in the creation of strategic innovations [14, 38–40]. Six variants of

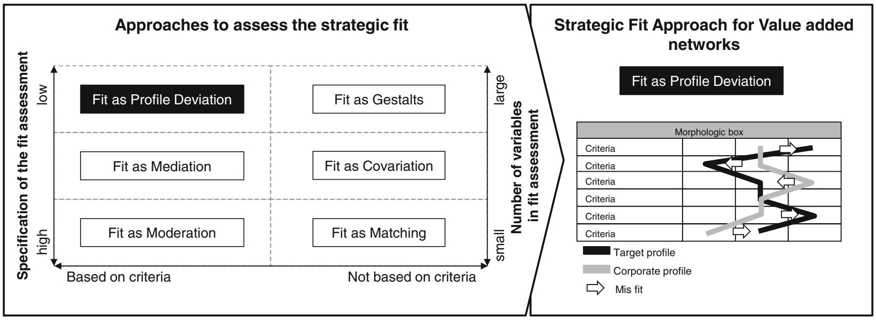


**Fig. 3** Classification of fit approaches

strategic fit-approaches can be distinguished. They result from the assessment of dependency of the fit on specific criteria, the amount of variables in the fit-equation as well as the specificity of the fit-concepts. The specificity of the alternatives differentiates according to the accuracy of recorded coherence. This corresponds with the regarded amount of variables (Fig. 3) [41, 42]. The methodology for the strategic fit assessment of value-added networks will be based on "Fit as Profile Deviation". In this approach the fit results from the degree of coherence between an actual and an externally defined target profile. This approach is characterized to be easily applied and has practical relevance.

The dimensions that are critical for a strategic fit can be identified by analysis of existing fit approaches. Child et al. developed a fit approach to assess the strategic coherence between two companies. Their fit-assessment is based on a Cultural Fit and a Strategic Fit [6]. Douma's et al. fit assessment is also limited to two companies, their fit analysis includes an Organizational Fit, a Cultural Fit, a Operational Fit, and a Strategic Fit [43]. Cumming et al. identified 4 success factors for a joint venture or strategic alliance between two companies: Risk-, partnering-, learning-, and task-related success [44]. Knop's fit approach defines fit dimensions between a company and a strategic network, that should show high coherence: Structural Fit, Cultural Fit and Strategic Fit [45]. Medcof identified 5 criteria for successful cooperation: Strategic Fit and the four "C" Capability, Compatibility, Commitment, and Control [46].

A synthesis of the existing approaches has been performed with regards to expand the existing approaches for a fit assessment of networks (Fig. 4). The methodology will consider the following fit criteria based on the synthesis of the aforementioned approaches and models.

## 3 Results

In the following the developed methodology for strategic fit assessment in value-added networks for disruptive innovations is introduced.

| | Child et al. (2005) | Douma et al. (2000) | Medcof (1997) | Cummings et al. (2012) | Knop (2009) | Synthesis | |
|---|---|---|---|---|---|---|---|
| Approach | 2 Fit-Dimensions<br>• Strategic Fit<br>• Cultural Fit | 5 Fit-Dimensions<br>• Organisational Fit<br>• Human Fit<br>• Strategic Fit<br>• Operational Fit<br>• Cultural Fit | 5 Criteria for successful cooperation<br>• Strategic Fit<br>• Capability<br>• Compatibility<br>• Commitment<br>• Control | 4 critical successfactors between 2 companies<br>• Risk-related<br>• Partnering-related<br>• Learning-related<br>• Task-related | 3 Fit-Dimensions<br>• Strategic Fit<br>• Structural Fit<br>• Cultural Fit | | |
| Fit Dimensions | Resources, Capabilities, Quality<br>Strategic Fit | Value-added, Market acceptance<br>Operational Fit | Capabilities/ Value-added, Complementarity of strength and weaknesses<br>Capability | Ressources, Quality | Resources, Competencies, Educational level and level of knowledge, Quality<br>Strategic Fit | Market and Products / Value Creation → Strategic Fit | Specific Fit |
| | Strategic targets<br>Strategic Fit | Conflict potential in strategy, Compatibility of strategies, Vision<br>Strategic Fit | Business model, Strategic targets, Motive for cooperation, Conflict potential in strategy<br>Strategic Fit/Commitment | Strategic targets | Corporate strategy<br>Strategic Fit | Motive Fit | General Fit |
| | Company size, Market power | Organisational compatibility, Flexibility, Complexity, Importance of cooperation, Dependency<br>Organisational Fit | Compatibility of methods and processes, Control mechanism, Dependency, Equal status<br>Compatibility | Control mechanism, Risk spreading | Company size, supply chain, locations, Economic fitness, experience in cooperation<br>Structural Fit | Structural Fit | General Fit |
| | Employee, Quality, Cost, Technology, Innovation, Customer and Environment orientation, internationality<br>Cultural Fit | Cultural/Human Fit | Social compatibility, Corporate culture, Engagement<br>Compatibility | Values, Norms, Rules, Interests, Social compatibility, Corporate culture, Management style | Corporate culture, Corporate personality, Regional culture<br>Cultural Fit | Cultural Fit | General Fit |

**Fig. 4** Fit dimensions for the fit assessment of value-added networks

## 3.1 *Methodology for Strategic Fit Assessment in Value-Added Networks*

In a fit as profile deviation approach the theoretically derived cooperative strategy (optimal value-chain and network setup for various production quantities) is compared to the potential partners, technologies and resources of the value-added network. The strategic fit evaluation is done by comparing the corporate strategy, motive, culture, and structure with the target profile (Fig. 5). The fit assessment follows a step-by-step top-down and bottom-up approach to acquire all necessary data, both will be explained for the application case of electric engine production in the following.

## 3.2 *Top-Down Analysis to Derive Target Profile for Electric Engine Production Network*

The market segment analysis identifies potential vehicle segments for electric engines, i.e., small to medium city cars with synchronous and asynchronous engines in the range of 30–90 KW. A target cost analysis shows product cost of 570 Euro for a 30 KW engine. The cost can be broken down to target production cost per process step. Also for each process step technological alternatives can be identified. A value analysis presents process steps with high impact on engine efficiency and other high valued performance attributes. A network analysis identifies the needed resources and competencies to address the chosen market

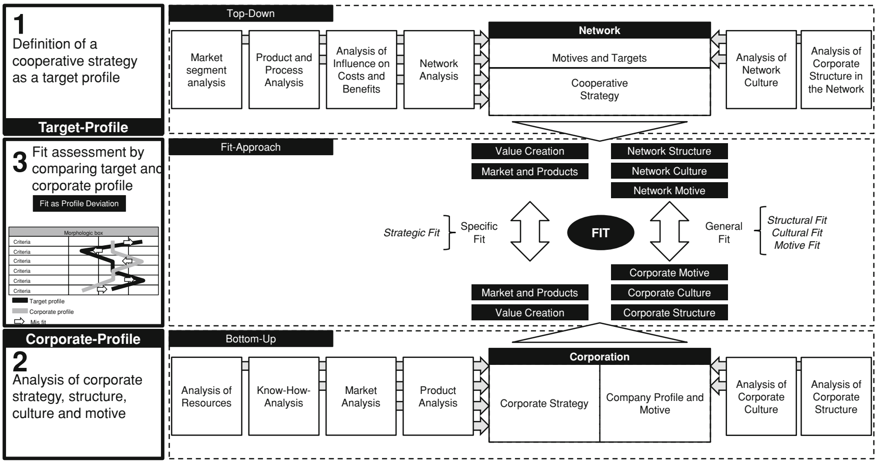


**Fig. 5** Methodology for fit assessment in value-added networks

segment. The network structure is based on small to medium size companies and on the principle of an "equal partner" network. Also a flagship company is defined to derive the cooperative strategy as well as to control and maintain the relationships to partners. The network culture is considered as open-minded and knowledge sharing. A common language for communication is set. Motive of the cooperation is to identify cost innovation and to share knowledge to gain competitive advantage in the field of electric vehicle production.

In a step-by-step procedure more than 50 variables to define the cooperative strategy (based on the aspects of the dimensions of a cooperative strategy in various approaches) are quantitatively assessed (qualitative criteria are classified on a scale to derive a quantitative values for each variable) and a target profiles for the 5 fields of fit were derived.

## 3.3 Bottom-Up Analysis to Derive Corporate Strategic Profile

Selected companies are analyzed concerning their specific value for the 50 variables of a cooperative strategy. In addition the offered resources and technologies are compared with the needed resources for a specific quantity range.

## 3.4 Strategic Fit Between Corporate and Cooperative Strategy in Electric Engine Production

The fit assessment is performed in spider web diagrams and a special designed resource analysis tool. The resource analysis tool incorporates the process selection based on the customer valuation and process cost to enable partner selection based on a dual strategy for the network. Misfits between a company and the value-added network can be easily identified. The misfits are weighted and combined to an overall fit performance indicator.

## 4 Summary

This paper focusses on the value-added networks of electric engine production. A cost, customer valuation and scalability model enables a flagship company to derive a cooperative strategy for a value-added network. The approach is assessing the strategic fit between the strategy of a company and the derived cooperative strategy of the value-added network. The methodology of fit assessment helps to design networks that are capable of cost and quality leadership as well as supporting a ramp-up of production quantities due to dynamic partner selection. Furthermore the methodology enables networks managers and small to medium sized companies to find partners with a strategic fit, resulting in a sustainable competitive advantage in a turbulent environment of disruptive innovation.

**Acknowledgments** All findings and newly developed methodologies are applied to the design and production planning of StreetScooter, an innovative battery electric vehicle for an urban environment. The StreetScooter is being developed by an interdisciplinary alliance of research institutes and industry partners. The results about the electric engine production were achieved during the project KERME, a project funded by the European Union and North Rhine Westphalia.

## References

1. Kampker A, Burggräf P, Nee C (2012) Cost, quality and scalability: impact on the value chain of electric engine production. In: Proceedings of 2nd international electric drives production, 2012
2. Schuh G, Kampker A, Burggraf P, Nee C (2011) Production system with respect for variable quantities for an economical electric vehicle production. In: Proceedings of 2011 IEEE international conference on industrial engineering and engineering management: IEEE, pp 1123–1128, 2011
3. Heracleous L, Wirtz J (2010) Singapore airlines' balancing act. Harvard Bus Rev 88(7/8):145–149
4. Kampker A, Burggräf P, Nee C (2012) Strategic fit in value added networks of electric vehicle production. In: Proceedings of industrial engineering and engineering management (IEEM), 2012 IEEE international conference on: IEEE, 2012
5. Fleck A (1995) Hybride Wettbewerbsstrategien: Zur Synthese von Kosten und Differenzierungsvorteilen. Wiesbaden: Dt. Univ.-Verl. [u.a.], 1995
6. Child J, Faulkner D, Tallman SB (2005) Cooperative strategy, 2nd edn. Oxford University Press, Oxford; New York

7. Kampker A, Burggräf P, Nee C (2012) Scalable production systems for electric vehicle production. In: Proceedings of the conference on future automotive technology focus electromobility, 2012
8. Petry T (2006) Netzwerkstrategie: Kern eines integrierten managements von Unternehmungsnetzwerken, 1st ed. Dt. Univ.-Verl, Wiesbaden
9. Kothandaraman P, Wilson DT (2001) The future of competition: value-creating networks: customer value in business markets. Ind Mark Manage 30(4):379–389. http://www.sciencedirect.com/science/article/pii/S0019850100001528
10. Preißner M (2008) Mittelstand leidet unter Bauchentscheidungen. Institut für Handelsforschung an der Universität zu Köln, Köln
11. Govindarajan V, Kopalle PK (2006) The usefulness of measuring disruptiveness of innovations ex post in making ex ante predictions. J Prod Innov Manage 23:12–18
12. Harvard Business School (2002) Harvard business review on strategic alliances. Harvard Business School Press, Boston, MA
13. Dussauge P, Garrette B (1999) Cooperative strategy: competing successfully through strategic alliances. Wiley, Chichester
14. Ansoff HI (1979) Strategic management. Macmillan, London
15. Chandler A (1962) Strategy and structure: chapters in the history of the industrial enterprise. MIT Press, Cambridge
16. Porter M (1999) Wettbewerbsvorteile—Spitzenleistungen erreichen und behaupten. Campus, Frankfurt am Main
17. Bea FX, Haas J (2009) Strategisches management, 5th edn. Lucius & Lucius, Stuttgart
18. Venkatraman N, Prescott JE (1990) Environment-strategy coalignment: an empirical test of its performance implications. Strateg Manag J 11:1–23
19. Ghoshal S, Nohria N (1993) Horses for courses: organizational forms of multinational corporations. Sloan Manage Rev 53(2):23–35
20. Harris E (2010) CEO survey: mergers and acquisitions—the 1997 business week symposium of CEOs (14 Feb 2010)
21. Zajac EJ, Kraatz MS, Bresser RKF (2000) Modeling the dynamics of strategic fit: a normative approach to strategic change. Strateg Manag J 21:429–453
22. Milling P, Hasenpusch J (2002) Strategiekonsistenz in Geschäftseinheit und Fertigung—Angleichung der Strategien als Voraussetzung für den Erfolg industrieller Unternehmen? In: Lingnau V, Schmitz H (eds) Aktuelle Aspekte des Controllings. Physica, Heidelberg, pp 143–163
23. Xu S, Cavusgil ST, White C (2006) The impact of strategic fit among strategy, structure, and processes on multinational corporation performance: a multimethod assessment. J Int Mark 14(2):1–31
24. Pothukuchi V, Damanpour F, Choi J, Chen CC, Park SH (2002) National and organizational culture differences and international joint venture performance. J Int Bus Stud 33(2):243–265
25. Stobaugh R, Telesio P (1983) Match manufacturing policies and product strategy. Harvard Bus Rev 61(2):113–120
26. Bleicher K (2004) Das Konzept integriertes management: Visionen—Missionen—programme, 7th edn. Campus, Frankfurt am Main
27. Gaus F (2010) Methodik zur Überprüfung der Logik eines Geschäftsmodells im Werkzeugbau, 1st edn. Apprimus-Verl, Aachen
28. Contractor FJ, Lorange P (eds) (1988) Cooperative strategies in international business: joint ventures und technology partnerships between firms. Health and Company, Lexington, DC
29. Haupt S (2003) Digitale Wertschöpfungsnetzwerke und kooperative Strategien in der deutschen Lackindustrie
30. Bresser RKF (1989) Kollektive Unternehmensstrategien. Zeitschrift für Betriebswirtschaft 59(5):545–564
31. Astley WG, Fombrun CJ (1983) Collective strategy: social ecology of organizational environments. Acad Manag Rev 8(4):576–587

32. Contractor FJ, Lorange P (1988) Why should firms cooperate?: The strategy and economics basis for cooperative ventures. In: Contractor FJ, Lorange P (eds) Cooperative strategies in international business: joint ventures und technology partnerships between firms. Health and Company, Lexington, DC, pp 3–30
33. Culpan R (1993) Conceptual foundations of multinational strategic alliances. In: Culpan R (ed) Multinational strategic alliances. International Business Press, New York, pp 13–32
34. Rugman AM, D'Cruz JR (2000) The theory of the flagship firm. In: Faulkner D, de Rond M (eds) Cooperative strategy: economic, business, and organizational issues. Oxford University Press, Oxford, USA, pp 57–73
35. Dyer JH, Singh H (1998) The relational view: cooperative strategy and sources of interorganizational competitive advantage. Acad Manag Rev 23(4):660–679
36. Rüegg-Stürm J (2005) Das neue St. galler management-modell: Grundkategorien einer integrierten Managementlehre, 2nd edn. Haupt, Bern
37. Stank TP, Davis BR, Fugate BS (2005) A strategic framework for supply chain oriented logistics. J Bus Logistics 26(2):27–45
38. Christensen C, Andrews K, Bower J, Hamermesh G, Porter M (1982) Business policy: text and cases. Irwin, Homewood, IL
39. Mintzberg H (1990) Strategy formation: schools of thought. In: Fredrickson JW (ed) Perspectives on strategic management. Harper Business, New York, pp 105–236
40. Porter ME (1996) What is strategy? Harvard Bus Rev 74(6):61–78
41. Venkatraman N (1989) The concept of fit in strategy research: toward verbal and statistical correspondence. Acad Manag Rev 14(3):423–444
42. zu Knyphausen-Aufsess D (1995) Theorie der strategischen Unternehmensführung: State of the art und neue Perspektiven. Gabler, Wiesbaden
43. Douma MU, Bilderbeek J, Indenburg PJ, Looise JK (2000) Strategic alliances: managing the dynamics of fit. Long Range Plan 33:579–598
44. Cummings JL, Holmberg SR (2012) Best-fit alliance partners: the use of critical success factors in a comprehensive partner selection process. Long Range Plan 45:136–159
45. Knop R (2009) Erfolgsfaktoren strategischer Netzwerke kleiner und mittlerer Unternehmen ein IT-gestützter Wegweiser zum Kooperationserfolg, 1st edn. Gabler, Wiesbaden
46. Medcof JW (1997) Why too many alliances end in divorce: learning, positioning and alliance partner selection. Long Range Plan 30(5):718–732

# Analysis of the Network of Relations of Organizations Set up at Walqa Technology Park

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**Abstract** The main purpose of this research work is to conduct an in-depth analysis of the existing relations between organizations located in Science and Technology Parks (STPs). The aim is to analyze the extent to which the entities located at Walqa Technology Park (Spanish acronym PTW), situated in Huesca, interrelate, and which factors have an influence in these relations. To this end, a total of 56 organizations located at PTW were encouraged to participate, via personal interview or e-mail. Later on, the network of relations formed by the different agents of the park were analyzed, verifying the hypothesis that states that the relations between them depend on the characteristics of the entities; in this case, on the type of entity, size and activity sector. A study of different properties of the network and of the nodes were studied, such as the density of the network and of the agents per se, the degree of centrality of an entity, the centralization rate as well as the degree of intermediation. With a response rate of 96 %, the main results show that, as a result of the relations established, the companies set up at PTW obtain: opening up of new markets and business credibility. Based on an overall perspective, the appearance of marked centrality patterns that group together entities such as technology centres and universities in the centre of the network, can clearly be observed, the reason being that they combine the largest number of technology collaborations and staff collaboration. From the viewpoint of size, small companies appear in the central network with a very high number of collaborations. Finally, depending on the sector, it can be seen that the most interrelated are those that belong to the ICT sector followed by those from the engineering and energy sector.

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## 1 Introduction

Over the last few years, one of the most accepted industrial locations by regional governments have been the science and technology parks (STPs). On a regional level, STPs provide a global framework that facilitates innovation and fosters local development. They also carry out an important role in improving competitiveness as they contribute to a reduction in unemployment and they correct existing divergences. These business agglomerations act as catalysts for economic development and facilitate the development and growth of new technology-based companies. They also favor the acceleration of business activity due to the agglomeration and exchange of knowledge, and due to the effect of sharing specialized production resources [1–3]. The main differences between STPs and other locations could be summed up by the fact that the former have mainly been planned, not only as spaces to locate companies and scientific/technological resources, but also that, in general, they are geared towards fostering the interaction of knowledge between agents [2–4], including innovative actions with a view to achieving benefits in different economic, social and territorial aspects.

STPs are considered as one of the main tools for innovation promotion policies both at a regional and state level. Although every STP has its own objectives and strategies, it can be said that in the majority of the cases they have a minimum common denominator: STPs favor the creation and installation of technology-based companies (TBC), fostering the transfer of technologies and knowledge, associating with Universities and Technology Centres [5, 6].

In Spain today, STPs are experiencing a moment of strong development. At the end of 2011 there were a total of 6,030 companies and institutions established in the STPs of the APTE with an employment volume of 154,187 workers. 28,384 of these workers carry out Research and Development (R&D) tasks, representing approximately 13 % of the R&D staff of the whole of Spain. With respect to turnover, the STPs of the APTE billed a total of €23.25 billion in 2011, representing approximately 2 % of the Gross Domestic Product (GDP). In 2011 the member parks of the APTE invested €1.20 billion in R&D. This investment by the parks represents approximately 9 % of the investment of the Spanish R&D. Noteworthy, too, are the number of companies with foreign capital in 2011, reaching a figure of 244, as well as the 931 incubation companies and the 844 new companies, between companies incorporated within the parks and established companies [5].

More specifically, the case that concerns us here, the Walqa Technology Park (PTW), emerged with the objective of becoming a pole for innovation and R&D, especially in the field of information technologies, biotechnology and renewable energies. Since 2002, it is a full member of the APTE and of the IASP (International Association of Science and Technology Parks). The PTW has a total surface area of 53 ha and 4 out of the 6 phases have already been developed. It currently has 14 buildings where local, regional, national, multinational, new entrepreneurs, universities and technology centres have set up. In December 2012, the PTW

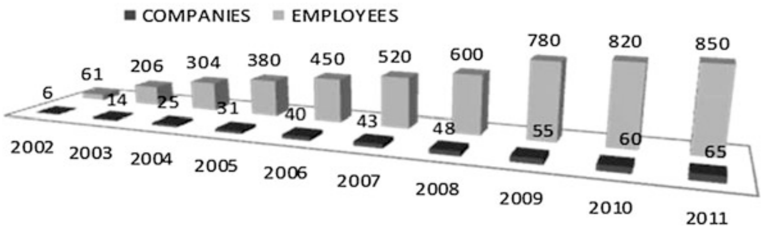


**Fig. 1** Evolution of the Walqa technology park

already had 850 workers in the more than 50 companies set up therein. In illustration 1, we can see the evolution and number of employees and companies since its origin (Fig. 1).

The analysis of the existing inter-organizational relationships, or collaborative relationships between companies, between organizations located in STPs have been subject to analysis from different viewpoints, both academic and institutional [7–10]. Certain studies focus on their importance, their nature and their potential synergies. Other studies aim to give a response to their consequences in the management, market, technological results, or if they entail improvements in business credibility, image and prestige. Siegel et al. [11] show the positive relation between the relationship between companies and innovation. Authors such as Martinez [4] also show that the relationships between the agents of the STPs have a positive effect on the development of new products and services in the companies set up in the STPs. Likewise, the advantages of collaboration between the managing entity and institutions of the STPs and the companies established therein have also been studied. The managing entity of the technology parks makes projects that may have gone unnoticed, become visible thanks to the park. The common thread per se, the park, can also entail a greater tendency toward collaborative relationships between companies and/or obtaining better results.

Our aim, with this recent research study on inter-organizational relationships in a Technology Park, is to contribute to the state of the play of this congress. Thus, we consider that this type of connection between the different agents and companies that we will describe, represent an instrument that permits an increase, not only in the competitive production of each one of the firms set up in these clusters, but also of the actual Park per se, and by extension, of the economy of the region where the activity is developed.

## 2 Method

To analyze companies set up in the PTW, a survey was prepared, which was sent to all the organizations. The survey contains several types of questions. Firstly, questions regarding the characterization of the entities appear, such as the number of workers the company employs, number of years in the park, turnover of the companies, etc. There are also qualitative type questions, mainly about levels of satisfaction levels with other entities and positive aspects for the companies due to the fact that they are established in PTW. More specifically, for this second type of question, the Likert scale has been used. This consists of a group of items in the form of statements with which the reaction of the responder is hoped to be measured. The answers are classified into 7 categories thus showing their degree of agreement or disagreement with these statements. Finally, responders were asked about the types of relationships and the type with other entities with technological/commercial cooperation or bodyshopping agreements. These surveys have been carried out in two different ways: by personal interviews or online.

The main method used to answer the surveys, was by personal interview. Given the relative geographical proximity of the PTW, appointments were made with the people responsible for each company, who were interviewed at their own facilities in the Park. Thus, 40 answers to the questionnaire were obtained, 71.4 % of the total. As it was difficult to arrange meetings with some of the companies, the survey was prepared using the Google Docs tool and especially the Forms application. In this way, another 13 answers were obtained, 25 % of the total. Thus, a response rate of 96.4 % was achieved with a total of 53 entities of the 56 targeted by the study.

Two lines of analysis were established to process the results. Firstly, the surveys were analyzed via the tool provided by Google Docs and secondly, a network analysis was conducted, studying the relationships between the companies depending on their activity, be they companies, R&D centres or universities, depending on the activity sector, and finally in accordance with their size.

## 3 Results

Firstly, the description of the sample analyzed is presented in this section (Table 1). Secondly, the network analysis is presented and here the high response rates must be highlighted, amounting to 94.6 %. In the majority of the cases, the person who answered the questionnaire was the owner of the company or the general manager. Half of them (50 %) are independent external companies and 28 % are subsidiaries of other larger companies and another 10 % correspond to start ups. Another aspect to be highlighted is that currently 59 % of the sample are independent companies and 23 % are subsidiary companies, but with a lot of autonomy.

As we can see in Table 1, the main activity sectors that stand out are the ICT's (18 %), and Computing, Software and Hardware (9 %). These are followed by the Energy-Environment and Medicine and Biotechnology sectors with 7 and 4 % respectively, and finally the Electronics and R&D Centres only represent 2 and 1 % respectively of the total. With respect to the value of the Asset in 2011, 34 % of the sample move in values of over €1 million, 14 % of the sample move in the interval €500,001–1,000,000. Noteworthy is the fact that 37 % of the sample, with

**Table 1** Characteristics of the sample

| Variable | Descriptor | % |
|---|---|---|
| Position of the responder | Owner | 32 |
| | Managing director | 19 |
| | R&D director | 8 |
| | Other | 41 |
| Origin of the enterprise | Independent external enterprise | 50 |
| | Subsidiary of another larger external corporation | 28 |
| | Start-up | 10 |
| | Other | 12 |
| Current, the company is | Independent | 59 |
| | A subsidiary with a lot of autonomy | 23 |
| | A subsidiary with little autonomy | 12 |
| | Other | 6 |
| Activity sector | ICTs | 18 |
| | Computing software and hardware | 9 |
| | Energy-environment | 7 |
| | Medicine and biotechnology | 4 |
| | Electronics | 2 |
| | R&D centres | 1 |
| | Others | 57 |
| Asset value in 2011 | >€1,000,000 | 34 |
| | €5000,001–1,000,000 | 15 |
| | €300,001–500,000 | 8 |
| | €100,001–300,000 | 6 |
| | <€100,000 | 37 |
| Turnover in 2011 | >€5,000,000 | 12 |
| | €1,000,001–5,000,000 | 16 |
| | €300,001–100,000 | 18 |
| | €100,001–300,000 | 20 |
| | <100,000 | 34 |
| Years in the park | 10 years | 14 |
| | 5–10 years | 28 |
| | 1–5 years | 48 |
| | <1 year | 10 |

an asset value of less than €100,000. As far as turnover is concerned, it is significant that 34 % billed less than €100,000 in 2011, followed by 20 % that billed between €100,000 and €300,000. Furthermore, 61 % employ less than 10 workers. Finally, two quite differentiated groups can be found according to the number of years that the companies have been established in the park: almost half of them (48 %) have been in the park for 1–5 years whilst 28 % have been there for 5–10 years.

The Network Analysis is based partly on the graph theory, for which a network is a series of dots or nodes linked together by a series of relationships that satisfy certain properties. What this analysis seeks is to find out the extent to which the entities of the PTW relate with each other, and what factors have an influence on these relationships. The network of relationships formed by the different agents of the PTW is analyzed and then it is compared with the hypothesis that states that the relationships between these agents depend on the characteristics of the entities; in this case, the type of entity, size, and sector of activity. A study of different properties of the network and of the nodes is also performed, such as the density of the network and of the agents themselves, the degree of centrality of an entity the centralization index and the degree of intermediation.

The last type of questions in the survey are analyzed first. In this section, the questions refer to the relationships of the company surveyed with other entities of the PTW. The five aspects they are asked about and the response percentage are as follows: collaboration with Universities and Technology Centres (70.8 %), technological cooperation with other companies (36.9 %), commercial cooperation with other companies (52.1 %), bodyshopping throughout their stay at PTW (7 %), and staff turnover with other companies or entities (13 %).

Secondly, the entities are classified according to three characteristics: type, size and sector of activity. In agreement with the type, the entities may be companies, technology centres or universities. In accordance with the size, each one of the entities is classified into micro-company, small company and medium company. Finally and depending on the sector the companies are classified into, those pertaining to the ICT sector, followed by the engineering and energy sector are the ones that have the greatest relationship. The result of the companies from the ICT sector was foreseeable, as they are the most numerous, with the highest innovation capacity and with such broad fields of application that they permit collaboration in diversified projects. After analyzing the companies with the aid of the UNICET 6 program, the network they comprise is developed and studied. This is one of the most commonly used computational tools for the Analysis of Social Networks.

## *3.1 Type of Entity*

In this first diagram (Illustration 2) an overview is given about how the entities of the PTW relate together. The circles represent each one of the companies surveyed, the squares symbolize the technology centres and the triangles correspond to the two universities set up in the park. In the figure, the link between entities widens, depending on the number of relationships they have (weight of the nodes). We can observe that the universities are the two central nodes of the diagram, followed by the technology centres with a considerable number of connections. Another additional advantage is that, on the following these centrality patterns, they can act as intermediaries between other nodes. On the other hand, there are companies that, like the technology centres and the universities, are very well-connected, thus comprising, together with the latter, the central structure of the network. Contrary to this, eight companies also appear in the lower left of the image, which do not maintain any contact (Fig. 2).

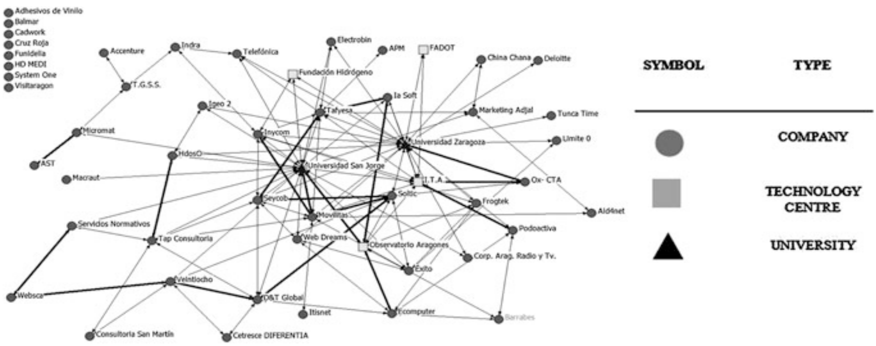


**Fig. 2** General network

## *3.2 Size*

Regarding the size of the companies that have a more important role within the network, we can see that not because they are big are they better related to the rest, but that companies of all sizes are present in Illustration 3. The size of the company can be distinguished depending on whether the colour is lighter or darker; the darker the colour the larger the company is. In principle, it may be thought that larger-sized players that: carry out more radical innovation processes, but have a more extensive customer portfolio within the actual technology park, with a larger number of technological corporation relationships between universities, would appear in the more central parts of the network as better related entities. Surprisingly, there is a larger number of smaller size companies that are very well-positioned and with an important number of relations (Fig. 3).

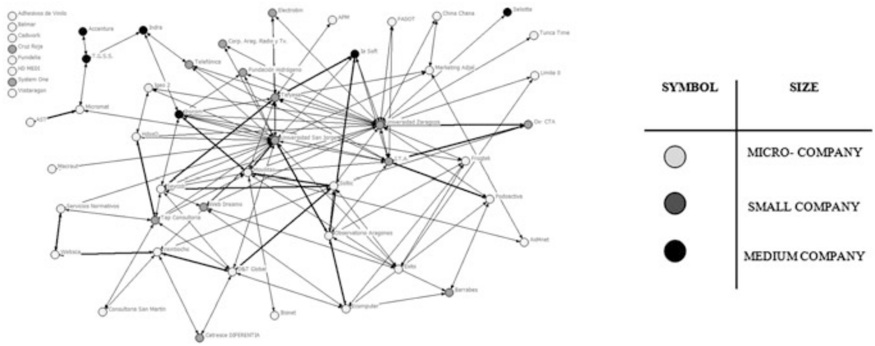


**Fig. 3** Network according to size

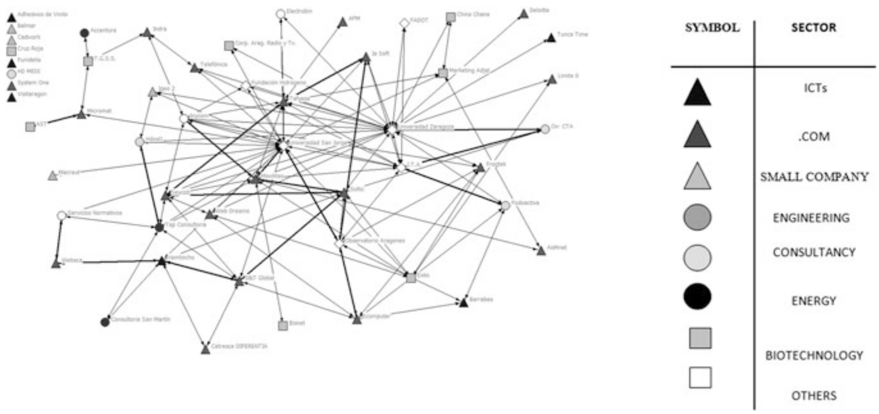


**Fig. 4** Network according to sector

## *3.3 Sector*

Finally, a classification has been made depending on the sector where the companies develop their activities. The companies have been classified into the different sectors as we can see in table 1. In Illustration 4, we can observe that in the area with the greatest density of interrelations, the companies that develop their activities in the ICT sector together with universities and centres are more important. This is due to the fact that this sector has great versatility to collaborate with other companies. This type of company has tools and resources that permit managing the information through the use of technologies, obtaining an exchange and distribution of all kinds of information, for all kinds of people, companies, or entities (Fig. 4).

## *3.4 Other Properties*

Finally, to conclude with the analysis of the network, a series of calculations have been made to study different properties of the network in general and of certain nodes in particular through the UNICET program. The density of the network has been studied in the first place. This is defined as the percentage of the relationships that are established with respect to the total number of relationships that could have been established. It has been taken into account that there is one relationship between each couple of nodes out of the five that could exist; in this case the density of the network is 7.82 %. The centralization index that responds to the special condition, whereby an actor exercises a clearly central role on being connected to all the nodes of the network, has also been calculated. Thus then, a 100 % index would correspond to the fact of being connected with all the nodes, that is, a star network, whilst an index of 0 % would correspond to the situation of a mesh network. In this case, the network has an index of 19.12 %. The last property calculated is intermediation. This concept is related to the frequency with which a node appears in the shortest path that connects another two nodes; that is, the geodesic path. Once again the universities are at the fore but we can observe how companies such as Movilitas and Veintiocho Estudio Creativo become important as they are well situated when connecting pairs of companies.

## 4 Discussion

One of the aims of this work was to analyze the companies set up at WTP, studying their level of satisfaction with being located in the park. Furthermore, we have studied the different collaborations with other entities, as the actual firms consider this to be a focal point to increase the competitiveness of their products or services. It is a process that both parties involved benefit from, as each one is specialized in a production phase that the other party does not have to carry out, therefore, allowing each one to focus on improving the specific activity they develop, within a common joint project. Below, we set out the main conclusions that can be drawn from this study. We can divide them into two groups: those referring to the concept of Science and Technology Parks as business clusters; and those that we have obtained about entities set up in this Park and the collaborations with other entities set up in the same Park.

Later the study focused on the PTW. As we have mentioned, we carried out a survey where we were able to see what type of entities the companies collaborate with: More than 50 % of the firms set up in the Park collaborate with nearby universities that are related to these clusters. 62 % collaborate with the technology centres located in the actual Park. Insofar as collaborations between companies located in the same location are concerned, it was documented that almost 70 % of them maintain technological cooperation agreements with others. We consider this information to be especially relevant as it is indicative of the benefits, already mentioned in the introduction of this section, which they can obtain from this type of relations. We have also verified that, on certain occasions, this collaboration is not total but partial. Thus, we have learnt that 56 % maintain commercial cooperation agreements. Other data obtained from our survey are especially important regarding those interrelations that occur to a lesser extent. Indeed, just 8 % state they carry out bodyshopping with other companies in the park—computer term that refers to the sale of human capital and entails the transfer of this type of personnel to third companies for profit-. On the other hand, it is worth mentioning, too, that 13 % state there is staff turnover—expression that is defined as the number of workers who leave and come back in, with respect to the total workers of a company, sector, hierarchic level, department or post. Unlike the previous case, this is an exchange, and not a sale, of people between the organization and its environment- (Illustration 5) (Fig. 5).

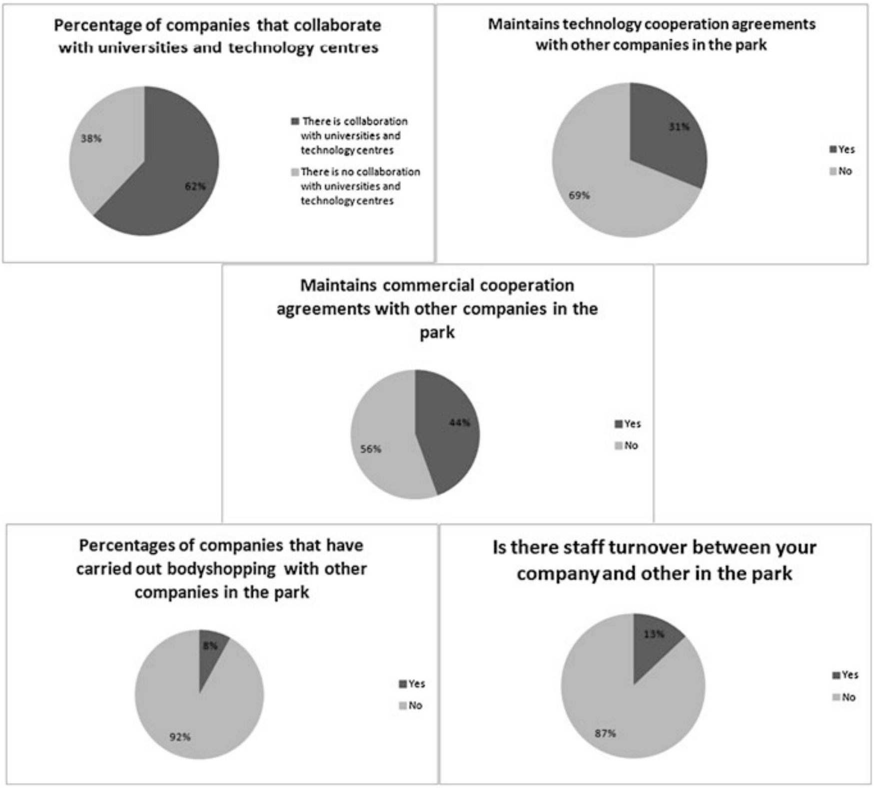


**Fig. 5** Collaborations

In the aspect of new innovation policies in the organization and management in the companies based on the relationships established in the park, it can be concluded that these relationships have not been decisive as the companies take up neutral positions respect to these statements. Regarding the level of satisfaction obtained, there is no doubt whatsoever, 90 % of the companies have an excellent relationship with the management body of the park. The same occurs with relationships established with other companies, universities and technology centres.

After analyzing the network made up by the entities set up in the PTW, the following conclusions can be drawn: from a general viewpoint, we can clearly observe the appearance of strong patterns of centrality that unite entities such as the technology centres and the universities in the central area of the network, as they represent the largest number of technological collaborations and of staff collaboration. These centres are mainly and most especially, the University of Zaragoza, San Jorge University, the Aragonese Observatory, and companies such as Ecomputer, Movilitas, Tafyesa, and Seycob which have the strongest links both due to the quantity of relationships that they have and due to the quantity of relationships they have with one single company. This makes them form a stronger connected sub-network.

From the viewpoint of size, unexpected conclusions have been obtained. In principle, it could be expected that the better situated and related companies would be the large business groups, large-sizes nodes, of which a higher level of innovation and greater quantity of relations is expected. Indeed, we can find companies of this type in the central network such as Inycom or Iasoft, but it is surprising that small-sized companies, classified previously as micro-companies (with less than 10 workers) appear in the central network with a very high number of collaborations. Some of these micro-companies are Movilitas, Soltic and D&T Global.

Finally, depending on the sector the companies are classified into, we can observe that the most related ones of those belonging to the ICT sector followed by the engineering and energies sector. The main role of the companies belonging to the ICT sector was foreseeable as they are the most numerous, with greater innovation capacity and with such extensive application fields that they permit collaboration in projects where the companies share resources, technologies, and staff.

As future work lines, the same analysis could be carried out in other Science and Technology Parks in Spain and even abroad and thus be able to compare the results obtained with the results obtained in the PTW. It would also be interesting to apply this analysis method to groups of companies in other areas, not only entities set up in parks. Thus, a comparison could be made and conclusions could be reached about the advantages and disadvantages derived from being set up in a STP.

## References


1. Phan P, Siegel DS, Wrigh M (2005) Science parks and incubators: observations, synthesis and future research. J Bus Ventur 20(2):165–182
2. Ondategui JC (2001) Los Parques Científicos y Tecnológicos en España: retos y oportunidades. Ed. Dirección General de Investigación de la Comunidad de Madrid
3. Méndez R (2010) Estrategias de innovación industrial y desarrollo económico en las ciudades intermedias de España. Atlántida Grupo Editor. Madrid
4. Martínez Cañas R (2009) Las relaciones interorganizativas y la generación de capital social en parques científicos y tecnológicos. Ed. UCLM. 2009
5. Memoria de Actividades. Asociación de Parques Científicos y Tecnológicos de España, 2011
6. Maillat D (1995) Millieux innovaterus et dynamique territorial. Economie Industrielle et économie spatiales. Económica. París, pp 211–231
7. Link AN, Scott JT (2066) U.S. University research parks. J Prod Anal 25(1–2):43–55
8. Vázquez G, Scott JT (2006) U.S. university research parks. J Prod Anal 25(1–2):43–55
9. Fukagawa N (2006) Science parks in Japan and their value-added contributions to new technology-based firms. Int J Ind Organ 24:381–400
10. Löfsten H, Lindelof P (2005) R&D networks and product innovation patterns-academic and non-academic new technology-based firms on science parks. Technovation 25(9):1025–1037

11. Siegel DS, Westhead P, Wright M (2003) Science parks and the performance of new technology-based firms: a review of recent U.K. evidence and an agenda for future research. Small Bus Econ 20:177–184
12. APTE (2007) Estudio del Impacto Socioeconómico de los Parques Científicos y Tecnológicos Españoles. Ed. APTE

# Distributed Manufacturing System in a Multi-Agent Approach: An Application for Oil Field Management

**A. P. M. Tanajura, V. L. C. Oliveira, H. A. Lepikson and F. G. M. Freires**

**Abstract** Multi-agent systems have been successfully used to represent distributed manufacturing systems. Each part or characteristic of the system can be represented by an agent which acts independently and in a cooperative way. Information exchange between agents and combined individual rules for each agent can lead to the emergence of a better integrated operation. Better decisions from a holistic viewpoint can be achieved when manufacturing asset management is supported by a multi-agent approach. A model to manage distributed manufacturing is proposed and applied to onshore oil fields. The distributed characteristics of oil field units, such as wells, collecting stations, compressing stations, supplies, and mean that they have to cooperate to reach production targets. The integrated management model carries out a cost analysis and helps to identify unprofitable assets and to support decision making processes as well. Agents help to reduce the load of information for the operator, giving him/her more time to focus on situations that require greater attention. Successful applications in which the proposed multi-agent model could help oil field surveillance and support decision-making process are presented.

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## 1 Introduction

An agent is a computational system that is situated in an environment and that is capable of acting independently in this environment in order to achieve its design goals. In multi-agent systems, the ability for interaction indicates that they may be affected by other agents, or by humans, and perform tasks in pursuit of their goals [1]. This is a typical in supply chain situation, where agents represent different links in this chain such as suppliers and customers in several instances.

Some authors present successful solutions for the application of multi-agent systems for problems in supply chain integration [2–4]. According to [2], Multi-agent Systems seem appropriate for supply chains because the different business units involved can be modeled as autonomous agents, as well as their management rules. For [3], the potential benefits of this approach are: the establishment of an effective mechanism for trading; the adoption of a technology for multi-attribute negotiation; the offer of an effective mechanism to improve performance across the supply chain, thus supporting decision-making. To achieve the desired level of collaboration, [4] presents a decentralized approach to the supply chain through three subsystems based on agents. The first is the communication subsystems within the plants (which will manage unforeseen events that may cause the need for new production schedule of the plant or part of it). The second is the interplant communication subsystem, which will manage events occurring in a plant that will affect other plants. Finally, the third is the communication subsystem of the supply chain, which will manage events in the plant that affect suppliers and/or external customers.

An oil field can be considered as a set of distributed systems consisting of surface facilities, wells, reservoirs, logistic systems, suppliers and staff working in the system. The supply chain approach is useful to study oil fields because it allows an enlarged analysis of decision, similar to a network of integrated operations. The proposed model seeks to represent each of the production functions of the field as an agent, as well as their relationships with service providers and equipment and the maintenance staff.

The independence of the agents is also a desired characteristic for oil fields, since production systems may evolve over time. Changes can be easily amended without any model modification. For example, a well may change its mode of production or even change its function from producer to water injection well, or a new collection station can be incorporated into the model.

Internally, the operatives seek the best result through cooperation rules that lead to greater profitability for the asset. The operatives are connected through a flow value where there is an increase in value at each stage as the raw material moves along the transformation process. The management involves the administration of manufacturing value stream (monitoring resources used at each stage of the process) as well as investments for improved outcomes of the system.

Externally, maintenance and provision service suppliers compete for work on the oil field. Therefore a natural progression of service improvement can be achieved through a careful selection of service providers on the oil field. The independence of the agents and their capacity to act and react also reflects the possibility of using them to monitor the facilities, minimizing some of activities previously undertaken by operators. This condition can lead the oil field to function as an unassisted plant.

## 2 Challengers in Oil Field Management

According to [5], there is huge complexity involved in managing an asset operating in the oil and gas industry. For the authors, the management of these assets is a complex activity due to several factors, among them: the need for physical control while physical and chemical rules of procedure are respected; frequent changes in operation according to economic, social, and strategic needs; equipment reliability and criteria of integrity, and safety of staff working on assets. The authors consider that the management of operating assets is the joint work of several disciplines and hierarchies. It requires the coordination of people and their knowledge of procedures incorporated in the work and the coordination of business processes. This can only be successful if it is guided by a clear strategy with stakeholders who are mobilized and aligned to the strategic objectives.

Traditionally, according to [6], efforts to increase the ultimate capacity of oil recovery have resulted in competition. This has often resulted in incompatible plans and proposals from various disciplines of the asset management team. Each one focuses on issues in their respective areas, but they have no ability to understand the ramifications for other disciplines or the asset as a whole.

The complexity of the problem is further aggravated by restrictions arising from the current workforce. The retirement of senior professionals reduces the number of experienced workers in the area of oil exploration and production. A small team means that fewer people understand the complexity and implications of competing proposals, and few people are qualified to evaluate these proposals and make recommendations. The authors also point out that the ultimate goal of all team members of a group of assets is to make decisions that benefit the entire business, not only their respective domains [6].

Yero and Moroney [7] corroborate [6] with regard to the difficulty of forming a technical body. From the authors' experience at Shell Exploration and Production, he mentions the difficulty of transmitting knowledge and lack of methods for sharing information in the technical area. This makes it imperative to implement systems that optimize people's time, standardize the work, capture knowledge, and automate surveillance activities.

In the opinion of [8], the areas that compose assets, such as wells, reservoirs, and facilities, are well developed but separate. There is a need for engineers to understand the systems in an integrated manner and they should be able to perform cost estimates for the facilities. This competence will enable better assessments at various stages that make up the development of active installations, reservoirs, and wells.

Rahmawati et al. [9] have had positive results with optimization and integrated operation of oil fields including the reservoir, the surface facilities, and an economic model. They believe that the current industry still has a very segmented supply chain. Each part of the chain is treated separately from the other. The authors attribute this to the fact that in different parts of the chain people are recruited with specific knowledge and use different tools to support decision-making. This limits integration, even in situations where integration has clear potential.

Many technologies for digital oil fields have been developed [10] and applied [11, 12]: Remote Real-Time Facility Monitoring and Control, Real-Time Production Surveillance, Intelligent Wells, 4D Visualization and Modeling, Remote Communications, Workflow and Knowledge Management Systems. These models represent an evolution from existing production workflows and applications in a collaborative decision-making environment that brings together reservoir, production, and process engineering domains [12]. All of these help to reach useful Integrated Asset Models. Nevertheless, these models are almost static, based on pre-determined configurations and, in general, have a hierarchical configuration, which results in useful but limited deterministic solutions. A distributed and non-deterministic model is needed to capture whole potential of the integrated asset management system required.

The authors [5–9] highlight the possibilities of gaining advantage with integrated asset management in the oil and gas industry, and [10–12] suggest some solutions in this direction. However, in spite of the technological development [12], there is much work still to be done in old assets, to solve the lack of: communication between different areas, integration between systems, standardized methods and procedures, or even trained professionals.

There is a gap in the oil industry: the need for decision-making taking into account not only the production systems, but also other elements that constitute the supply chain of this industry. There is the possibility to offer the engineers and managers an integrated view of an oil field including service providers and cost analysis of each part of the field. This situation is even more critical in mature oil fields. In these, the yield is not as high as more recent ones and operation investment is not justified in all such fields [13]. Thus, this research aims to improve decision-making in onshore mature oil fields through an analysis of economic variables and techniques. It considers the oil field as a set of wells, reservoirs, surface facilities, suppliers, and teams which act to release the oil and pipe it to the refinery in processing conditions.

## 3 The Model

Because the elements that compose the field are distributed in nature, similar to a supply chain, a multi-agent approach presents a suitable solution for modeling the oil field. This has been observed by different users of this approach [2–4]. The independence of the agents is also a desired characteristic for oil field. The production systems can be modeled separated with specific rules and production targets. In oil fields, the production systems may change over time, e.g., the mode of production of a well may change or even its role from oil producer to water injection well or a new collecting station can be incorporated into the model. In the multi-agent model, these changes can be done without modifying the whole model. The model can provide the platform that pulls together simulations, economic models, to provide a total asset solution with full transparency and capabilities to seek optimization along the entire value chain. Each agent in the model can access different existing systems, with their own local culture, to reach a better global solution.

The independence and capacity of action and reaction of the agents also reflects the possibility of using them to monitor facilities, minimizing some of the activities previously undertaken by the operator. As previously mentioned, this can lead the oil field to be an unassisted plant. When the agents are intelligent, in addition to monitoring, the system could evolve to analyze the situation, to suggest action, and to act, resulting in better conditions for the entire field.

After creating a generic model where agents are described, rules are defined, and relationships are mapped, we conducted a case study to confirm the expected benefits. For the case study, a mature onshore oil field located in the state of Bahia (Brazil) was chosen. The field has around 200 wells with an estimated production of 270,000 bbl/month. We used monthly data over a period of 5 years. Some variables that had no historical record or measurements were estimated by professionals.

Another aspect to be considered in the construction of the model concerns the ontology. The ontology is the representation of abstract concepts such as events, time, physical objects and beliefs. In multi-agent systems, this is the knowledge representation of the agent. All the actors involved in the same environment and that relate to each other must share the same ontology. The possibilities for status display of industrial control systems based on ontology are mentioned by [13]. According to the authors, the use of ontologies for an explicit description of the world has many advantages, including ease of integration and extensibility. The fact that knowledge in the system is expressed in a standardized semantic form contributes to a uniform view of the system as a whole and as individual agents. The development of the ontology contributes to a proper construction of the architecture of the model, and to define the rules that will lead to cooperation among the agents to achieve a better result in the field as a whole. The ontology of the proposed model will be detailed and presented in another paper.

## *3.1 The Multi-agent Framework for Oil Field*

The proposed model considered three types of agents: operational, intervention and supply agents (Fig. 1). These agents are classified according to their role in the supply chain. The operational agents are those directly related to production. They do the processing of the product from extraction of oil and gas from the reservoir to the refinery. This category of agent includes: wells and other smaller stations; collecting station; carrier systems; compression unit; oil transfer unit; water handling and injection units; and storage unit. Intervention agents are those who perform preventive or corrective maintenance in industrial facilities, as well as small repairs and even larger investments. There are two types of intervention agents: internal and external intervention agents. The latter are partner companies that perform services and are managed by internal intervention agents. The external supply agents procure inputs (spare parts, chemicals and other necessary items to conduct operational processes) for production and are driven and coordinated by the internal supply agent.

An input and output analysis in each of the agents has been performed. This assay was carried out in order to identify input and output variables in each set of agents and their dependency relationships among them. It is noteworthy that, with the advance of oil and gas from the reservoir to its transfer to the refinery, there is added value along the supply chain. The oil at the output of a production well has a lower value than at the output of the collection station, e.g., difference in value between a production well and its collecting station is the cost added by the collecting station to perform its function. The complete flow from wells to refinery can be seen in Fig. 1 below.

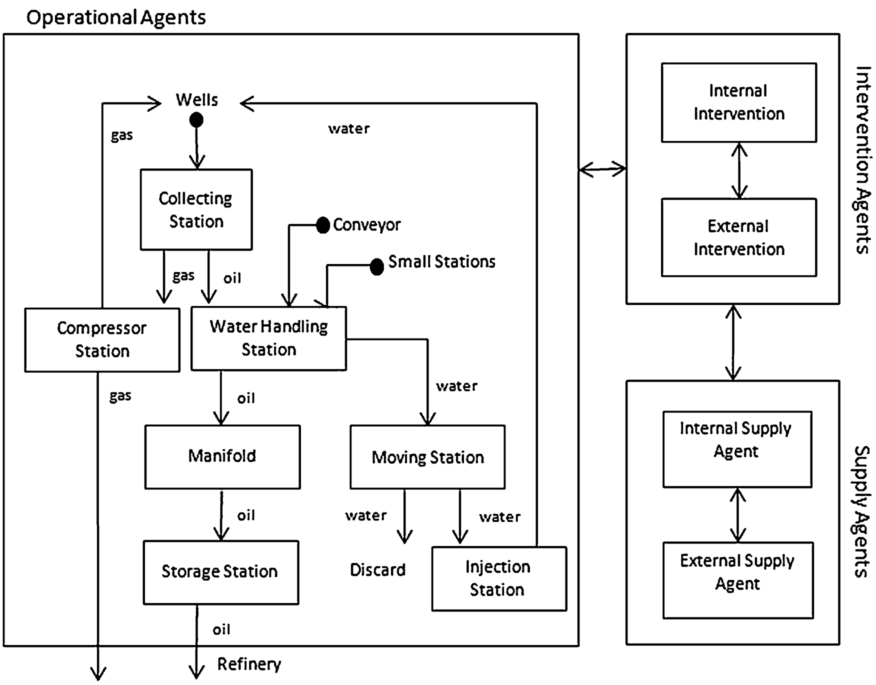


**Fig. 1** Multi-agent framework for an oil field

The costs incurred by each operating agent are the expenses needed to perform their functions, such as labor, energy, supplies, and maintenance service requests. The latter are made by the internal intervention agent who may require the supply agent to procure services, parts, and equipments. The agent that performs the service will have a price paid by the agent who requested the service. The operational agent, that provides the product with a cost to other agent, will also have an income, paid by the one who purchased it. Thus, incomes are amounts paid for services rendered or products purchased by other agents.

The profit function can be obtained from the difference between incomes and costs for the entire system as well as the agents individually. For the sake of simplicity no physical losses or accumulation are considered in each of the agents in the model and the amount of product that arrives at the agent is equal to the amount that leaves it.

The product gains added value in each part described in the framework. After passing the agent, the oil or gas assumes a value that is at least equal to its value on arrival at the agent plus the costs incurred by the agent that performs the operation. For the all assets it is considered that:

$$\text{Profitability} = \text{Gain} - \text{Costs}$$

where, Gain = Oil volume transferred to refinery + Gas volume transferred to refinery

Costs = maintenance cost + investment costs + team costs + supply costs + energy costs + raw material acquisition costs; at each point of system.

The injection agent provides an important service to the oil field: supplying pressure from water injection with the goal of increasing oil production. The location of the injection point of water in the reservoir, compared to other production wells, influences the production at each of the wells. Thus, it is considered that the total cost with the water injection in the reservoir should be distributed among the wells that benefit. There is a cost consideration for the distance between the production well and the injector well so that the greater the distance the lower the cost associated with the well.

This "simplification" is useful as the effect of oil injection into a reservoir affects the production in each well differently. There are geological factors that exert their influence on production and consequently the results of the actions of injection, but they are not considered in this model. It is assumed that the closer the well is to the injection point the greater the effect of the action on the production of this well, therefore the higher the cost borne by this well agent.

The agent can trigger alerts whenever the cost or performance is not compatible with its function. For example, if the cost of a well exceeds the revenue from the volume of oil transferred to the collection station, the agent can send a warning message about this. Alerts sent may signal the need for intervention, investment, changes in the wells settings, or even the abandonment of the operation, depending on the rule modeled for each agent within the context of the field.

## 3.2 Results

The framework was initially designed emphasising relationships between agents in order to represent the actual conditions in the oil field. Despite the plethora of service types, materials and equipment that can be used the oil field, only 2 types of possible intervention services were included, type 1 and type 2, for intervention agent and only 2 categories of materials procured by the supply agents: categories A and B.

JAVA was used as the programming language. It was chosen for its simplicity of coding; it is an object-oriented language; it is useful for the development of mature environments and is freely available. It is worth noting the portability that JAVA language provides by allowing program execution regardless of operating system. JAVA components such as the Framework Java Agent Development Framework (JADE) were used to facilitate the implementation of multi-agent systems obeying features and specifications such as autonomy, reasoning ability and knowledge-based messaging.

The modeled system in JAVA is also useful as a tool for monitoring production systems from established rules based on Statistical Process Control (SPC). The figures below show the two main screens of the system. They were designed to be the field manager's interface. Through the screens (still in Portuguese) an integrated view of all systems can be displayed; the income of every production elements and the income of the entire field (Fig. 2). This figure shows an overview of the production system with its operational agents. It is possible to see the flow from wells (Poços) to refinery (Refinaria). The economic result for each agent and the whole field is shown on this screen (Valor de saída).

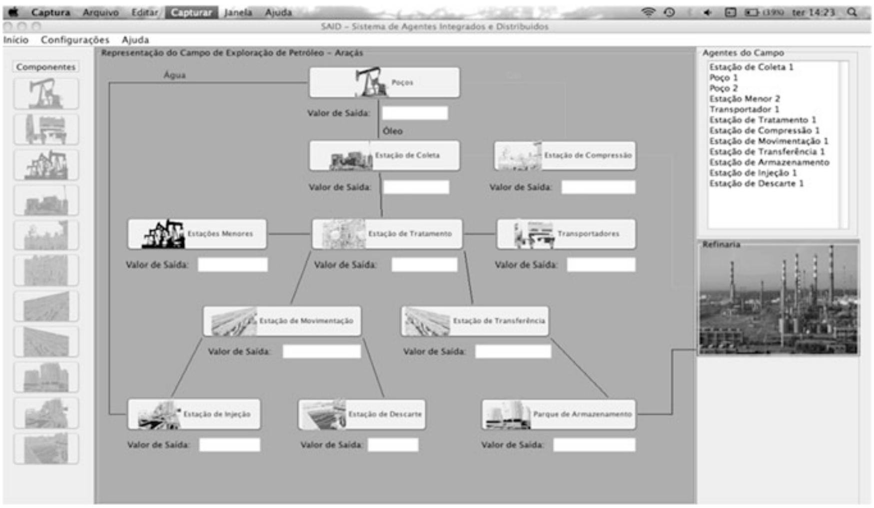


**Fig. 2** The main screen


**Fig. 3** The screen showing a production graph (*1*) and messages exchange among agents (*2*)

It is also possible to follow the history of production and cost variables graphically, with a comparison between the current state and prior periods. Messages exchanged between agents in the system can be seen as well (Alerta, in Fig. 3).

The system should evolve to a condition where the agents are intelligent and do not simply react to rules. They need to be programmed in order to indicate the best operating condition, or service to be performed. To achieve this, the environment of the agent must reproduce the oil field and the agent must learn and develop its own knowledge. The learning process of the agent is based on the evaluation of actions and in the reinforcement of those that are better suited to the desired goal. Artificial intelligence techniques are embedded in the agents to achieve this.

Finally, it can be said that the system as a whole has some motivations: oil field units with distributed characteristics should cooperate to reach production targets; oil field integrated cost analysis provides identification of unprofitable areas which helps to make better decisions and investments. In mature oil fields profitability analysis is especially important, as investment rises to keep production steady; intelligent agents help to reduce the load of information to the operator, giving him more time to focus on situations that require his attention. It is a tool for real time simulation and diagnosis with a holistic approach, and this is the next step in this research work.

## 4 Potential Benefits and Conclusions

The framework proposed for oil fields management is a PhD project from Federal University of Bahia, Brazil. This project, which has been developed in our research group, offers a systemic view for operators, supervisors, and managers who are involved in decision-making processes. The integrated view of the oil field in one main display screen with cost analysis gives to the engineer a view of all the impacts arising from the decision-making process and areas affected by this process. It alerts to the importance of criteria for prioritizing investments and services that maximize the overall result of the field.

The model, supported by digital oil field technology, also helps in the identification of inefficiency. The agents act as supervisors identifying potential problems and alerting inefficient conditions. The Alerts are generated from Statistical Process Control rules. When a production or cost variable reaches an upper or lower control limit an alert is issued for this condition. Through artificial intelligence techniques, rather than simply detecting points of inefficiency, the model can still evolve for solution detection and implementation. An intelligent agent can indicate a better production strategy, a more reliable supplier, the right intervention, and direct the oil field toward profitability.

The operational performance analysis is reflected through the cost of oil at each stage of the process and the income of the whole oil field shown on the main screen of the system. Here there are graphs showing income and investment costs for each stage of production, for example, oil extraction, gas compression, and water handling process. The manager has critical information for the asset management, investment prioritization, and analysis of the flow value with cost information of extraction and oil processing at each point of the system.

It is also possible to do some simulations and investment and disinvestment analysis. For example, it is possible to disable wells, to include new injector wells, to change services providers and supplies. These changes in network operations can be tested with new operation conditions, even before they enter into operation, always with a focus on maximizing the overall result of the field.

Internal engineers focus on one of the stages in oil field, such as wells, surface facilities, and suppliers. This may lead to the optimization of a number of subsystems; however, the sum of the optimized subsystems may present a problem for the optimization of the system as a whole. So the system proposes an integrated view and applies agent technology in the whole oil field from a systemic perspective.

The proposed model was developed based on an oil field located onshore in Brazil, but the proposed approach can be extended to other applications, including off-shore oil fields. Each operation on the platform, wells and other ground support systems can be represented by agents. These intelligent agents modeled with cost information and production data for each production system can help managers to make more rational decisions.

Finally, it can be said that the proposed model integrates the various systems in an oil field and each production step is modeled as an intelligent agent. Each stage of production has individual goals and performance and they interact with other agents in a collaboratively way to achieve the overall goal of the field. It offers an effective mechanism to improve the oil field performance, improve the decision-making process, offering a systemic view for operators, supervisors, and managers and provide new perspectives for oil field management. We believe that the model proposed can be successfully applied to oil field management on a daily basis and further evaluation will be carried out to validate its effectiveness in gathering intelligence from real operators in real applications.

## References


1. Wooldridge M (1999) Intelligent agents. In: Weiss G (ed) Multiagent systems—a modern approach to distributed artificial intelligence. MIT Press, Cambridge
2. Ferreira L (2009) Um modelo de simulação baseado em agentes para análise de cadeias de suprimentos. PhD thesies, Universidade Federal do Rio Grande do Sul, Escola de Administração, Programa de Pós-Graduação em Administração, p 179, 2009
3. Jin CH, Li QM (2008) Study on a multiagent construction supply chain management system. In: Proceedings of 2008 4th international conference on wireless communications, networking and mobile computing, 1–5, IEEE, doi: 10.1109/WiCom.2008.1606, 2008
4. Álvarez E, Díaz F (2011) A web-based approach for exceptions management in the supply chain. Robot Comput Integr Manuf 23(2):217–233. doi:10.1016/j.rcim.2010.12.004
5. Al Meshabi O, Khazandar M (2010) Attitude of collaboration, real-time decision making in operated asset management. In: Proceedings of SPE intelligent energy conference and exhibition, Utrecht, The Netherlands, 23–25 Mar 2010
6. Cabrera B, Musri D, Selva C, Lardone C (2007) Developing a holistic global approach to asset management. In: Proceedings of SPE annual technical conference and exhibition, Anaheim, California, U.S.A., 11–14 Nov 2007
7. Yero J, Moroney TA (2010) Exception based surveillance. In: Proceedings of SPE intelligent energy conference and exhibition, Utrecht, The Netherlands, 23–25 Mar 2010
8. Boschee PAM (2012) Challenges of accurate cost estimation. Oil and gas facilities, 2012
9. Rahmawati SD, Whitson CH, Foss B, Kuntadi A (2012) Integrated field operation and optimization. J Petrol Sci Eng 81:161–170
10. http://www.booz.com/global/home/what-we-think/reports-white-papers/ic-display/41901842. Accessed 12 Mar 2013
11. Al-Khamis MN, Zorbalas KI, Al-Matouq HM, Almahamed SM (2009) Revitalization of old asset oil fields into I-fields. In: Proceedings of SPE Saudi Arabia section technical symposium and exhibition, Al-Khobar, Saudi Arabia, 09–11 May 2009
12. Lima CBC, Sobreira G, Rossi D, Kumar A, Sauvé B (2010) State-of-art digital oilfield implementation in Petrobras Campos basin. In: Proceedings of SPE intelligent energy conference and exhibition, Utrecht, The Netherlands, 23–25 Mar 2010
13. Obitko M, Vrba P, Kadera P, Jirkovský V (2011) Visualization of ontologies in multi-agent industrial systems. In: Proceedings of IEEE symposium on emerging technologies and factory automation, ETFA, 2011, proceedings of 2011 IEEE 16th conference on emerging technologies and factory automation, ETFA 2011
14. Babadagli T (2007) Development of mature oil fields—a review. J Petrol Sci Eng 57(2):221–246

# Part V
# Lean and Six Sigma Applications

# Exploiting Augmented Reality in Lean Manufacturing: Opportunities and Challenges

**Francesco Capozzi and Marco Sacco**

**Abstract** The purpose of this paper is to investigate Augmented Reality applied into a real industrial context (Industrial AR) from a new perspective: AR is not anymore seen as a standalone technology for assisting specific manufacturing tasks, but rather as a totally integrated framework within future factory workplaces. In the last 15 years, both academic and industrial research communities have seen the huge potentiality of AR in improving industrial performances in several scenarios, but it is undeniable that no killer-apps or de-facto standard as well as scalable solutions have been developed yet. The paper addresses the issue from a new and different point of view showing how AR can potentially be exploited in order to boost lean-based manufacturing and management processes, thus guaranteeing more efficient production and higher competitiveness. The paper is organized with the aim to underline the new and feasible opportunities offered by the proposed approach, as well as the main technological and conceptual challenges connected to it. Finally, a potential framework capable of enabling AR features for visual management in real factories is proposed.

## 1 Introduction

Augmented Reality (AR) application to industrial scenarios has gathered growing interest in the recent years, and the main reason behind this success is its potentiality to improve or support user ability in doing certain tasks, by literally augmenting the amount of available and useful information. Industrial production and management, on the other hand, have evolved in their history especially thanks to the adoption of new technologies able to boost performance of several processes.

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The aforementioned concepts clearly explain why, in the past 15 years, both academic and industrial research communities have strongly worked and invested in developing AR-based technological solutions to be applied in multiple contexts of the lifecycle of a production site. In literature, there are several articles presenting demonstration sessions where AR is applied in a wide variety of scenarios such as assisted picking, assembling, and maintenance (see [1–3] for a non-comprehensive list of articles).

Nevertheless, it is undeniable that this effort did not completely pay out yet, since most of the solution developed in Industrial AR context did not make it “out of the lab,” meaning that only a small percentage of them was successfully deployed in practical scenarios and actually used within industrial context. Many researchers already covered the problem of the lacking of an AR killer-app. As mentioned in “Is there a reality in Industrial Augmented Reality?” [4], the author classifies most of the state of the art existing solutions and find out that almost all of them result incompliant with some simple requisites such as the practical ability to be applied in real contexts and their actual cost benefits. The author concludes affirming that the answer to the question in the title is, nowadays, still negative.

In Ref. [5], author notices that a killer application should be (1) reliable, as it should provide robust and reproducible solutions, (2) user friendly, since users must find them safe and easy to set up, learn, use, and customize, as well as (3) scalable, being able to be applied beyond simple prototypes and be easily reproduced and distributed in large number by plant owners, operators, and manufacturers. Furthermore, an important aspect is represented by the economical sustainability, meaning that AR should solve problems that cannot be solved with less money by applying other technologies. There sure are many different reasons that explain the lack of such affordable solutions; one of them, for instance, is most likely represented by the important technological challenges to be overtaken, and consequently by the high cost of involved technologies.

The aim of this paper, however, it is neither to analyze such reasons, nor to undervalue the importance and the potentiality that AR offers to industrial contexts. The authors rather propose a new way to approach the development of new augmented reality applications, which in our opinion would (at least) partially solve some of the aforementioned issues.

In a highly competitive context as nowadays global market, any technological innovation has to aim at lowering production costs and timing thus boosting overall performance. In order to respond to this need, industrial AR should be addressed with a new perspective, that is tackling the fundamental requirement that an actually affordable solution should respect: scalability. From this point of view, scalability represents the capability to deploy the same core application to a wide variety of scenarios and fields of application. Switching the point of view from task-centred AR applications to scalable ones could also lead to the definition of some widely approved and standard solutions. The benefits of this approach are obvious, since efforts of many actors could be channeled toward a unified objective with the effect of bringing down development and technological costs.

Under these perspectives, lean-based manufacturing and management represent the killer-scenarios for truly exploiting scalable and affordable industrial augmented reality. Lean thinking is a comprehensive organization method that aims at improving production, services, and process performance. Lean manufacturing, in particular, is derived from the successful manufacturing organization implemented in Toyota [6]. Lean manufacturing is based on the main concept of completely eliminate the waste. The idea is that any operation and action, as well as any goods or object that does not add any value to the process (or product) should be eliminated. The latter is implemented by efficiently using resources and empowering teamwork and information sharing with the results that lean manufacturing uses, in general, less resources than typical mass production methods.

Despite lean thinking concerns every activity and process, the paper focuses on the information sharing and communication that represent, within a company, a task of fundamental importance. Authors address the concept of visual factory [7], which is a lean-based approach that aims at improving information transfers through intuitive visual approaches.

The key point is how augmented reality can be fruitfully exploited under lean perspectives in visual factories that will therefore become virtual factories, eliminating waste and adding value by delivering the right information, to the right person at the right time.

The paper is organized as follows. Section 2 provides an overview on AR history and technology; Sect. 3 tackles the concept of visual factories and visual control for both manufacturing and management. In Sect. 4, the opportunities that augmented reality offers to boost visual factories performance are presented. In Sect. 5 the focus is the conceptual and technological challenges connected with this new approach. In Sect. 6 authors propose a conceptual scheme that enables AR in virtual factories. Section 7 draws the conclusions.

## 2 Augmented Reality at a Glance

Augmented reality is a variation of the most known virtual reality (VR) that is a technology that creates a digital 3D environment in which the user is totally immersed inside a computer-created virtual world, with no perception of the real world that surrounds him.

In its most general definition, augmented reality is a form of mixed reality where something virtual is added to the human natural perception of the real world. Despite this definition, the most common form of augmented reality (and the one the definition is usually referred to) is the one that involves the eyesight. In this case, virtual objects are somehow overlapped on the real scene viewed by a user. In 1997, [8] Azuma defined AR as system that (1) combines real and virtual environments, (2) interacts in real time, and (3) is registered in 3D. This definition underlines the idea that AR does not just introduce virtual objects within a real view, but also requires a certain degree of interaction with the system (for instance, changing its properties depending on the position of the viewer) and their geometric coherence to the viewer position and movements. In particular, an AR system must be aware of the environment it has to augment, and, in order to match virtual and real world, objects movements in both worlds must be tracked. The difference between AR and VR becomes here more evident: while in VR everything is artificially created and objects' positions are clearly defined, in AR the system has to follow changes in real-world and properly adapt virtual objects to match those changes.

Augmented reality has been applied, in some cases with success, to many fields, from marketing to architecture, from industrial to military applications. The common concept to aforementioned areas is that AR is used to increase the amount of information contained in the real scene, for instance by adding objects, colors, or text.

Enabling technologies for AR systems include [9]:

- Tracker systems: this is of fundamental importance for coherently locating the virtual objects with respect to the position and the movements of the viewer.
- Displays: typical ones for AR are Head Mounted Displays (HMD). They are placed as helmets in order to let the user freely move around the scene. In general, several AR applications make also use of modern mobile devices such as smartphones and tablet.
- Graphics boards and software: 3D models rendering in an interactive and unpredictable context is a consuming task that needs enhanced and high-performance technology.

Research community has soon started to show the potentiality of AR in production processes and manufacturing environments, where it can be used to enhance all levels of control in both tangible and intangible functions of production, including assembling, maintenance, costing, process planning, scheduling, quality control, and management information system [10]. As an example, AR providing additional instructions to the human operator, thus reducing both the assembling time and the error probability, can aid assembly tasks. In the same way, typical warehouse picking operations usually performed by operators with common "shopping lists" can be supported with the use of HMD that points the correct items on the shelves.

However, as already pointed out in the previous section, while researchers have shown the huge potentiality of this system in industrial scenarios and many companies have strongly invested in developing its enabling technologies, so far neither killer-apps nor de-facto standard have been identified, that would let AR applications to be more scalable and consequently economically sustainable. One of the main reason could be found in the fact that often the implementation of different AR application requires specific settings of the enabling technologies (i.e., tracking systems, displays, and graphics tools) making every solution different from each other, with a consequent increase of production costs. Moreover, complex AR systems make use of HMD, high-quality sensors, and processing hardware, to create a more complete experience for the final user. Nevertheless, when dealing with maintenance and training it is better to avoid excessive intrusive hardware, such as heavy HMD or big displays for the user, while still keeping a high level of detail and perception of the augmented environment. The final user must feel free to move and at ease with the AR system hardware, but at the same time, in order to take advantage of the information provided by AR, he must perceive the augmented environment as close to reality as possible. The latter still represents an important challenge that needs to be overtaken to let AR technology to finally take off in industrial scenarios.

## 3 The Visual Factory for Lean Production

The visual factory is connected to the concept of a workplace where many management and production operations are guided/helped/facilitated by a strong visual approach for information exchange. The concept of visual factory is strongly related to the one of lean-based management and production because it has the waste reduction as its main objective. This theme has been widely studied already in the past, and many resources can be found in literature about this topic (see, for instance [11–13]).

Visual thinking is commonly used in everyday life with the aim to facilitate the information transferring. A very basic example is connected to the driving. All kind of road signals, semaphores, as well as cars blinkers are common form of visual-based information exchange. This approach is immediate and, when properly designed, it stimulates the right parts of the human brain without the need of further elaborations. The latter strongly differs from simple text messages that require certain level and time of elaboration that also depends on many factors such as the culture, the known languages and the responsiveness of the reader.

In industrial environments visual approach is nowadays widely used to provide just-in-time information delivering, along with the principle of transferring the right information at the right person at the right time (Fig. 1). Usually, it is transferred from basics (e.g., a walk side of a factory highlighted with yellow tape

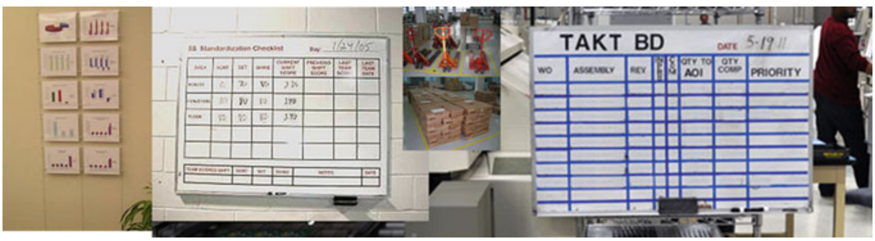


**Fig. 1** Examples of common visual controls

on the floor) to most advanced information (e.g., cardboard panels are used in management meetings to give a snapshot on the production status of an entire plant).

The outcomes of this approach are perfectly aligned with those of lean-based procedure [13], such as:

- reducing non-value adding activities,
- reducing mistakes from employees and suppliers;
- reducing time for employee orientation and training;
- reducing search time in navigating the facility and locating tools, parts and supplies;
- reduce unnecessary human motion and transportation of goods;
- improving floor space utilization and employee safety.

In the rest of this section some examples of how such visual approach is used in helping specific tasks of industrial and manufacturing lifecycle are presented. In details, some specific tasks that could be further improved by using innovative technologies are mentioned: visual factories and visual workplaces are perfect scenarios for deploying AR-enabled technologies indeed.

## *3.1 Visual control for Lean Management*

Management and business operations make massive use of visual controls. The first and more obvious example is in the usual daily stand-up meeting that is run by management teams. Such meetings have the main characteristics in their being very short but still able to cover the entire status of a production plant. They are based on intensive interaction, coupled with a detailed list of actions, issues, status, and progress, all updated and captured in real time on a whiteboard. Here the visual aspect plays a fundamental role, since people is able to map each item of that list with a precise symbol/color on the board.

Typical project management visual controls are GANTT and WBS diagrams that are used for project planning and for tracing the status of on-going projects. The same approach is used in software development and management. Many Agile development methods, in fact, make use of big boards and post-it notes to rapidly identify and differentiate tasks and activities and their operational status.

Factory and production management also takes advantage of visual control when, for instance, they have to deal with rapid surveys of the production status of a plant; this is usually made by means of semaphores or blinking lights that signals potential problems in specific productions cells.

### 3.2 Visual Workplace for Lean Manufacturing

One of the first objectives of visual techniques applied to manufacturing environment is to simplify the operation and the movement of an operator in the production cell. The workplace is filled with signs, labels, color-coded markings so that even a non-experienced operator can recognize what is going on, understand the process, and detect what is properly done and what is out of place. Moreover, the same kind of control that is proper of people in charge of management tasks can be enabled, with different perspective, for the single worker; in this way every operator can know the status of its work and detect potential errors in the process.

From a pure production perspective, instead, visual control can help human operators in task such as assembling part of the product, picking the right component, and even performing quality control by simply comparing specific pieces with a photographic view of the expected result. In general, it is a common belief that visual controls help in keeping things running as efficiently as they were designed for.

## 4 The Opportunities: An Augmented Factory

The description of the principles behind the visual factory and some examples of its application seems to be naturally related to the potentiality of AR, which could, in addition, even boost the benefits of the visual approach to factory management and production.

Augmented reality can be adopted to merge visual-based lean procedure with the information and communication technologies, bringing together the intrinsic advantages of both. This leads to the concepts of augmented factory, that is a factory where visual controls that keeps the property to be understood quickly by everyone, are displayed through AR technologies, meaning that every visual content can be updated in real-time and can be customized depending on the viewer himself.

In a more general fashion, it is possible to define as Virtual Factory (VF) an integrated environment that considers the factory as a whole, merging real factory with virtual tools, and provides an advanced planning, simulation, decision support and validation capability, meant to facilitate the sharing of resources, manufacturing information and knowledge. Within this definition, AR represents a fundamental tool for integrating real-time adaptive visual controls to the factory environment.

## 4.1 Opportunities for Lean Management and Manufacturing

When dealing with management task, this approach gives a series of opportunities. It is possible, as an example, to imagine a plant supervisor that can survey the production line simply by pointing the camera of a tablet on a production cell and browse all provided information on virtual boards; at the same time, a security manager could be visualizing on the same virtual boards different information, probably related to his duties. In general, virtual boards could be (virtually) spread in the plant in a way that a person walking around it can always have under control all the information he is interested in.

Virtual boards for assessment meetings and virtual semaphores for immediate visual feedbacks in a completely virtual environment are already been applied to industrial scenarios [14]. The idea behind this paper is to integrate such virtual objects within the real factory, thus augmenting its visual content.

The proposed approach bring several benefits to lean factory management, as visual management techniques have the property to be understood quickly by everyone, and ICT integration would guarantee personalized and always up-to-date information content, with the final result to keep production running smoothly and safely.

The integration of virtual objects within real scenes can be also fruitfully operated in lean manufacturing and strictly productive scenarios. Here, a human operator can keep under control a series of information depending on the specific task he is carrying out. Augmented content could help by providing the right timing of several operation such as assembling components and moving materials; it could visually signals where and how to store specific items, with the advantage that such visual information would be non-invasive toward other worker that probably will need a different set of information.

## 4.2 Opportunities for Augmented Reality

Some limits of current diffusion of AR technology in industrial scenarios have already been pointed out in previous sections. Nevertheless, the integration of augmented reality with visual controls for lean management and manufacturing also represents an important opportunity also for further development of AR technology itself.

The main idea is to change the point of observation of future AR applications in a way that is less focused on a single task to support with complex AR features and rather more concentrated on a wide variety of apparently minor tasks to "augment" in a simpler way. This description, besides being coherent with lean-based approaches, includes also the very important concept of scalability. Developing a really scalable application intrinsically cuts down expected costs, as the same application can potentially be applied on many different scenarios and targets a larger market segment. The meaning of scalability is here twofold, because it is intended both as the expectation to be deployed in different types of scenarios and the practical feasibility to be deployed in large numbers outside the development lab.

In next section the authors propose a general architecture for an augmented factory, which is a complete framework where virtual objects, depicting visual representation of real factory data, and real factory environment are melt in the same view. The proposed architecture also offers a further opportunity to the future development of AR-base technology, that is the possibility, for several and heterogeneous research groups, to work together to the development of the same AR framework.

## 5 The Challenges

The potentialities offered by augmented reality application to industrial scenarios have been limited by a series of technological issues that, as already mentioned in previous sections, are often related to the high costs of technology and software development, and, in a highly competitive market AR solutions should solve problems that cannot be solved with less money by applying other technologies.

From the pure technology point of view AR displaying technologies poses the main issues. In particular, monitor based visualization can be easily accomplished with the utilization of both normal screens for static situations and smartphones and tablets for mobile scenarios. On the other hand, the main challenge is represented by the utilization of wearable computers and HMD that would enable AR exploitation while moving with free hands. The challenges are here related to the high costs of the technology and the not yet really comfortable usage of such devices that in general do not fit in industrial and production environments.

The approach proposed in this paper, moreover, poses significant issues regarding the importance of designing common and standard interfaces for the visualization technology. The idea is that a general framework, as the one proposed in the previous section, should equally work when using different displaying technologies, thus enabling a series of opportunities and guaranteeing scalable and dynamic adaptation of a AR application to different scenarios. It is worth to note that most of currently "off-the-shelf" displaying technologies have their own interfaces and software development kits (SDK) to work with, and this actually represents an important limitation to their spreading opportunities. Developing standard application to program interfaces (APIs) for connecting different AR displays to the same framework would, instead, represents a fundamental activity to boost their utilization and to lower their production costs.

## 6 The Proposed Framework

Herein a potential architecture for an augmented factory framework is presented. The most general version of this framework (Fig. 2) merges together:

- computer vision, computer graphics, tracking and displaying technologies connected to AR,
- an information retrieval systems,
- an information harvesting systems (IHS),
- a data input interface.

The main idea behind this conceptual scheme is that the AR engine, that includes all AR enabling technologies, should be integrated with the information system that collects all production-related data. The AR engine has the task to select useful information and visualize them on virtual boards on the users' AR displays. The information retrieval mechanism, therefore, should be able to select all relevant information for the specific users (probably depending on his duties). In the presented scheme, no particular AR displaying technology is highlighted, since the same task can be performed by different technologies depending on the specific scenario. As matter of fact, a manager surveying the plant from his office at the first floor will likely use a mobile device such as a tablet, in order to have a

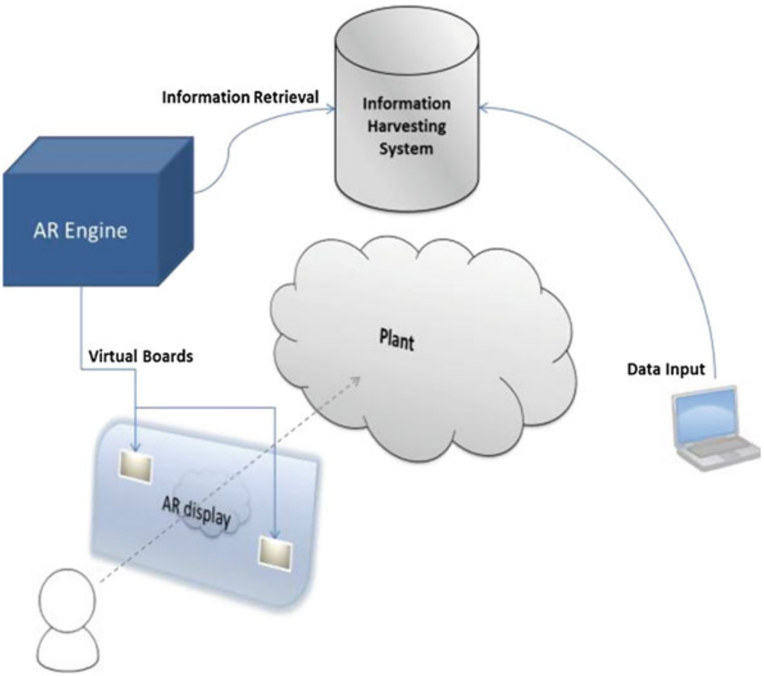


**Fig. 2** A general architecture for a framework for augmented factory

good level of control about what information should be visualized over the AR interface. On the other hand, a worker or a production supervisor working at the base floor will likely use something smaller and lighter.

Many studies and research projects have focused on this kind of approach. The main concept is that a central information harvesting and knowledge management system collects all the information regarding the factory, from the layout to the production plans, from the measurements taken by several sensors in the plant to general information manually inserted by human operators.

The Virtual Factory Framework (VFF) [15], developed within the VFF project, is a new modular, open source, extensible architecture to support interoperability and factory data exchange. It consists of 4 pillars (Fig. 3).

- Semantic Virtual Factory Data Model
- Semantic Virtual Factory Manager and its Repository
- Decoupled Virtual Factory modules
- Real Factory integration

The IHS, here, is represented by the semantic VF Data Model, that consists of a set of coherent standard extensible set of ontologies for the integrated representation of the factory objects and knowledge domain, based on Semantic Web technology [16, 17]. All the data and knowledge related to the factory are stored in repositories and governed by the Semantic Virtual Factory Manager (VFM), that provides the functionalities of access control, data versioning and selective data query. Several decoupled software tools, called VF modules, can be implemented to access and modify the data in the repositories to support specific activities in the product/process/factory life-cycles by interacting with the VFM. Therefore, VFF

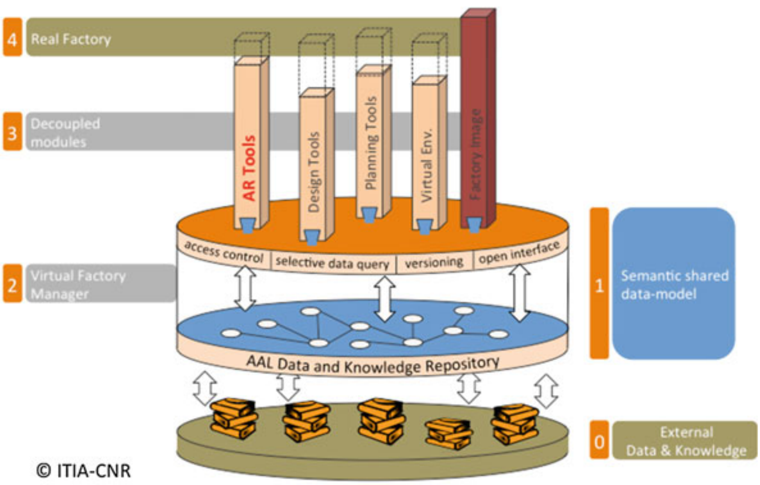


**Fig. 3** The augmented factory as a VFF module

provides the central governance and data management system that let both software application and people to insert and retrieve useful data.

Within this context, the aforementioned augmented factory can be re-interpreted as a new way to apply the virtual factory framework, where the AR engine would work as a VF module capable of selectively retrieve desired data and visualize useful information on virtual boards in the real factory. The generality of the AR part of the system has been chosen on purpose, as the excess of customization represents the main limit to scalable frameworks. In this case, instead, once available every single component of the information system and implemented the communication interface among them, every AR application would be reduced to a sort of plug-in of the AR Engine.

Moreover, designing the AR engine as an open VFF module, and thanks to the open-source nature of the VF framework, the efforts of worldwide spread researchers and developers could be concentrated in the production of a common, unified, and finally scalable framework for industrial augmented reality.

## 7 Conclusions

This paper investigated industrial augmented reality under a new perspective that is applying it as a visual control technique to lean-based management and manufacturing scenarios. The proposed approach aims at empowering production performance and appears to be more sustainable than usual AR scenarios as it is based on more scalable solutions, in terms of both technologies and scenarios differentiation. Augmented reality can be used to enable a series of personalized, real-time visual control and services, supporting common activities and processes in the life cycle of a plant, and aiming at reducing time and resource waste. The visual factory, then, becomes a virtual factory, where virtual boards are introduced in the real factory layout. A specific framework was proposed to target the challenge of make this solution actually scalable. In this case, an AR engine can be implemented as an open-source software tool working as a module of a more complex virtual factory framework, that collects all factory-related data and knowledge through a set of ontologies, and capable of retrieving desired data and visualize useful information on the virtual boards. The open-source approach, moreover, will let research community to concentrate efforts for developing really scalable, sustainable, and useful industrial AR solutions to fit with nowadays highly competitive market.

## References


1. Aiteanu D, Hillers B, Graser A (2003) A step forward in manual welding: demonstration of augmented reality helmet. In: Proceedings of IEEE and ACM international symposium on mixed and augmented reality, pp 309–310
2. Boulanger P (2004) Application of augmented reality to industrial tele-training. In: Proceedings of first Canadian conference on computer and robot vision, pp 320–328
3. Gausemeier J, Fruend J, Matysczok C (2002) AR-planning tool: designing flexible manufacturing systems with augmented reality. In: Proceedings of the workshop on virtual environments (EGVE '02), pp 19–25
4. Fite-Georgel P (2011) Is there a reality in industrial augmented reality? In: 10th IEEE international symposium on mixed and augmented reality (ISMAR), pp 201–210, 26–29 Oct 2011
5. Navab N (2004) Developing killer apps for industrial augmented reality. Comput Graph Appl IEEE 24(3):16–20
6. Wang Y, Qi E (2008) Enterprise planning of total life cycle lean thinking. In: Proceedings of IEEE international conference on service operations and logistics, and informatics (IEEE/SOLI'08), pp 1712–1717
7. Galsworth GD (2005) Visual workplace/visual thinking: creating enterprise excellence through the technologies of the visual workplace. Visual-Lean Enterprise Press, p 222
8. Azuma R (1997) A survey of augmented reality. Teleoperators Virtual Environ 6(4):355–385
9. van Krevelen DWF, Poelman R (2010) A survey of augmented reality technologies, applications and limitations. Int J Virtual Reality 9(2):1–20
10. Khan WA et al (2011) Virtual manufacturing. Springer series in advanced manufacturing, 1st edn. p 18, 802
11. Ellis S (2008) The visual workplace handbook. Outskirts Press, Denver, pp 36
12. Hirano H (1995) 5 pillars of the visual workplace. Productivity Press, Tokyo, pp 365
13. Brady Inc (2012) Visual workplace handbook. Brady, pp 21
14. Di Summa M, Modoni G, Candea G, Radu C, Grafiti R, Sacco M (2012) Virtual assessment meeting: a 3D virtual meeting tool integrated with the factory world. In: Proceedings of JVRC'12, pp 45–48
15. Pedrazzoli P, Sacco M, Jönsson A, Boër CR (2006) Virtual factory framework: key enabler for future manufacturing. In: 3rd international CIRP sponsored conference on digital enterprise technology (DET06), pp 83–90
16. Ghielmini G et al (2011) Virtual factory manager of semantic data. In: Proceedings of 7th international conference on digital enterprise technology Athens, pp 268–277
17. Terkaj W, Pedrielli G, Sacco M (2012) Virtual factory data model (VFF ontology). In: OSEMA 2012, 2nd international workshop on ontology and semantic web for manufacturing, 24–25 July 2012

# Performance Measurement for Efficient Lean Management

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**Abstract** Lean Management is a very broad management method. Many companies try to implement the lean management concept nowadays. It represents a multifaceted concept based on integration of the methods JIT, total quality management, total preventative maintenance, human resource management, Six sigma, KAIZEN, KANBAN, productive maintenance and involved employees etc. The problem in practice is how to monitor the efficiency of the lean management system. The performance measurement is an important diagnostic tool for management and its implementation may be one solution of the afore mentioned problem. Design of the performance measurement system should be based on lean metrics and a process controlling system. Process performance measurement tools and techniques applied to enterprise environments are essential for the enterprise continuous improvement. Therefore, the aim of this paper is to present research study for implementation of the performance measurement based on the Balanced Scorecard method and the process controlling for the lean management.

## 1 Introduction

The way how to improve companies' performance and quality on the market is a very real issue nowadays. The situation on the global market and globalization are the main reasons why companies look for new challenges and opportunities in how to achieve success on the market. One way is the focus on improvement of performance and quality. By improving both performance and quality, companies can save costs, get better results and more satisfied customers. The articles [1, 2] deal with this issue and have confirmed the mentioned idea.

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The application of lean management in relation to the performance management system can be one solution of the mentioned problems. This fact emphasizes the aim and issue of this contribution. The paper deals with description of the ideas leading to performance management system in the companies implementing lean management. The research problem and questions presented in this paper are:

1. How to implement the performance measurement system for the efficiently lean management?
2. How to set-up the strategic performance indicators in relation with metrics for lean management?

This paper is divided into two main sections. The first section provides a description of lean management, introduces the methods for performance measurement and lean metrics. The second section presents design of the performance measurement system for lean management.

## 2 Theoretical Framework and Literature Review

Lean Management is a very broad management method. Many companies try to implement lean management concept nowadays. It represents a multifaceted concept based on integration of the methods JIT, total quality management, total preventative maintenance, and human resource management, six sigma, KAIZEN, KANBAN, productive maintenance and involved employees etc.

The lean management is an improvement methodology based on a customer-centric definition of value. Lean processes provide value in the most effective way possible through a combination of the elimination of waste and a motivated and engaged workforce. Combining BPM and Lean (BPM/Lean) an enterprise has the ability to optimize processes and the ability to take the journey through the continuous improvement life cycle all the way to automating solutions with process control and governance [1].

The article [2] mentioned interaction between performance and lean management. The paper presents the following important results:

1. The lean practices such as reduced setup time, pull production system, and shorter lead time have strong positive structural contributions toward performance.
2. The statistically significant but relatively moderate direct link between lean production (independent construct) and business performance (second dependent construct), thus indicating instead a significant indirect effect of lean production on business performance.
3. The significant critical values indicate that product conformance, product performance, product reliability, product feature, and product durability have positive and direct effects on business performance.

These presented results from article [2] are very important for the proposal of the performance measurement system in practice. The results indicate the important critical metrics which should be added in the performance strategy framework. The literature presented in the previous review deals with theory of lean management and the performance measurement. On the other hand the problem is how to implement the presented theory, namely how to monitor the efficiency of the lean management system in practice. This paper tries to present one way leading to the problem solution. Finally, I would like to emphasise the fact that the performance measurement is the important diagnostic tool and the lean metrics should be integrated to the company performance measurement. The performance measurement gives feedback to managers and has presents the information for the planning, monitoring, and improvement of a business strategy.

## *2.1 Methods for Performance Management*

Axson [3] defines performance management "as a management encompassing all processes, information and systems used by managers to set the strategy, develop plans, monitor execution, forecast performance, report results and make decision". The current literature presents different methods for the process performance management. Firstly, they are methods based on financial analysis of basic enterprise economic indicators (e.g. Economic Added Value measurement, DuPont analysis) [4]. Secondly, they are management methods using financial and non-financial indicators (typically represented by Balanced Scorecard method, European Foundation for Quality Management model, Six Sigma, Value Based Management).

The Balanced Scorecard method (BSC) presents the way how to define and implement the key process indicators and metrics for performance evaluation in relation to the processes and a global business strategy. This method supplements traditional financial measures with three additional perspectives: the customers, the internal business process and the learning and growth perspective. It is supposed to be a tool describing an organization's overall performance across a number of measures on a regular basis [5].

Many companies have adopted the Balanced Scorecard as a way of evaluating managerial performance. The basic idea is very straight forward. Kaplan and Norton began by arguing that "What you measure is what you get" and that "an organization's measurement system strongly affects the behavior of managers and employees". They went on to say that "traditional financial accounting measures, like return-on-investment and earning-per-share, can give misleading signals for continuous improvement and innovation." To counter the tendency to rely too heavily on financial accounting measures, Kaplan and Norton argued that senior executives should establish a scorecard that takes multiple measures into account. They proposed a Balanced Scorecard that considered four types of measures [5]:

1. Financial Measures: How do we look to shareholders?
2. Internal Business Measures: What must we excel at?
3. Innovation and Learning Measures: Can we continue to improve and create value?
4. Customer Measures: How do customers see us?

The BSC method implements the strategy map. The strategy map is a visual map for how an organization will execute its strategy [5]. This strategic management approach has the following goals:

- to clarify and translate vision and strategy,
- to translate strategy into action and executing it,
- to communicate and link strategic objectives and measures,
- to plan, set goals and align strategic initiatives,
- to enhance strategic feedback and learning.

The concept of the Balanced Scorecard can be used for the performance measurement according to the needs of the lean management if the metrics indicate the lean strategy. It means that the metrics and key processes indicators should be established in four perspectives according to the philosophy of lean management.

## 2.2 *Lean Metrics*

Metrics can be defined as an indicator of the performance. These indicators are determined from the strategy goals and they are used for the measurement of the strategy fulfilment. The issue of the lean metrics, their definition and description is mentioned in the related articles [6–8]. The lean metrics should be based on lean production strategy:

– reduced setup time,
– continuous improvement programs,
– pull production system,
– shorter lead time, and
– small lot sizes.

The paper [6] mentions several facts, that most of the existing metrics have poor links to production issues and better links to financial and accounting ones. The definition of effective performance metrics is a key to how to achieve defined goals. The metrics should be defined according to the S.M.A.R.T.E.R.S approach (it is means—Specific, Measurable, Attainable, Relevant, Timely, Evaluate, Reevaluate, Satisfactory goals, and their metrics). Not only performance metrics but the performance measurement system is the key element for how to manage a

**Table 1** The examples of the lean metrics [7]

| | |
|---|---|
| *Safety* | *People* |
| Reportable incidents | Targeted training hours |
| Days worked without a lost time accident | Voluntary turnover |
| | Production to skilled trades ratio |
| Ergonomic management | |
| *Quality* | *Responsiveness* |
| Delivered quality | On time delivery |
| Rework/repair cost | Manufacturing lead time |
| Customer complaints | Inventory turns |
| *Financial* | |
| Margin $ | |
| Manufacturing space used | |
| Conversion cost (labor $/unit) | |

company based on the lean idea. The aim of the performance measurement system should be definition and execution of the lean metrics. Table 1 presents an example of the suitable metrics.

## 3 Design of the Performance Measurement System for Lean Management

The idea is the application of the Balanced Scorecard method for lean management. The aim is to set a performance measurement system. It means the integration of the lean metrics into the BSC perspectives and establishes the "lean strategy" as part of a company strategy. The lean strategy can be declared as a sequence of "if—then" in this case. The next example presents the application of metrics determined according to the BSC method for Printed Circuit Board (PCB) manufacturing, especially for the process PCB assembly. The chain of causation between improving of training of staff and cost reducing has been formulated as follows:

> If you improve quality of training on problems of a manufacturing printed circuit board (PCB), then the staff will be able to understand more about the problems in the process manufacturing. If they understand more about the problems of manufacturing, then the quantity of correct PCB's will be higher. If the quantity of correct PCB's is higher, then the customers will be satisfied. If the customers are satisfied, then the profit will be higher and the cost will be reduced.

The example of the causes and results chain is illustrated in Fig. 1.

Recommended steps leading to the implementation of the performance measurement system based on BSC are:

1) Analysis of processes and their modelling.
2) Design of a performance measurement framework in four perspectives.

The aim of the first step is the description and visualization of the current problems, identification and description of all process attributes and activities

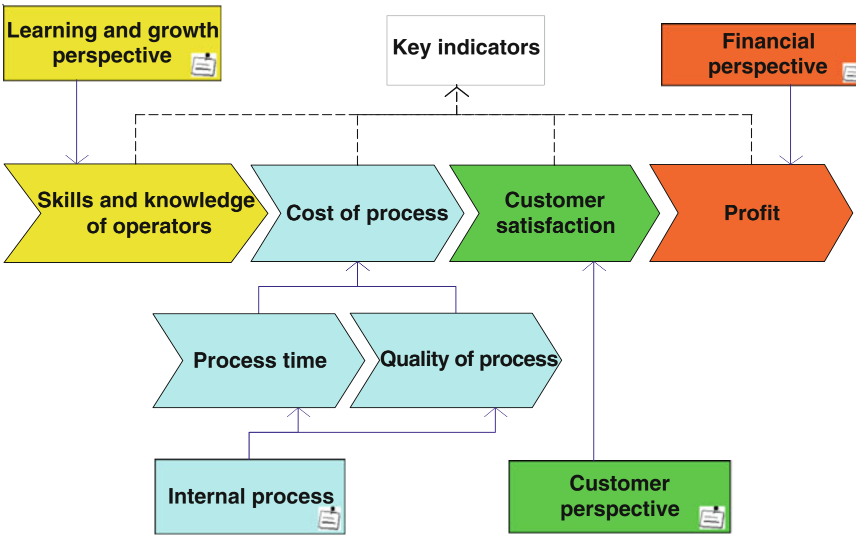


**Fig. 1** Example of BSC method application

during this process. The Value Stream Mapping and Current Reality Tree, identification of process attributes, Strengths, Weaknesses, Opportunities and Threats analysis (SWOT) are suitable tools for these process analyses. The results may be described in the structured table (Fig. 2) or Value Added Chain diagram (Fig. 3). This diagram is used to identify the processes that are directly involved in the creation of the added value in companies. The results of analysis are used for definition of the strategic goals that are established according to the lean strategy and quality policy.

The construction of the BSC framework is the aim of the second step. Firstly, the measurable goals of the lean strategy should be linked to one of the chain of

***Process identification map record***

| Processes | Sub processes | Process Type | | | | | | Input | Output | Key process measured parametrs |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Main | Supportive | Control | Key | Hard | Soft | | | |
| Material Cutting | | X | | | | X | | Requirements | Material on required dimension | Process time |
| Drilling PCB | *Drilling* | X | | | X | X | | Material on required dimension | Drilled PCB | Process Time, Failure drilled PCB Number, Quality |
| | *Inspection* | | X | | | | X | Drilled PCB | Tested PCB | Process Time, Cost |
| | *Diagnostic Planning* | | | X | | | X | Testing requirements | Diagnostic Plan | Process Time |
| | *Diagnostic Process* | | X | | | | X | Diagnostic Plan | Diagnosis | Process Time, Cost |
| Plating Preparing | | X | | | X | | | Drilled PCB | Prepared PCB | Process Time, Failure PCB number, Quality |
| Plating PCB | | X | | | X | X | | Prepared PCB | Plated PCB | Process Time, Failure PCB number, Quality |

*PCB Printed Circuit Board*

**Fig. 2** Structured table for quick process analysis

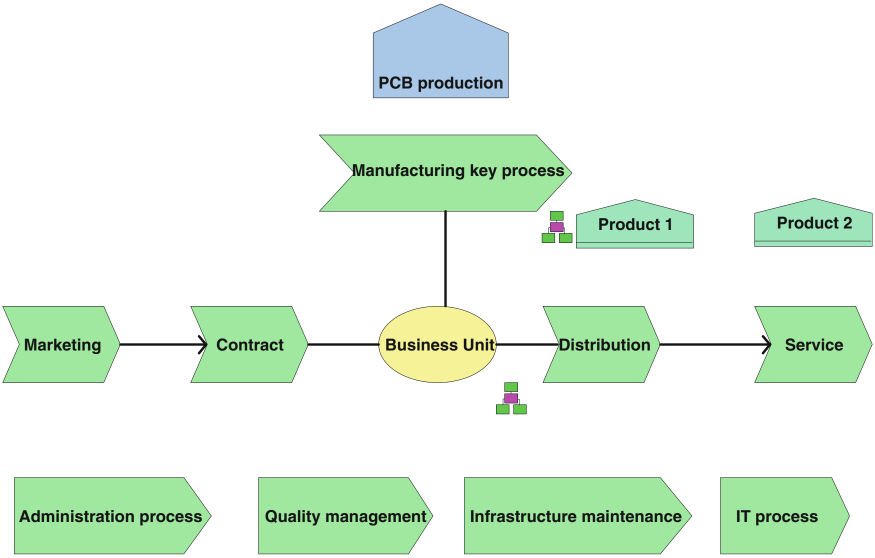


**Fig. 3** Value added chain diagram of PCB production

causes and results between all perspectives (Fig. 1). The examples of goals and metrics (indicators) are shown in the Table 2. The Table 2 contains the planned and the real values. The real values are results of the process measurement. The important part of the process measurement method is to set-up the number of metrics or indicators and period of measurement in relation with total costs of production.

**Table 2** Example of application BSC for printed circuit board manufacturing

| Perspective | Goals | Metrics (indicators) | Planned values per quarter | Real values per quarter |
|---|---|---|---|---|
| Financial | Increase of return on investment | Internal return on investment (%) | 5 | 3,5 |
| | Profit | Internal productivity (earnings/costs) (%) | 2–4 | 0,8 |
| Customers | High customer satisfaction | Internal sales return [number] | 10 | 12 |
| Internal business process | High quality of products | Failure [number] | 50 | 75 |
| | Increase of production capacity | Process time [hour] | 2 | 2,5 |
| | | Costs of process [EUR] | 50 | 45 |
| Learning and growth | Development of skills and experience | Training course [number] | 2 | 1 |
| | Development of firm's environment | Satisfaction of staffs [score] | 1–1,5 | 4,5 |

Conditions and parameters for the measurement should be comparable at all times. The results of the process measurement have to be comparable with planned value and the difference out of tolerance area should be identified and analyzed—application of the Plan Do Control Act (PDCA) methodology. Results of the company performance measurement are input for the process benchmarking. The benchmarking is one of the tools for comparison of the performance between industrial companies from the same sector.

## 4 Advanced Methods

Advanced methods are based on the Corporate Performance Management concept and the process execution and automatization. The Corporate Performance Management (CPM) concept was coined by Gartner Group with the aim of how to describe the combination of processes, methodologies, metrics and technologies to measure, monitor and manage the performance of the business. CPM is thus directed at continuous monitoring of the effectiveness of the results of all company processes and the constant optimization thereof, i.e. its objective is a monitoring system that monitors the business performance of all pertinent business processes all the time, detects and reports weaknesses and problem situations, ideally even suggests optimization of the option and evaluates the success of improvement measures. Process Performance Management may be regarded as the heart of CPM [9, 10]. The present trends based on Corporate Performance Management implementation are:

- Process mining for automated weak point analysis.
- Right time monitoring.
- Dynamic organizational analysis.
- Linking performance and risk management.

The performance management principles are integrated to the information system used. The Business Intelligence application usage of the management dashboards and multidimensional databases are the core of the information systems today. This system has the following important functions:

- Visualizing real process structure.
- Key performance indicators and their analyses.
- Process documents.
- Weak point analysis.
- Process mining.
- Management views.
- Offline reports.

The described system can be applied for the process controlling. The process controlling is a very useful tool for the lean approach. The basis for the process controlling is a process-oriented key performance indicator system that links the process perspective to the essential controlling aspects for business.

The key performance indicators must enable conclusions to be drawn regarding the effectiveness of the processes (e.g. customer satisfaction) and their efficiency (e.g. processing time, delivery reliability, process quality, and costs). In addition, the process-oriented key performance indicator system is configured so that it would be possible to make statements about the actual course of the process. Pre-configured process key performance indicators are calculated and aggregated for each imported process stage. Controlling platform includes a core set of key performance indicators, and these are set as default. The key lean performance indicator types can be divided into three groups:

- time-related key performance indicators (e.g. throughput times, processing times, frequencies),
- cost-related key performance indicators (e.g. process costs/rates on the basis of the performance standard),
- quality-related key performance indicators (e.g. number of processors, error rates, deadline reliability).

The process owner can use the controlling platform for monitoring the optimum balance of the magic triangle "Time-Quality-Cost". The controlling platform may be used for Value Stream Mapping too.

The setting of key performance indicators have to be calculated and defined flexibly and in such a way that it can be expanded based on the need of changing requirements. Besides calculating key performance indicators, it is also necessary to be able to visualize the structure of actual processes since. It is the only way how to obtain generalized explanations for their performance behavior. This solution may be very important for the process improvement.

## 5 Conclusion

The implementation of the process performance measurement is one key process for the establishing of the lean management system. The setting of the lean metrics should be part of the process performance system and based on usage of the nonfinancial indicators. This paper presents methods for performance measuring for the lean management. The Balanced Scorecard method has been evaluated as one effective method for this solution. The benefit of the BSC application is the building an effective system for the performance measurement and diagnostic processes. The example of the application was given in the practical example. This paper has mentioned the advanced method for the performance measuring. The process performance controlling based on Corporate Performance Management implementation in combination with BSC method makes a powerful tool for the measurement and evaluation of the performance. This approach comprises the following components:

- Evaluation of the efficiency of business processes based on key performance indicators.
- Transparent representation of procedures actually performed for cause analysis.
- Deduction of optimization measures.
- Continuous monitoring of success developments.
- Multi-criterial view to reality and performance.

This solution corresponds with the new trend in process management and lean management—implementation of the Corporate Performance Management. The first experience of the presented solution confirms that designed solution helps to achieve the aim of lean management approach—reduction of process time, process improvement and control of quality. The development of the “Process Performance Management” based on the lean management principles is prospective and interesting direction of the research today.

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## References

1. Dicken C, Walker C (2012) BPM and lean: part 1-the plan. BPTrends. http://www.bptrends.com/. Accessed 14 Dec 2012
2. Agus A, Hajinoor MS (2012) Lean production supply chain management as driver towards enhancing product quality and business performance. Int J Qual 29(1):92–121
3. Axson DAJ (2010) Best practices in planning and performance management. Wiley, New York
4. Boyd DT, Kronk LA, Boyd SC (2006) Measuring the effects of lean manufacturing systems on financial accounting metrics using data envelopment analysis. Investment Manage Financ Innov 3(4):40–54
5. Person R (2009) Balanced scorecard and operational dashboards with Microsoft excel. Wiley, New York
6. Andreeva N (2009) Lean manufacturing performance—metrics and evaluation. In: Proceedings of 18th national scientific and technical conference with international participation, Sofia, Bulgaria, pp 414–419
7. Krichbaum BD (2012) Establishing lean metrics—using the four panel approach as a foundation for lean scorecard. White paper. http://www.processcoachinginc.com/. Accessed 15 Dec 2012
8. Reagan R (2012) Process improvements, measures and metrics, the products of lean six sigma. BPTrends, March 2012. http://www.bptrends.com/. Accessed 14 Dec 2012
9. Scheer A-W, Jost W, Hess H, Kronz A (2005) Corporate performance management, ARIS in practice. Springer, Berlin
10. Weske M (2007) Business process management : concepts, languages, architectures. Springer, Berlin. ISBN 978-3-540-73521-2
11. Tupa J, Basl J (2006) Implementation of the CQT methodology for business process optimization. J Appl Comput Sci 2(2):73–92. ISSN 1214-4029
12. Hubbard DW (2010) How to measure anything, Wiley, New York

# Lean Management Methods in Product Development: A Case Study

**Daniel Soares, João Bastos, Diana Gavazzo, João Paulo Pereira and A. J. Baptista**

**Abstract** The current reality of intense competition has forced many companies to increase their performance and competitive advantages by pursuing innovation and improving and streamlining internal methods of designing products and processes. With shortening of product life cycle, in order for companies to survive, the need for a continuous stream of multiple innovations over time has arisen. However, the resources consumed by companies, whilst developing a product or process, are increasingly high, even in integrated approaches, and often the finished product or process arrives too late to provide the company with an edge over its competitors. Due to the large impact Lean philosophy has had in recent decades, within the manufacturing area, through the increase of efficiency and generation of continuous improvement, more companies have progressively applied Lean methods in their units of product and process development. This paper seeks to present a reference model for Lean implementation in the areas of product and process development in order to support companies in their path to streamline and make their innovative processes more efficient. The proposed reference model includes a concrete case study example that helps to explain the main concepts behind the proposed approach.

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## 1 Introduction

In a global economic environment with increasingly changing demands and with a growth in consumers' expectations, organizations feel the need to be more competitive by offering better products and services while consuming fewer resources. Only with a continuous improvement mentality and an agile structure to adapt to change is it possible for organizations to have long-term sustainability prospects. This need is most urgent in the cases of companies that incorporate units of Research and Development (R&D) responsible for the integrated development of products and/or processes. The companies' ability to develop and exploit their innovative capabilities is widely recognized as a critical factor for their performance and a competitive advantage in addressing the markets' demands. In an environment where competition is intense, the gains generated by any innovation may be transitory, since the competitors quickly assimilate these advantages. Therefore, a continuous stream of multiple innovations over time is the only means to enable companies to continue generating high levels of profitability.

Moreover, the resources consumed within product and process development units are increasingly high, even in integrated approaches, and often the finished product or process arrives too late to provide the company with an edge over its competitors. This scenario has motivated organizations to adopt the Lean approach. Despite knowing this is a tough path, an increasing number of organizations are choosing to take it, fully aware of its relatively long implementation period and continuous efforts to ensure that obtained results are kept and maintained. During this implementation period, one comes across barriers, that may or may not be permanent, both inside and out of the organization. However, over time the entire organization tends to shift towards a Leaner point of view, efficiency then increases, waste reduces and a continuous improvement way of thinking grows exponentially.

This paper describes a case study of an R&D unit a year on from implementing the Lean methodology in their product and process development. Since the experience has been underway for over a year and enabled the company to achieve significant productivity gains and cost reductions. The current paper seeks to present the reference model that the research unit developed for the implementation of Lean, what difficulties were identified in the implementation phase of the philosophy and what gains were obtained.

Thus the paper has the following structure: introductory section that presents the case study followed by Sect. 2, with research topics and the research foundations. Next is Sect. 3 which presents the proposed approach for the product development process improvement. In Sect. 4 the case study focusing in the significant results obtained is described and in Sect. 5 conclusions and further comments are presented.

## 2 Foundations and Research Topics

In this section of the paper the main principles and guidelines that support the implementation of the Lean philosophy in the product and processes development activities are presented.

### *2.1 Product Design and Development*

The development of a product or equipment is typically organized in a sequence of phases, from the early product definition and specification, associated to the needs that will be addressed and solved, to the final physical testing that will validate the created new design (see Fig. 1). The first phase of "Product Definition and Project Planning" occurs with the start of the product development project or, in some cases, with the request for a quotation prior to the projects' approval. The phases of "Idea and Concept Generation" and "Concept Development" are the most creative ones, since they determine hypothesis to the product model that can solve the problem and accomplish the objectives associated to the specifications. Subsequently, the created concepts are concretized, usually by means of a CAD model, during the "Concept Development" phase. During the "Concept Validation" phase the models are used to perform mechanical, physical, and/or other kinds of dimensioning analysis, in order to validate the concept. Nowadays, this phase commonly known as "virtual validation phase" is the one that revolves around Computer Aided Engineering (CAE) tools which are typically applied during this phase. The "Detailed Design" phase consists in the preparation of the concepts developed prior to the construction of a functional prototype, where product characteristics and dimensions are defined with precision, as is the final technological manufacturing process which will allow the prototype to be created in the "Prototyping" phase. The "Product Testing" phase corresponds to the stage where the product is subjected to physical validation tests, that eventually also serves as homologation standard verification tests.

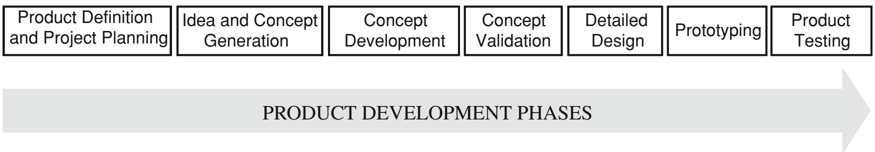


**Fig. 1** Typical product development phases

## 2.2 Lean Management Approach

### 2.2.1 Lean Pillars

The concept of lean production was first used by the authors of the International Motor Vehicle Project carried out by MIT in the 1980s to describe a different approach originally developed in the Japanese automobile manufacturing industry which is distinguishable with the mass production approach commonly used by the Western producers of that period. This new approach is often called “Just in Time” (JIT) in the industrial world, but the authors of the book “The Machine That Changed the World”, which popularized the term Lean Production, believed that leanness goes beyond JIT and more accurately describes the organizational and operational production systems used in the Japanese automotive industry at the time [1].

Even though many authors use the terms JIT and lean production indistinctively, Womack clearly stated that leanness is more descriptive of how persistent the organizational change must be to fully benefit from a JIT approach. The key parameters are the same in the two concepts, but lean systems apply them more comprehensively throughout the enterprise to activities beyond the shop floor and in relationships with suppliers, customers and other important partners throughout the supply chain. In reality leanness means developing a value stream to eliminate all waste, including time, and to ensure a leveled schedule [2]. In order to achieve this goal, it is useful to outline the characteristics of a lean system.

As indicated in the definition presented above, there is a strong emphasis on reducing the use of all resources in the company to a minimum—labor, capital, materials, space, and time. Lean enterprises are always looking for ways to cut the use of any of these resources anywhere in the company. JIT methods are at the core of these efforts and include:

| | |
|---|---|
| Pull flow approach | Multiskilled workers |
| Small-lot production | High levels of subcontracting |
| Production levelling | Selective use of automation |
| Kanban production control | Improve quality at the source (Jidoka) |
| Inventory reduction | Eliminate waste |
| Rapid setups and orders | Supplier networks integration |
| Machine and line rationalization | Teamwork and participation |
| Work standardization | Continuous improvement (Kaizen) |

In each of the above methods, the main goal of lean production is to reduce the waste in human effort, inventory, time to market, and manufacturing space, to become highly responsive to customer demand while producing world-class quality products in the most efficient and economical manner [3].

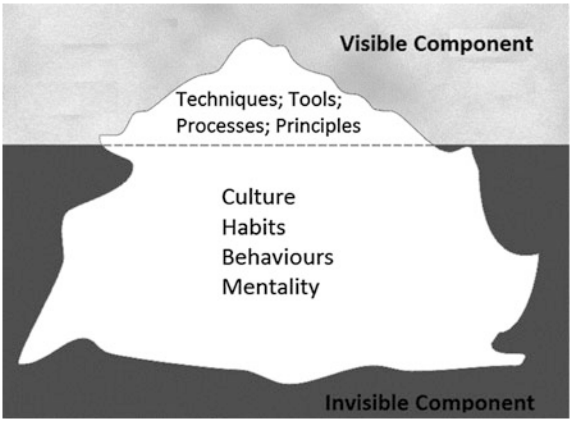


**Fig. 2** Visible and invisible lean components

### 2.2.2 Respect for Humanity

The respect for humanity concept may sound strange when applied to an industrial environment. However, the concept is more easily assimilated with the definition given by Taiichi Ohno: "The ability to add your creative ideas and changes to your own work is what makes it possible to do work that is worthy of humans"[4]. In other words, Taiichi Ohno states that creativity and changes are not automatized processes performed by machines, but human characteristics that are necessary whilst on the path to a Lean environment. The current president of Toyota, Fujio Cho, wrote the following on this subject: "Toyota firmly believes that making up a system where the capable Japanese workers can actively participate in running and improving their workshops and be able to fully display their capabilities would be the foundation for a human respect environment of the highest order" [5].

The respect for the human dimension of the individual, contributes to a feeling of belonging, involvement and total commitment to the organization, thus establishing a basis for proactive sustainability and a culture of continuous improvement. One of the reasons, why so many attempts to implement a Lean methodology fail, is precisely by ignoring the core message of the Toyota system (its two pillars), reducing Lean to a mechanical and superficial use of management tools, i.e., its visible component, thus ignoring the invisible component that is underlying that particular culture: mentality, habits, and behaviors (Fig. 2). These invisible routines are known by the Japanese term: Kata [6].

### 2.2.3 Lean in Services and Product Development

Many implementations of lean initiatives particularly in manufacturing environments have shown that the isolated application of leans tools and techniques does not lead to sustainable improvement if it is confined to the shop floor. As Liker and Morgan [7] have demonstrated, lean thinking cannot stop at the "GEMBA" (shop floor), “but managerial lean principles must extended beyond, to the board room, the sales office, and quite clearly in the product development process” just as they do in the Toyota company. In reality, the application of the lean principles in the Toyota’s product development system has led to superior levels in the quality of the new Toyota products. Simultaneously, the appliance of lean approaches has enriched Toyota to provide new and innovative products with a consistent speed to market of 12–15 months from the moment of the initial idea to the start of production. This compares with competitors which require from 20 to 30 months to accomplish the same task.

In product development workflows are, in its majority, information that is not visible and is often elusive. Variability hinders the process of standardization and reuse of work/product previously executed and wastes are hard to visualize and account for. For example:

- The clutter of files in a computer;
- Time wasted on over-engineering;
- Time wasted on rework caused by a difficult access of existing information and the subsequent search;
- Loss of very specific knowledge of a particular R&D project caused by staff turnover;
- Time spent on training new staff, again caused by turnover.

One of the features of the product development process is the large variability of the type of documents created/acquired and their respective amounts throughout the project. Namely, the volume of CAD files, calculation sheets, presentations, reports, research, and correspondence. These factors hinder the planning and standardization practices of documental management which in turn hampers interchangeability of teams across projects.

Despite the difficulties, the potential for optimization using lean methodologies in product development process is huge. According to Morgan and Liker “There is much more opportunity for competitive advantage in product development than anywhere else. While a robust production system can affect quality and productivity, the ability to affect client defined value and cost reduction is much greater in its initial stage, in the product development process” [8].

## 2.3 Dichotomy Between Lean in Manufacturing and Product Development

The application of lean methodologies to the product development process has specific differences when compared to its application to production processes. Added to these differences one can mention the contrast between the work in progress (WIP) flow in each kind of process (product development or production). In fact, nowadays, in modern product development process, where almost all documents and files are digitally stored and accessed by software programs, the visibility of the flow in product development is almost inexistent or unnoticed, since almost all the communication flows by email or by intranet/internet channels. On the contrary, in common production processes lines, the materials, components, machinery equipment, machine tools, and the work in process (such as unfinished parts) are easily visible and accountable. Thus, the visibility and waste identification is clearer for production processes than for product development processes, with their well-known wastes such as stocks, unbalanced production lines, machinery breakdowns or downtimes, unorganized layouts, etc.

In product development processes the flow or work in progress is mainly characterized by information signals and flow which are most of the time non-visible to all the project teams or company collaborators. Typical intangible aspects of product development phases consist in: time invested with over-engineering, in other words, extra work and solution refinement conducted without perceived value or payment by the customer; all rework tasks; long accessing time to documents or files due to poor information data organization or cataloging; non-use of previously acquired results or knowledge (from documentation or colleagues), i.e., the creation of already existing knowledge/results by a collaborator, simply because he or she was unaware of the existence of this data.

## 3 Proposed Approach for Process Improvement in Product Development

This section presents a conceptual approach for the implementation of “Lean” practices in product and process development activities. This approach is supported in new reference model adapted from the traditional “Lean Manufacturing” philosophy and the Toyota Production System (TPS) principles.

This model aims to identify guidelines necessary to implement a Lean Methodology in an product development organization. Given the specificity associated with each organization in the practical application of this model, the goal is not to create a set of rigid concepts or rules to follow but basic orientation lines that may possibly be shared among organizations to establish the necessary action plan. The conceptual model that will be described next is shown in Fig. 3.

The first and critical step is to know the organization, its current culture, market position, and the standards associated with their activity. This knowledge is critical because it is exactly the difference between organizations that prevents the replication of simple concepts, methods, practices, and tools among them. This component can be classified as being the foundation on which everything will lay. Management must understand the need to ensure the growth of the organization’s culture over time through supportive management by mentoring and teaching. This will allow consolidating the invisible component of Lean in the organization, the Kata.

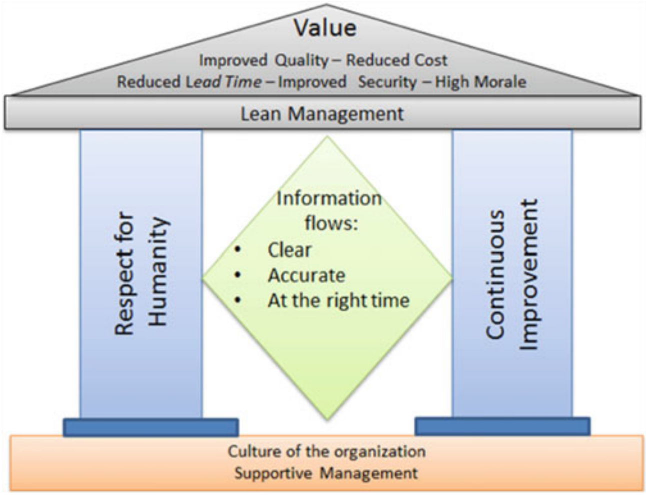


**Fig. 3** Reference model

By respecting the human dimension of all individuals, allowing them to add their own creative ideas and changes to their own work place and provide them with personal and professional development will allow the application of their true capacities and skills, capitalizing their intrinsic motivations in competitive advantage and thus creating a feeling of belonging and involvement with the organization leading to a continuous improvement mentality.

The goal of a Lean Management implementation is to improve the organization performance by creating more value to the client and stakeholders, improving quality and reducing costs and Lead Time.

One of the greatest (if not the greatest of all) challenges in process improvement or continuous improvement programs is to assure that the performed improvement event and its results, that are translated in some form of gain, persists in time, after a specific change process is concluded. The Plan-Do-Check-Act (PDCA) cycle, also known as Deming Cycle, has become a very common lean tool when performing continuous improvement activities by an iterative four-step problem solving process.

Each process improvement should clearly point its objectives and specific goals, establishing levels of stable process improvement (phases 2 and 3 of the diagram in Fig. 4), on which the regression ("rollback" of the circle PDCA) of the process improvement achievements is made difficult since it has already become standard procedure in the organization. During a single or grouped process improvement, between two stable levels, predicting actions that may lead to the failure of that particular improvement is necessary so as to find counter-actions that act as blocking mechanisms. By doing this, regression of the implemented improvement is avoided whilst the complete change and standardization of the applied measures is not secured in a stable level. The blocking mechanisms,

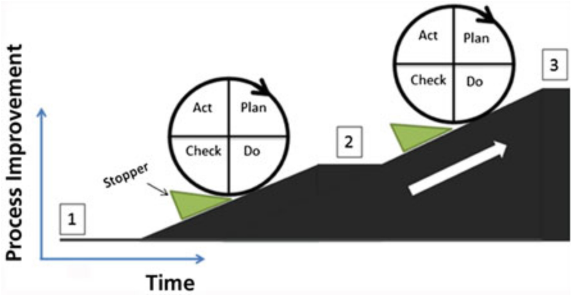


**Fig. 4** PDCA cycle and process improvement levels with definition of stable levels: beginning of the improvement process (*1*); first stable level of improvement (*2*); second stable level of improvement (*3*)

described as stoppers in the diagram of Fig. 4, do not consist in this approach as the "standardize work procedures" as it appears in some Lean methodologies concepts, those are represented as the stable levels, this is, as the steps of an improvement stair.

The stopper blocking mechanism are rather defined in the Plan stage of the PDCA cycle, where the kaizen team focus on all the possible and more probable modes of failure for the process improvement, and perceive intrinsic motivation reasons to the team apply the changes, not as a mandatory action, but as a way that effectively is useful to the organization. The stopper can also be achieved with controlling mechanisms, such as informatics routines that contain already forms of standard work or, as last option, since it relies on human control, someone of the organization that will manage a new created procedure during all the implementing phase until the stable level is reached.

During a typical process of a new product development project the work team can easily generate high quantities of digital data and information (processed data). In the absence of a structured folder tree and a file naming convention, a system folder or a whole server directory can grow without any control regarding its organization and corresponding access. This scenery provokes severe problems to access or store data and information for a set of running projects, and also whilst obtaining information regarding a past project. With modern day product development, the majority of the project time is spent working on digital supported files and documents, the waste associated to search files and documents and accessing folder directories is very significant, because such processes are repeated hundreds or thousands times per project. One typical solution to access unsorted directory information (such as reports, documents, pictures, etc.) consists in using search tools. However, even with the relatively high efficiency of such tools, this approach continues to be a big time waster and does not guarantee that the wanted file or document is located.

During a continuous improvement program applied to general services office or product development department, an initial and very complex activity may consist in organizing all file systems using the 5S methodology. Firstly it is very difficult to perform such a task without affecting the on-going projects and work-flow and, as such, collaborators tend to increasingly resist such processes, since their productivity and comfort to the current structured will firstly diminish the importance

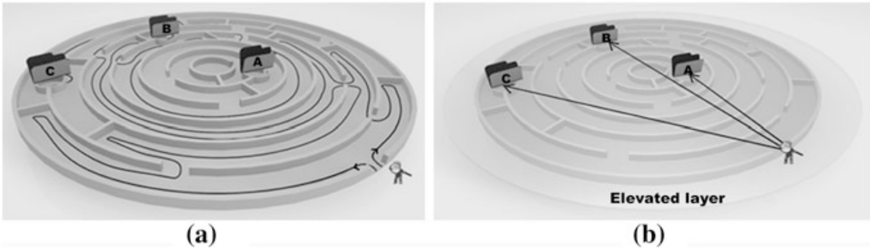


**Fig. 5** **a** Folder access representation by a spaghetti diagram associated to a maze illustration for an unstructured system directory; **b** Folder access representation on a direct and structured access that exists in an above organized layer to the maze (system directory)

of any attained gains. However, over time, this changes and collaborators start to acknowledge gains brought about by this applied 5S methodology. Secondly, the time of adaption to a new file system organization can be long and require a disciplined execution program.

Figure 5a describes a representation of accessing a certain folder through the concept of a spaghetti diagram associated to a maze illustration for an unstructured system directory. File system navigation is not carried out continuously but rather click-by-click, and the time spent with the searching process is a continuous variable that can be represented by the path of the spaghetti line along the maze. Each dead end hallway represents the stopping and the turning back that occurs when a given subfolder is searched unsuccessfully. A possible solution to simultaneously achieve a fast and direct way to access a specific high frequency accessed folder/file is to imagine an elevated platform or layer above the maze (Fig. 5b), where there is an organized access by means of shortcuts and links that allow the creation of teleporting paths over the maze into the files/folders. This kind of methodology of organized layers of links over the maze is created with 5S organization technics and a visual management approach.

## 4 The Case Study

In this case study the two supporting pillars of Lean Management will be addressed. Individuals contributed with their own creative ideas to improve the way work was performed and their skills and areas of intrinsic motivations were gathered and processed to allow for a better team creation and task allocation. Improvements were also made to processes related to key areas such as documental and operational management, and also to supporting activities, by means of standardization which ultimately contributed to an increase the organization's performance.

## 4.1 Respect for Humanity

The first action was the creation of a digital inbox where everyone was encouraged to contribute with their own ideas for improvement. Next, a digital form listing the more relevant competencies related to product development was distributed to all individuals and they self-evaluated (on a scale ranging from 0 to 5) their individual skills as well as their intrinsic motivation in the particular area or task (related to the skill that is being evaluated). This also included an evaluation of soft-skills and languages and some spaces were left in blanks to allow for any unmentioned skills and hobbies to be registered.

These indicators have been processed and bound to a radar chart for quick profile visualization and comparison. A sample is shown in Fig. 6 where the red line chart is related to the intrinsic motivation and the blue line is related to the current skills.

These indicators allowed the creation of teams according to the project's needs whilst also allowing engineers to work and excel in their favorite areas, which in turn contributes to an increase in personal satisfaction and opens a pathway to creativity and innovation. With these considerations, staff turnover is expected to decrease and motivation to increase which in turn is expected generate a rise in persistence and subsequently performance [9, 10].

Other parallel gain that was not evaluated in this work, in terms of gain, consists in using the compiled product development department's skills matrix for promoting effective colleague cooperation whenever one collaborator has a specific technical difficulty. In other words when one has a query regarding a determined technical topic, by accessing the skills matrix one may quickly find a colleague of another concurrent project who can probably help to, not only rapidly solve the problem at hand but also contribute to knowledge sharing. Furthermore, the skills matrix allows the training needs of the team members to be identified in technical topics which are relevant to the department's strategy.

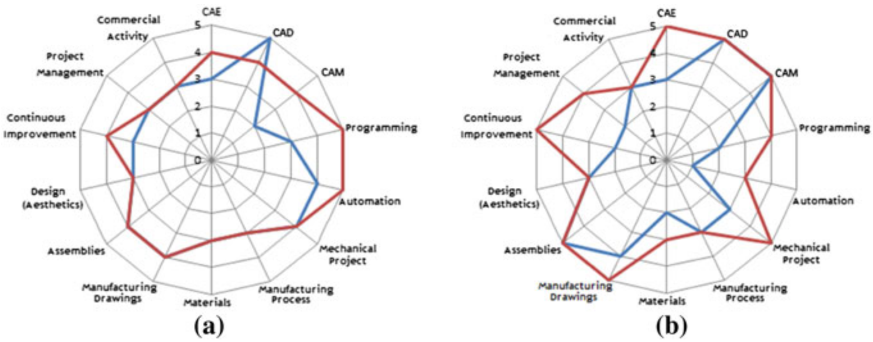


**Fig. 6** Radar chart examples for skill assessment (*blue line*) and intrinsic motivation (*red line*)

## 4.2 Continuous Improvement

One of the areas of intervention was the standardization of documental practices, namely the project's folder structure and the creation of a file naming convention as shown in Fig. 7. The file naming convention also includes some basic rules such as the characters that mustn't be used and date format according to ISO 8601. This allowed for significant reduction in time spent on file searching and improved version traceability thus contributing to improved interchangeability among work teams.

Two of the department's libraries were also reorganized, one in physical format and another in digital format using EndNote software with more than 1,000 cataloged documents. These libraries are composed by frequently used supplier catalogs, technical books, and other engineering information contained in books, catalogs, pamphlets etc. A 5S methodology was applied to both libraries resulting in a reduction in search times. To achieve fast and direct access to a frequently used folder or file during the process of product development, by using the layer system described previously in this paper, one of these layers was created in such a way that the person that needs to access this folder or file can skip over all the unstructured files.

This layer was created in such a way that it may be easily accessed, used, updated and, in the future, extended into other layers (i.e., each layer has a corresponding tab that leads to several different informational groups). Two versions of the Portal were created. One for product development engineers, with 6 tabs (Library, Projects, Quality, Contacts, Equipment, Software), and another one with the same tabs, plus a management tab, for the project management engineers. During this study the Portal was created. This Portal was composed of organized layers over the file directory to structure a fast access to frequently used files and folders during product development (see Fig. 8).

To assure that the Portal was easy to customize and update without any need for advanced knowledge in informatics, Office PowerPoint was used to create this Portal. In order for this Portal to be used and accessible by everyone at any time, in such a way that no one could alter or unintentionally break any of the links a so called Stopper, albeit a simple one, was thought of. This stopper was simply saving and distributing the Portal as a power point show as oppose to a PowerPoint file

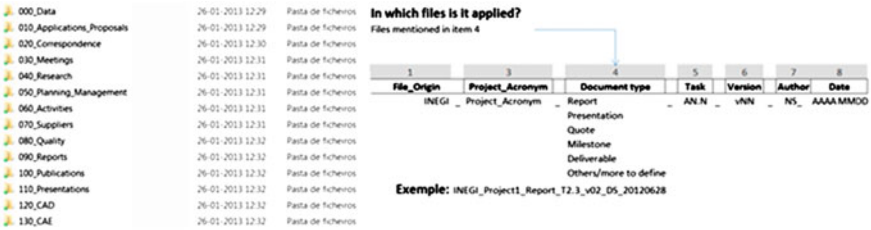


**Fig. 7** Examples of the standardization processes


**Fig. 8** Technical portal view—example of library documents and files layer represented as a tab

that may be altered and saved by anyone. By doing this any risks of broken links are diminished making the solution a viable one and so dodging any discredit towards the Portal's efficiency within the team.

During the period of the file system re-organization (one of the performed improvements) the Portal proved to be a very effective tool which avoided loss of productivity of the project teams. This was due to the fact that, access to the frequent folders and information was made simple by the Portal whilst the whole of the folder system was being altered, allowing the Portal's links to always achieve the desired location for whatever information the engineer was looking for. Besides all the advantages brought about by organizing all the files and pathways to create the Portal, this tool also allowed for an opening of a direct communication bridge between team members. This was due to its distinctive characteristic of opening a lot of doors though only one click, be it to register suggestions or problems, get updates on useful information determined by the management team or even look into the team's after-work leisure agenda, such as football or surfing, get-togethers and other events that promote team morale and interaction.

### *4.3 Global Results*

This work allowed the achievement of several qualitative gains, namely:

- Standardization of document management practices, thus making the process more efficient not only by reducing search times and improving document versions identification and traceability, but also by minimizing the effects inherent to inter-changeability of work teams.

- Centralization of support and specific information related to on-going projects, which reduces rework and increases quality (due to the reduction of rigid and compromised solutions).
- Maximizing the use of human potential through access to indicators related to the skills and intrinsic motivations of individual team members, which allows for the mapping of the overall skills in the department, and the identification of any training needs, while also allowing for an optimal selection of those who will receive training. The skills and motivational indicators also allow for the creation of work teams and a better distribution of individual tasks so as to enhance professional development, increase individual satisfaction and minimize turnover.
- Introduction to Lean Thinking concepts to the whole department, permanent collection of suggestions for improvement and implementation of actions that promote an environment of continuous improvement and respect for humanity.

In addition to the qualitative gains, quantitative gains were also possible to measure. For instance, the improvements made to the processes in the addressed areas, resulted in a performance increase on average of 56 % (individual improvements ranging from 20 to 90 %). These results are expected to increase once the team starts to assimilate the new processes since they were obtained during the early stages of implementation team was still adapting. This shows that there is a lot of potential for process improvement in product development using Lean management principles.

## 5 Conclusions

Many companies throughout the world are seeking to learn from Toyota's system and Lean philosophy. Many of them have seen success with lean tools in manufacturing operations and want to apply this approach to their own product development processes. This paper proposes an application of Lean practices in services and product development processes using an adapted reference model to the R&D environment inside companies.

The approach proposed is based on two main pillars: the impregnation of the continuous improvement thinking in every involved agent; and the implementation of respect for humanity practices that support intellectual and material involvement and retribution from each one of the individuals involved in the innovative development of new products and services. The proposed reference model is exemplified through an application case that ultimately shows many of the advantages that derive of the proposed approach.

Despite this work focus a case study were an innovative approach for the application of lean methodologies in the product development process is presented, the studied approach can be straightforwardly implemented in other office related activities (general office administration, health care services, etc.) and the dichotomy between skill competences and intrinsic motivation can be applied in almost all work environments for simultaneously enhanced productivity and satisfaction of each worker and the overall performance of the company.

## References


1. Womack J, Jones D, Roos D (1990) The machine that changed the world. Rawson Associates, New York
2. Naylor J, Naim M, Berry D (1999) Legality: integrating the lean and agile manufacturing paradigms in the total supply chain. Int J Prod Econ 62(1–2):107–118
3. Bruun P, Mefford R (2004) Lean production and the Internet. Int J Prod Econ 89(3):247–260
4. Yamada H (1997) Encyclopaedia of shop floor waste elimination—the practical philosophy of the Toyota production system
5. Cho F et al (1977) Toyota production system and Kanban system materialization of just-in-time and respect-for-human system. Int J Prod Res 15(6)
6. Rother M (2010) Toyota Kata
7. Liker J, Morgan J (2006) The Toyota way in services: the case of lean product development. Acad Manag Perspect 20(2):5–20
8. Morgan J, Liker J (2006) The TOYOTA product development system. Productivity press, New York
9. Vollmeyer R, Rheinberg F (2000) Does motivation affect performance via persistence? Learn Instr 10:293–309
10. Bloom B (1976) Human characteristics and school learning

# Analysis of the CSFs of Lean Tools and ERP Systems in Improving Manufacturing Performance in SMEs

**Osama Alaskari, M. Munir Ahmad and Ruben Pinedo-Cuenca**

**Abstract** The aim of the work presented in this paper is to determine the most important critical success factors (CSFs) which have the strongest impact on the implementation of lean tools and ERP systems within small-medium enterprises (SMEs). In order for SMEs to be competitive and responsive to the market, they need to assess their practices. This can only occur by adopting the appropriate practices related to the business and manufacturing strategy of the company. The various competitive practice methods being used by organizations are Total Quality Management (TQM), Supply Chain Management, Six Sigma, Lean tools, Material Requirements Planning (MRP), Manufacturing Resource Planning (MRP II), Enterprise Resource Planning (ERP) systems. These methods are considered as tools and practices, which can lead to improve the performance of SMEs. The approach, which has been adopted in this work, consists of two phases; the first phase is a literature review, in order to identify the set of CSFs that have an impact on lean tools and ERP systems implementation. The second involved the design of a questionnaire and the gathering data from SMEs regarding the factors, which they consider influences the successful implementation of lean tools and ERP systems. Ten SMEs were involved in completing the questionnaire and the first analysis was based upon six the received responses. This study has indicated that there is a positive correlation between the CSFs of lean tools and the CSFs of ERP systems.

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# 1 Introduction

Currently, enterprises are struggling to maintain their competitiveness in the market. Lean tools and ERP systems began to be the subject of greater attention from enterprises, including SMEs, adopted lean tools, and ERP systems to assist enterprises to survive in such an environment. The contribution of the SMEs to improve many economies are critical, thus to survive and prosper they must increase their productivity and competitiveness. Small companies make a major contribution to the gross domestic product in the European Union (EU) [1]. In the United Kingdom (UK), 99.8 % of all enterprises are SMEs, while in the remainder of the EU their share is about 90 % [2]. The pressure on SMEs has increased due to globalization, and the quality and service requirements from their customers [3]. Whilst there are many tools, techniques, and methodologies that SMEs can adopt to improve their performance, such as Total Quality Management (TQM), Supply Chain Management, Six Sigma, Lean tools, Material Requirements Planning (MRP), Manufacturing Resource Planning (MRP II), and Enterprise Resource Planning (ERP) systems, in this paper, CSFs of lean tools and ERP systems were studied. This paper reviews the current literature on the implementation of lean tools and ERP systems in CSFs via various methods, and with questionnaires to investigate the importance of CSFs. As the aim of this research is to determine the most important CSF, which has had a strong impact on implementation of lean tools and ERP systems within SMEs, the two following assumptions were posed:

**Assumptions1**: There are some common factors among CSFs of lean tools and ERP systems.

**Assumptions2**: There is a high degree of correlation between CSFs of lean tools and ERP systems.

To verify these assumptions, the CSFs in the implementation process of lean tools and ERP systems were identified through the literature review and industrial survey carried out within ten SMEs.

# 2 Literature Review

## *2.1 Critical Success Factors*

Critical success factor (CSFs) were proposed by Daniel (1961) [4], and popularized by Rockart (1979) [5]. Study of information systems, over the past two decades demonstrated that the CSF methods has been widely adopted and used in a variety of fields of study to determine the most critical factors influencing enterprise success [6]. However, there is not one particular definition of success, as it differs between writers depending on their perspective. CSFs were defined by Rockmart as “the limited number of arrears in which results, if they are satisfactory, will ensure successful competitive performance for the organization" [5]. Whilst, Bruno and Leidecker have defined CSFs as "those characteristics, conditions or variables that, when properly sustained, maintained, or managed, can have a significant impact on the success of a firm competing in particular industry" [7]. Companies who study CSFs permit them to focus their efforts on specific aspects, to decide whether they have the capability necessary to meet CSFs requirements, and if so attain the CSFs requirements [8]. The CSFs concept is the most important for overall organizational objectives, mission, and strategies [9].

### 2.2 Enterprise Resource Planning

ERP systems are complex systems that integrate data and business processes. Many companies introduced ERP systems in order to reduce the non-integration of systems and enhance interactions and communications with their customers and suppliers [10]. Although ERP implementations have been known to have a high rate of failure, ERP continues to be adopted and expanded into new areas. The high failure rate of ERP implementation calls for a better understanding of its CSFs [11]. According to Wong, B. and Tein, D. in information systems implementation research, there has been a lot of attention given to measuring success in implementation [12]. However, the concept of CSFs is well established and widely used in both ERP systems and information systems research [13]. Nevertheless, many researchers have tried to identify CSF that has affected ERP implementation. Rasmy has defined CSFs in ERP implementation as "factors needed to ensure a successful ERP project" [14]. According to Ramaprasad and Williams's survey, the CSF method is used in three key areas including project management (63.49 %), information systems implementation (49.21 %), and requirements (47.62 %) [15]. Furthermore; Kenneth J. emphasis the continuing use of CSFs in order to help focus on the benefits of ERP systems [16]. There are mixed expectations about the actual CSFs of ERP, also numerous CSFs which are similar but they represent by dissimilar terms. In spite of the contrast in the number of CSFs, there is common ground among the majority of these identified lists; there are similarities of the most CSFs highlighted. However, previous studies in CSFs of ERP within SMEs have been undertaken by many researchers [17, 18, 19, 20, 21, 22]. Huin found that, unless differences between SMEs and large firms are understood, managing ERP projects in SMEs "will continue to be slow, painful and at times even unfruitful" [18].

### 2.3 LEAN Tools

The term lean manufacturing was first introduced by Womack and Jones in 1990 in The Machine That Changed the World, which describes the Toyota Motor

Corporation production system (TPS) [23]. Lean tools start from the premise that by adding value and reducing waste, are the primary goals of any business to processes. Many companies have reported some benefits when they moved toward becoming lean by adapting different lean tools, such as Just-in-Time (JIT), setup reduction, 5S, Total Productive Maintenance (TPM) [24]. The results of the survey carried out by Strozniak, demonstrate that 32 % of manufacturers use predictive or preventive maintenance; 23 % of manufacturers use continuous-flow production, and 19 % of manufacturing firms have adopted cellular manufacturing, but less than 20 % of manufacturers adopted other lean tools such as lot-size reductions, bottleneck/constraint removal, and quick-changeover techniques [25]. The literature indicate that most practitioners and researchers have highlighted lean tools to reduce inventories, lead times, rapid product development processes are workface management: Set-up time reduction (SMED), Pull system (Kanban),TPM, Mistake Proofing (Poka Yoke), 5S, Value Stream Mapping, JIT, Visual Management, One Piece flow (Takt Time), Standardized Procedures/work, Kaizen [26]. Many companies are in the process of implementing lean tools. However, many of these companies are still coping with mastering an understanding of lean tool core concepts. Companies are faced with some of the challenges and difficulties, which could be avoided or overcome by identifying the CSFs of lean tools; in other words, there are so many CSFs, which if identified and well understood, will support and overcome these obstacles and difficulties [27]. Therefore, the study and understanding of CSFs of lean tools is essential.

## 3 Methodology

The basis for this investigation is particular to SMEs, the subject in this study are all from manufacturing sector that located in the North-East of England, thus it is essential to determine and characterize the SMEs. In order for a company to be considered as SMEs there are some conditions, however, the SMEs which involved in this studies were required to conform to the definition on the European Commission 2010: "SMEs companies with less than 250 employees and maximum turnover of 50 million Euros or with a balance sheet total of 43 million Euros" [28].

The two methods have been employed in this paper: a literature review and survey. A comprehensive literature review was conducted by searching hundreds of articles from journals and conference papers, using key words identified in initial research in the literature. For this research, the unit and level of analysis involved a plethora of journal articles and conference papers and subsequently carried out extensive search into related databases such as:

- Scopus
- Science Direct
- Emerald Intelligence

- IEEE Transactions
- Google scholar

Initial research into the literature review was conducted in order to select keywords, which are utilized in searching for related topics, focused on the required subject. The alternative keywords or phrases that describe the concept were determined; this provided a number of different keywords, which were combined to search for information. This enables the researcher to gain additional information since journal articles may not use identical terms for describing a given topic, alternative terms or American/UK spellings, singulars and plurals were taken into account. To ensure that search processes within databases obtained the best results, several techniques including Boolean operators AND, OR, and NOT; wildcards and phrase searching keywords and terms were used. When a good result was found it was used as a launch pad to examine closely any record which was particularly relevant to the subject, by searching their references, this led to further references. This research identified 83 CSFs of lean tools when the focus was on the words themselves and not on their meaning. However, after comparing and contrasting these 83 CSFs the similarities, thus detected, caused the number to be reduced to 18 key factors fundamentally critical for the implementation of lean tools, these factors are presented in Table 2. Similarly CSFs of ERP systems, were identified 22 CSFs were determine for this research and are presented in Table 3. This comparison method, shown in Fig. 1, was utilized to ascertain the similar factors among identified CSFs of both lean tools and ERP systems.

Identified factors of lean tools and ERP systems were format in the survey and sent it to SMEs located in North-East of England, to ascertain the weight the respective SME place on each factor. Ten SMEs were involved in completing the survey, the first analysis was based upon six responses as other could not complete/respond to the survey. The respondents were asked to categorize the factors based

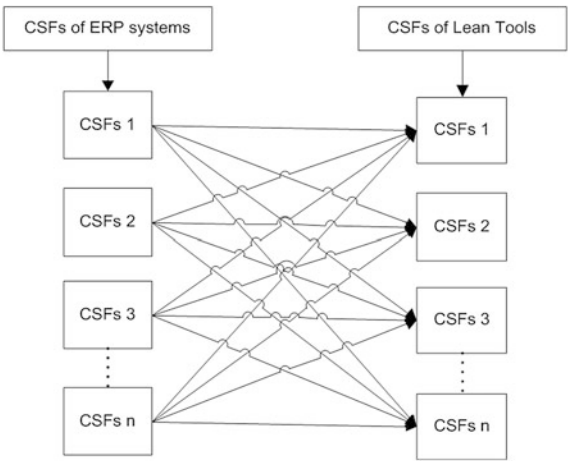


**Fig. 1** An approach to identify similarity of CSFs

on their importance, Likert Scale provided ranges from 1 to 4 utilized to indicate the importance of the statement, as shown in Table 1.

The collected data was analyzed using the following statistical techniques, in order to determine the important weight. Frequency index (F.I): A formula is used to rank CSFs based on their important weight as identified by the participants [29].

$$(F.I)\ (\%) = \sum_{a=1}^{4} a(n/N) * 100/4 \quad (1)$$

where:

$a$ is the constant expressing weighting given to each response (ranges from 1 for not important up to 4 for very important)
$n$ is the frequency of the responses
$N$ is total number of responses
$I\ W$ important weight = [(F.I) (%)]/100

# 4 Results

From the literature review it was observed that, despite the need for research of both lean tools and ERP systems in SMEs, the amount of research conducted on this issue is limited. Therefore, more research requires to be conducted to build adequate knowledge. The numbers of studies carried out on CSFs of ERP systems is greater than that of CSFs of lean tools. As a result, a large number of CSFs associated with ERP system have been found compare with number found in the studies of CSFs associated with lean tools. Table 2 present the important weight of CSFs of lean tools highlighted by the participants of the survey. It notes that most important factors are: Effective communication (ID 15), Determine goals and objectives (ID 13), Commitment of the top management (ID 1), Lean champions (ID 9), Problem solving by involving people (ID 4). The less important CSFs are visible management commitment (ID 11), views and understand lean as a philosophy rather than another strategy (ID 10).

From the result obtained, Table 3 present 22 CSFs of ERP systems and their important weight in terms of participants point view. The top five of CSFs are: Top management support (ID2), Clear Goals and Objectives (ID17), Effective Communication (ID 1), Business Process Reengineering (ID 12), User Training and Education on Software (ID 13).

**Table 1** Importance weighting

| Scale | Importance (F) |
|---|---|
| 1 | Not important |
| 2 | Slightly important |
| 3 | Important |
| 4 | Very important |

**Table 2** CSFs of lean tools

| ID | CSFs of lean tools | IW | Rank factors |
|---|---|---|---|
| ID 1 | Commitment of the top management | 83.33 | 6 |
| ID 2 | Standardization | 66.67 | 3 |
| ID 3 | Realistic timescales for changes | 66.67 | 3 |
| ID 4 | Problem solving by involving people | 75.00 | 5 |
| ID 5 | Continual evaluation during the lean effort is critical | 62.50 | 2 |
| ID 6 | Getting shop floor commitment and employee trust | 70.83 | 4 |
| ID 7 | Involve and value employees at all levels of the organization | 62.50 | 2 |
| ID 8 | Financial capabilities | 66.67 | 3 |
| ID 9 | Lean champions | 75.00 | 5 |
| ID 10 | Views and understand lean as a philosophy rather than another strategy | 62.50 | 2 |
| ID 11 | Visible management commitment | 58.33 | 1 |
| ID 12 | View lean as a long term journey | 66.67 | 3 |
| ID 13 | Determine goals and objectives | 83.33 | 6 |
| ID 14 | Comprehensive training and education | 70.83 | 4 |
| ID 15 | Effective Communication | 87.50 | 7 |
| ID 16 | Effective leadership | 62.50 | 2 |
| ID 17 | Change in organizational culture | 70.83 | 4 |
| ID 18 | Highly motivation of staff to improve the service | 75.00 | 5 |

Carrying out the method showing in Fig. 1, the verification of the similarities of CSFs lean tools and ERP systems. Ten CSFs which shows a similarity between CSFs of lean tools and ERP systems were identified; these factors are presented in Table 4 and Fig. 2. The correlation test was conducted using the Statistical Product and Service Solutions (SPSS) software package on these 10 CSFs. The results of correlation test shows that, there is a positive relationship between CSFs of lean tools and ERP systems, as showing in the Table 5, a high correlation of $r = 0.798$, and a significant level of 0.006, which is less than 0.05, meaning that the correlation is significant and can properly be realized in the practice. Figure 3 illustrates the CSFs are linearly related. Although, these factors have strong positive correlation it does not necessarily imply that one is the cause of the other. Nevertheless, these results suggest that the CSFs shown in Table 4 should be given high priority when companies attempt to adopt either an approach.

## 5 Discussion

Prior studies have documented the CSFs of lean tools and CSFs of ERP systems. However these studies have either focused on lean tools or ERP systems individually. In this study we determine the most important CSFs which have the strongest impact on the implementation of lean tools and ERP systems within

**Table 3** CSFs of ERP systems

| ID | CSFs of ERP systems | IW | Rank Factors |
|---|---|---|---|
| ID 1 | Effective communication | 83.33 | 6 |
| ID 2 | Top management support | 87.50 | 7 |
| ID 3 | Project team organization and competence | 75.00 | 5 |
| ID 4 | Sponsorship | 66.67 | 3 |
| ID 5 | Legacy system management | 66.67 | 3 |
| ID 6 | Monitoring and evaluating progress | 66.67 | 3 |
| ID 7 | Project champion | 70.83 | 4 |
| ID 8 | ERP package selection | 62.50 | 2 |
| ID 9 | Vendor support | 58.33 | 1 |
| ID 10 | Financial resources | 62.5.0 | 2 |
| ID 11 | Empowered decision makers | 66.67 | 3 |
| ID 12 | Business process reengineering | 75.00 | 5 |
| ID 13 | User training and education on Software | 75.00 | 5 |
| ID 14 | Project management | 58.33 | 1 |
| ID 15 | Appropriate use of consultants | 58.33 | 1 |
| ID 16 | Trust between partners | 75.00 | 5 |
| ID 17 | Clear goals and objectives | 87.50 | 7 |
| ID 18 | Change culture | 62.50 | 2 |
| ID 19 | Change management | 66.67 | 3 |
| ID 20 | User involvement and participation | 66.67 | 3 |
| ID 21 | Use of consultantsservices | 62.50 | 2 |
| ID 22 | System technological | 70.83 | 4 |

**Table 4** similar CSFs

| CSFs | IW of CSFs lean | IW of CSFs ERP |
|---|---|---|
| 1.Financial resources | 66.67 | 62.50 |
| 2.User training and education | 70.83 | 75.00 |
| 3.Monitoring and evaluating progress | 62.50 | 66.67 |
| 4.Project champion | 75.00 | 70.83 |
| 5.Trust between partners | 70.83 | 75.00 |
| 6.User involvement and participation | 62.50 | 66.67 |
| 7.Top management support | 83.33 | 87.50 |
| 8.Effective communication | 87.50 | 83.33 |
| 9.Change culture | 70.83 | 62.50 |
| 10.Clear goals and objectives | 83.33 | 87.50 |

SMEs as well as tested the extent to which relationship between CSFs of lean tools and CSFs of ERP systems. The literature review evidences that, in order of SMEs to win the market competition they need to improve their quality, effectiveness, delivery, and flexibility, therefore; lean tools and ERP systems appear to be the most relevant systems to be adopted in order to meet all these needs, however, there are another tools that also share similar implementation problems such as TQM, six sigma, etc. But lean tools and ERP systems have some advantage, as

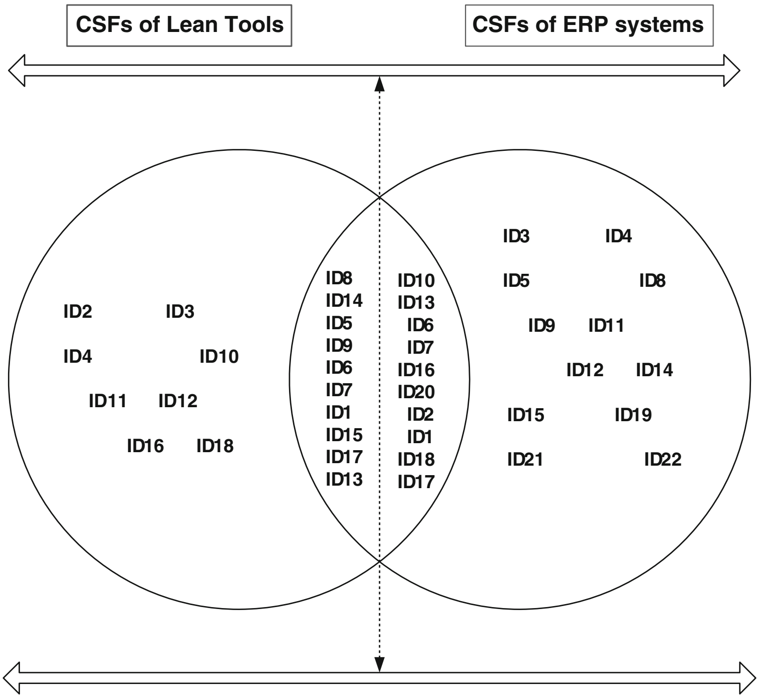


**Fig. 2** Similar CSFs

**Table 5** Correlation

| | | IW of CSFS of lean tools | IW of CSFS of ERP |
|---|---|---|---|
| IW of CSFs of lean tools | Pearson correlation | 1 | .798** |
| | Sig. (2-tailed) | | .006 |
| | N | 10 | 10 |
| IW of CSFS of ERP | Pearson correlation | .798** | 1 |
| | Sig. (2-tailed) | .006 | |
| | N | 10 | 10 |

**Correlation is significant at the 0.01 level (2-tailed)

lean tools consist of various tools which provide chance to the SMEs to select the tool which is suitable and applicable to their processes and strategy, thus company can adopt lean as piecemeal not as whole, also there are many ERP systems that SMEs can select and implement any one meet their needs. It has been found that there are a large number of studies focusing on CSFs of ERP systems compared with that of studies on CSFs of lean tools. Nevertheless; among of the identified CSFs of both lean tools and ERP systems there are ten similar factors; which justifies assumption 1 that there are common factors among the CSFs of lean tools and ERP systems. Further investigation highlighted that there was a positive

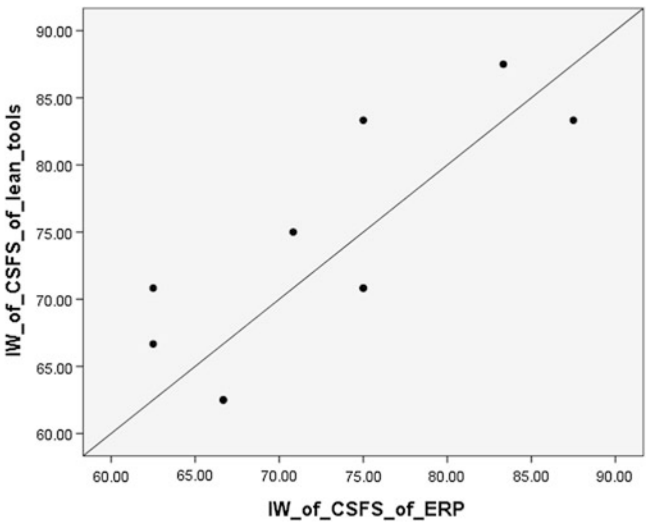


**Fig. 3** Scatterplot correlation of CSFs

correlation between these ten similar CSFs. By analyzing the correlation among these ten similar CSFs, it was found that as the important weight of the CSFs of lean tools increases the important weight of CSFs related to the ERP systems also increases, thus this justifies assumption 2 that there is a high degree of correlation between CSFs of lean tools and ERP systems. This study indicates ten CSFs which has more impact on both lean tools and ERP systems implementation, therefore, SMEs should provide more attention to these factors in order to adopt either systems successful. The individual evaluation and treatment of each of these factors are crucial to reduce the number of key difficulties which were encountered in the past, regardless whether the factor associated with lean tools or ERP systems, and this will maximize the benefits as well as help to create an appropriate environment to implement both techniques. The most notably result is that, most of these CSFs are directly associated with people aspect, for instance, the first two factors showed in the Table 3 requires be addressed by the company's top management team. Our result provides evidence that determine the CSFs can assist SMEs to adopt any improvement initiatives.

## 6 Conclusions

In this study CSFs of lean tools and ERP systems were identified from the literature and a questionnaire was sent to SMEs to determine the most important ones. A literature survey was carried out, 18 CSFs of lean tools and 22 CSFs of ERP systems were identified. These CSFs were formatted in a questionnaire, and sent to ten SMEs in order to determine the importance they placed on each factor. Some points were noted, although there is a significant difference between SMEs and large companies, the company size does not have significant impact on CSFs of lean tools and EPR systems, for example the top management commitment factor one of the most important factors in this study can also be found in similar studies in large companies. Therefore, similar conclusions can also be drawn for large companies. As the assumptions of this work were supported statistically, the authors believe that, in spite of in fact that SMEs in North-East of England are many, yet their features such as level of knowledge and culture are quite similar. Thus result which can be drawn from small sample can be represent large number of SMEs within the region to some extent. However, this is can be pointed out as potential of future work should be undertaken through larger of samples utilizing same method in order to prove this assumption.

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## References

1. Smith A, Kemp R, Duff C (2000) Small firms and the environment: "factors that influence small and medium sized enterprises" environmental behaviour. In: Hillary R (ed) Small and medium enterprises and the environment. Greenleaf Publishing, London, pp 24–34
2. Hillary R (ed) Introduction: SMEs and the environment. London: Greenleaf Publishing; pp 11–22, 2000
3. Underdown R, Tallury S (2002) "Cycle of success: a strategy for becoming agile through benchmarking", Benchmarking: An Int J vol 9(3), pp 278–292
4. Daniel DR (1961) Management information crisis. Harvard Business Review 39(5):111–121
5. Rockart JF (1979) Chief executives define their own data needs. Harvard Business Review, March-April
6. Rockart, John F (1982) The changing role of the information systems executive: a critical success factors perspective. Massachusetts Inst Technol
7. Leidecker JK, Bruno AV (1984) Identifying and using critical success factors. Long Range Plan 17:23–32
8. Boynton AC, Zmud RW (1984) An assessment of critical success factors. Sloan Manage Rev 25(4):17–27
9. Freund YP (1988) Planner's guide critical success factors. Plann Rev 16(4):20–23
10. Kogetsidis H, Kokkinaki A, Soteriou V (2008) Enterprise resource planning implementation in the retail sector: a case study on the effects of the implementation of an ERP system in Cyprus. J Int Business Entrepreneurship Develop 3(3/4):270–283
11. Simona sternad, samo bobek (2006) Factors which have fatal influence on ERP implementation on slovenian organizations, J Info Organ Sci, vol 30(2)
12. Wong B, Tein D (2003) Critical success factors for ERP projects. In: Proceedings of the national conference of the Australian institute of project management
13. Somers TM, Nelson K (2001) The impact of critical success factors across the stages of enterprise resource planning implementations, In: Proceedings of the 34th Hawaii international conference on system sciences, Los Alamitos, IEEE Press

14. Rasmy MH, Tharwat A, Ashraf S (2005) Enterprise resource planning (ERP) Implementation in the egyptian organizational context. In european and Mediterranean Conference on Information Systems; Cairo, Egypt: Citeseer:
15. Ramaprasad A, Williams J (1998) The utilization of critical success factors: a profile. In 29th Annual Meeting of the Decision Sciences Institute; LasVegas, USA
16. Kenneth J (2002) Trimmer, Lela D. Carla Wiggins, ERP implementation on rural health care 16(2/3):113–132
17. Bernroider E, Koch S (2001) ERP selection process in midsized and large organizations. Business Process Manage J 7(3):251–257
18. Huin SF (2004) Managing deployment of ERP systems in SMEs using multi-agents. Int J Project Manage 22(6):511–517
19. Sun AYT, Yazdani A, Overend JD (2005) Achievement assessment for enterprise resource planning (ERP) system implementations based on critical success factors (CSFs). Int J Prod Econ 98(2):189–203
20. Brent Snider, Giovani JC da Silveira, Balakrishnan J (2009) ERP implementation at SMEs: analysis of five Canadian cases, Int J Operat Production Manage, vol 29(1), pp 4–29
21. Doom C, Milis K, Poelmans S, Bloemen E (2010) Critical success factors for ERP implementations in Belgian SMEs, J Enterprise Inf Manage, vol 23(3), pp 378–406,
22. Ahmad M Munir, Pinedo Cuenca R (2013) Critical success factors for ERP implementation in SMEs. Robot Comput-Integr Manuf, vol 29(3) pp 104
23. Womack J, Jones T, Roos D (1990) The Machine that Changed the World. Rawson Associates, New York
24. Abdullah Fawaz (2003) Lean Manufacturing tools and Techniques in the process industry with a focus on steel, university of Pittsburgh
25. Strozniak P (2001) Rising to the challenge Inductry Week/IW, vol 250(14), pp 30–34
26. Bicheno J (2009) The lean toolbox, The essential guide to lean transformation, PICSIE Books, Buckingham
27. Skaf KM (2007) Application of lean techniques for the service industry: a case study M.S., Southern Ilinois University at Cabondale, 104, pp 1446981
28. European Commission (2010) European SMEs under pressure: Annual report on EU small and medium-sized enterprises 2009. European Commission, Directorate-General for Enterprise and Industry, Report prepared by EIM Business and Policy Research
29. Assaf SA, Al-Hejji S (2006) Causes of delay in large construction projects. Int J Project Manage 24:349–357

# The Impact of Autonomy on Lean Manufacturing Systems

**Hanna Theuer, Norbert Gronau and Sander Lass**

**Abstract** An increasing number of companies implement lean principles into their production processes due to changing market conditions, a higher market competition, and the high success of the Toyota Production System in the 1970s. Since lean manufacturing focus primarily on changes in the process organization, most of these changes do not require complex technologies. Additionally, many companies establish IT systems, e.g., a Manufacturing Execution System (MES) or an Enterprise Resource Planning System (ERP), as well as RFID and sensor technologies, for the improvement, and monitoring of their processes. They may enable autonomous production that shifts the decision making from central to decentral.The question is how human factors, IT systems, and smart communication technologies can support the objectives of lean manufacturing. This paper provides an approach for the analysis of the correlation of lean manufacturing and decentrally controlled production by modern technologies, modern software systems as well as human, and organizational factors. Thus, the effects of the usage of autonomy for a decentralized production control and benefits for various objectives can be classified. Therefore, the paper introduces a three-layer cluster for the classification of the level of autonomy.

## 1 Introduction

Changing market conditions, variable customer demands, and growing customer requirements are some reasons for manufacturing companies to create flexible and adaptable processes to fulfill the customer demands in a high quality. There are several methods for dealing with the named challenges: lean production, advanced

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software systems, and decentralization of decision making with the help of intelligent autonomous technologies. While lean production focus on the elimination on non-value adding processes, software systems may assist the process by the automatization of decision making due to algorithms. With the help of autonomous technologies—e.g., sensor networks or RFID—it is possible for production objects to proceed the information making and decision execution on their own. This decentralization of production control seems to be an adequate method to deal with the current requirements on production processes.

When regarding autonomy in production processes in literature, there is a clear focus on technology [1, 2]. There are three conditions for autonomous objects: independent information processing, independent decision-making, and independent decision-execution [3]. Regarding these three issues, it turns out that there is more needed than technology to enable autonomy in production.

The question is how human factors, IT systems, and smart communication technologies can support the objectives of lean manufacturing. This paper firstly presents three enablers of autonomy. The breaking down of the different kinds of waste of lean manufacturing sets the basis for the analysis of the correlation of autonomous and lean production as well as the possible influence of autonomous production control on different process lead times. The paper works out at which level of autonomy the improvements can be categorized. Market surveys among IT system providers and expert interviews serve as validation for the results of this research.

## 2 Three Enablers of Autonomy

In general, autonomy describes the ability of interacting elements to proceed, make decisions, and execute these decisions independently [3]. Thereby it is mostly assumed that these elements are machines and other hardware components that are able to communicate with the help of software components. According to the etymology, of the term "autonomy", it is defined as the capacity of a rational individual to make an informed,un-coerced decision [4]. Transferred to production systems, that means that there are—in addition to the definition of autonomy that is mainly based on hardware with software related intelligence—two other possibilities to create an autonomous controlled production: autonomy via software and autonomy by human action and organization. All three (hardware, software, and human) are able to proceed intelligently, either independently or due to a combination of them. The degree of combination may vary from a high interaction to a nonexistent one.

In order to generate a holistic view on a decentrally controlled production, it is necessary to consider different enablers. Additional to "intelligent" technologies that are able to make the decision making—in accordance with given targets—on their own, also modern software systems like e.g., MES and ERP can make decisions. Also, a decentrally controlled production can be enabled by human factors. The following section describes the three enablers.

**Enabler 1: Human Autonomy**

To enable a human autonomy, humans must be capable to make and proceed decisions on their own and in a team respectively. Preconditions for this are among others flat hierarchies, the transfer of responsibility, communication among various persons and departments, and suitable organizational structures [5].

**Enabler 2: Software Autonomy**

There is a wide range of specific software used in production systems [6]. Among the most common are:

- Manufacturing Execution Systems (MES)
- Machine Data Logging
- Operating Data Logging
- Advanced Planning and Scheduling (APS)
- Warehouse Management Systems (WMS)
- Computer Added Quality (CAQ)
- Staff Working Time Logging

Every software system focus on different aspects of production, but there are also some system providers that provide integrated systems and those that include basic functionalities of other systems respectively (e.g., a MES that includes quality management functions [7]). With the help of software systems, it is possible to reduce the system‘s complexity and automatically proceed the decision making by using existing software algorithms. A market research among German MES providers shows that the three most offered lean methods within manufacturing execution systems are Kanban, Kaizen, and Total Quality Management [8].

**Enabler 3: Machine Autonomy**

"Autonomous Control describes processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of Autonomous Control is the realization of increased robustness and positive emergence of the entire system due to distributed and flexible coping with dynamics and complexity" [9]. Requirements for Autonomous Control are differentiated in information processing, decision-making and decision-execution [9].

Information processing includes data input, data storage, and data aggregation. Relevant data has to be tagged to the production object. Therefore, specific technology is necessary [3]. Examples for such technologies are sensors, e.g., Radio Frequency Identification (RFID) or barcode [10]. Decision making combines the aiming system with predefined rules as well as communication with other production objects. For the decision execution, the communication of different production objects as well as the capability of a production object to performance alternative processes is necessary [3].

Supplemented by organizational aspects that include strategies of organization and concepts of control, an Autonomous System can be modeled. It has elements that are able to make decisions in an autonomous and decentralized way. This would create the opportunity of a production that complies with relevant rules and allows the adoption to changes with a minimum of external intervention. All relevant data is stored, read, and evaluated by a given algorithm. Based on this, regulations are proceeded [3].

# 3 Waste in Lean Manufacturing

Originally designed for mass production in automotive industry at Toyota, Lean Production took on in importance even for small batch production during the last years. The globalization and the linked changing market conditions are one of the main reasons for this. For many companies, Lean Production becomes the focus of attention. After World War II engineers reconsidered all production processes with the aim of strengthen them. The main aim is the minimization of all waste—a term used in the lean philosophy for all parts of the production process that does not add a customer value to the work piece—in order to streamline the processes. This improves the adherence to delivery and minimize costs. Lean Production distinguishes three kinds of waste—based on Japanese words and called the "Three Mu": Muda (losses due to waste), Mura (losses due to deviation), and Muri (losses due to congestion) [11, 12]. As Muda is the worst waste, this paper will focus this type of waste. They provide the basis for the assignment and analysis of autonomy in manufacturing in order to improve lean processes.

"The basis of the Toyota production system is the absolute elimination of waste." (Taiichi Ohno 1912–1990)

Figure 1 pictures five different types of time and waste used in lean production. Originally there are seven Muda: Overproduction, transport, inventory, motion, waiting, over processing, and defects [13]. The following substantiates them [14–17]:

## *3.1 Overproduction*

The field of overproduction distinguishes two kinds of waste: the quantitative and the time related. Whilst in the quantitative the produced quantity of goods exceeds the needed quantity, in the time related waste the goods are produced before they are needed for the fulfillment of orders in due time.

Both kinds result in higher stock levels. In case of the quantitive, those products that are not needed at the moment of completion have to be put into storage. Additionally there is the risk of a total loose of the products, meaning that they cannot be sold totally. In this case, all operations for producing and storage that already have been done at the single products are a waste.

For the elimination of overproduction, there are methods like just in time (JIT), just in sequence (JIS), or the productions without stock.

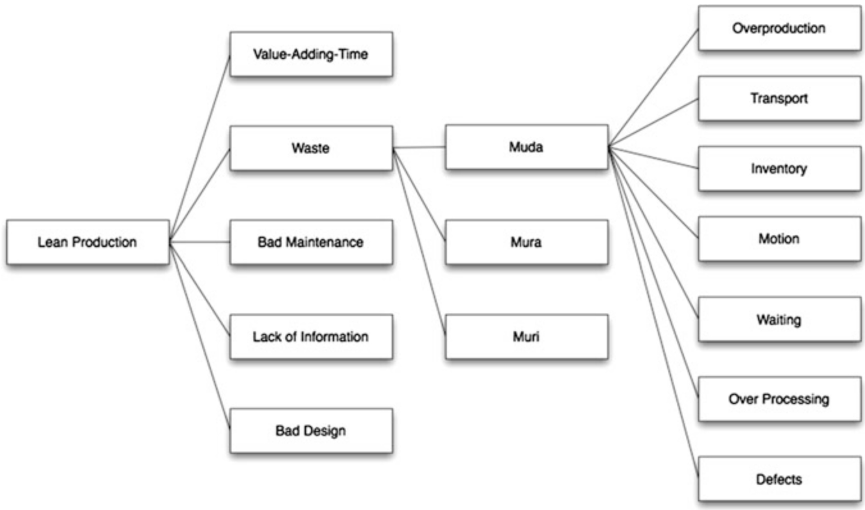


**Fig. 1** Times and types of waste in lean production

## 3.2 Transport

This kind of waste occurs in case of avoidable transports, e.g., due to an unfavorable arrangement of machinery or production plants. It causes long transports between the single processes. Additional sources are (long) ways to warehouses, double handling during the work process, and the getting of necessary tools and documents. At Toyota, every provision of material that does not serve an immediate assembling is considered to be a waste.

An optimized information flow between production and logistic can help to avoid this kind of waste.

## 3.3 Inventory

Inventory is defined as the stock of an item on hand at a particular location or business. It is mainly kept in warehouses. The main task is the economical coordination of varying dimensioned flow of goods. Additional functions are speculation, refinement, balancing, protection, as well as sorting.

The establishment and maintenance of warehouses causes costs. Products that are in storage, increase the fixed capital of a company. An advantage of storing products is a high flexibility towards customer demands. It is of great significance to determine the best size of storage. Advantages and disadvantages have to be analyzed and balanced.

An excessive warehousing has close links with overproduction. Additional to the already names wastes it causes an increased space requirement which in turn causes costs. Both types of waste may cause other types of wastes. As they often cover the other types of waste, they overlay the linked needs of improvement. Therefore, the elimination of inventory is a central subject in lean production.

### 3.4 Motion

This waste essentially consists of inefficient movement routines. They can occur if e.g., tools have to be searched or if tools are kept in a bad and un-ergonomic position, e.g., high or on the floor. This category also classifies long distances due to an unfavorable production layout or ways to storages. Muda motion can be reduced by standardization of working processes and 5S—a method that focus cleaning and standardization of the working environment. The elimination of storages eliminates the ways between process and storage. Long distances due to an unfavorable production layout can be reduced by an U-layout arrangement of production processes.

### 3.5 Waiting

Waiting times may result if a human or a machine hindered from doing value-adding work by interruptions, e.g., long set upon times or waiting times caused by untuned process times. They can include waiting for machines, material, person, transport, tools, the order, information, and decision.

### 3.6 Over Processing

An optimal manufacturing process consists only of value-adding process times. All non-value-adding times are waste and should be eliminated. Long set-up times, unfavorable, incorrect or missing tools and devices, as well as poor transport systems are possibilities for disturbing the optimum.

### 3.7 Defects

Defective products have to be repaired or reworked if the defect occurs during the production. This results in unplanned expenses, e.g., working times of staff, machinery times or additional required material. The later the defect is detected in the process, the more working processes have to be reversed and the more serious this kind of waste is.

## 4 Correlation of Lean and Autonomy

Based on the different kinds of waste presented in Sect. 3, this section deals with the correlation between autonomy and lean.

### *4.1 Setup Times*

The total set up time can be determined by summing up the products of the duration of a single setup and the number of required setups. The impact of lean production is to reduce the particular setup times using a targeted analysis and improvement. Short setup times enable small lot sizes and frequent setups with a constant total time. The most common method for the reduction is Single Minute Exchange of Die‘ (SMED). It is primarily based on the distinction of internal and external set ups times and constructively design which allows a quick setup (e.g., the use of clamps instead of screws). Internal setup times have to be executed directly on the machine—he machine is blocked for any production work. External setups can be executed while the machine is working. By shifting internal to external setup times, acceleration can be achieved. The sequence of production orders and the thereby linked setup times can be determined by all three enablers of Autonomy. Frequency and the point of time of the planning are the main reasons for differences as both determine the required amount of setups. The duration of a single setup cannot be influenced by autonomy.

In manual planning (enabler human), the determination of the sequence of production orders is usually done in advanced for several days—e.g., on Friday for the entire following week. Suddenly occurring events cannot—or just with a big effort—be considered. As this extra effort often transcends the expected benefit, the process continues with the non-optimal planning.

Due to the possibility of automatization, a MES can drastically reduce the planing horizon—from weekly to daily or even one per working shift. Necessary changes and certain events can be considered much better.

By the use of technologies of the third enabler of autonomy, planning, and reaction cycles can be even reduced to a few minutes. Additional to mere planning, they allow a reactive control and regulation. That implies that the sequence of production orders can be determined in respect of the current production situation and upcoming orders. The real-time availability of information can reduce additional waste. As soon as an order is assigned to a certain machine, the necessary external setups can be started.

## 4.2 Waiting Times

Section 3.5 named seven kinds of Muda in which waste occur due to waiting times. Improvements are possible at all three enablers of autonomy.

Human Autonomy can reduce or even eliminate waiting times by different methods of lean manufacturing. SMED helps to reduce set-up times in a drastic way (see Sect. 4.1). Multiple machine work and balancing of process times are methods of reducing waiting times to machinery. Total Productive Maintenance (TPM) helps to reduce machine breakdowns by preventive maintenance. Small working teams with a high self-responsibility enable quick decision making due to short ways of decision making.

The second enabler allows additional chances for the improvement. By the use of machinery data acquisition, there are up-to-date information on the machine status and the progress of orders in process. Associated with a high frequented planning of production orders, a contemporary reaction to e.g., machine failures is possible. Re-plannings of orders to alternative machines are one option for an adequate reaction. In conjunction with staff working time logging systems, an additional planning and allocation of staff—e.g., in consideration of the staff‘s qualification—is possible.

Autonomous technologies enable tracking and tracing of objects. In manufacturing, this is particularly valuable for the tracking of material, transport vehicles, orders, and tools. Useful information regarding the availability can be obtained. Often, high-quality tools have a limited disposability as they are used at the same time at different working stations and machines. A synchronization of them is essential. Autonomous technologies can achieve improvements.

## 4.3 Inventory

Autonomous methods affect inventory times only secondary. There are several factors that affect the necessity and duration of the storage of products. The definition of production orders, line balancing, and the sequence may are some examples for influential factors. Transparency also has a crucial role. It is difficult to obtain satisfactory results to the necessary of extra storage efficiently if it is not obvious, which product or material is stored at which quantity. It is also essential to know if stored products are available or reserved for other orders.

In the area of the human enabler of autonomy, marking of quantities, and the definition of fixed sizes of the storage size can increase the transparency of the currently available material.

Warehouse management systems, as well as MES and ERP systems, are important for the software based enabler. Often they can cause real-time status reports on different storages and the assignment of stored material to future orders. The occurring reservations cause that the material is treated as ‘not available’.

Autonomous technologies offer the chance to a real-time tracking of every production objects. Sensors that are tagged on the objects allow their localization at every time. Further analytics are possible, due to the information storage for the (planned) availability.

## 4.4 Transport Times

The determination of transport can be done either manual (human enabler) with the use of algorithms or by the help of software systems. Two problems that may occur are a high complexity of decision making and not up-to-date information of transport vehicles.

Autonomous technologies can reduce the second problem by using a network of sensors that allow up-to-date information of the current location of a transport vehicle, its physical status (e.g., breakdown) as well as their order progress.

## 4.5 Defects

A fast fault detection highly important. Otherwise, there is the risk that a faulty process produces more faulty products. Besides it may happen, that other processes operate at the product, and in the end the result has to be destroyed because the graveness of the failure. This would generate waste. Robust processes are an essential requirement for gaining a low error ratio. Nevertheless, the measurement of quality is mandatory in most cases.

The safest way of failure checking is a 100 percent test. However, this results in a high effort and causes high costs. Either the employee himself or a quality team check every part after every process. When detecting a failure, the cause of failure has to be examined, and eliminated.

Software provides extensive possibilities for the analysis and evaluation of process and product data. A comparison of actual and planed values is possible by the help of an integrated data recording of actual values. Statistical test methods and evaluations, as well as graphical representations, provide the ability for a pursing data analysis and identification of trends [18].

Autonomous technologies enable a self-analysis and self-evaluation of products due to integrated sensor technologies. They can decide by their own, whether the failure can be ignored, a rework or a sorting is required. A warning can be given to the process at the same time. Moreover, there is the opportunity to discover hidden information due to a big amount of data and algorithms.

## 4.6 Conclusion

The paper points out that the consideration of the three different enabler of autonomy is reasonable. As there are various possibilities for the improvement of production and the reduction of non-value-adding times in all three, a comprehensive analysis provides the chance to fulfill the primary objective of the production system.

It shows that—in order to get the best results—especially in the area of technological autonomy it is essential to generate a close linking of the different tasks. A separate consideration and implementation cannot result in a good performance as information about on area may be needed to proceed the information finding in another one. For this reason, it is essential to integrate the information and proceed a comprehensive implementation.

## 5 Outlook

It is necessary to continue the development of an autonomy model that considers the three different enablers of autonomy. This model clearly has to identify the distinction as well as the communication of the different parts. The model enables the classification of different methods with different objects—e.g., like shown in this paper methods for the elimination of waste—with consideration of autonomy in production. Additionally, it is essential to create key figures that focus on the autonomy of the different enablers as well as such that focus on their interaction. The Autonomy Index AI [19] will provide a reasonable basis for this. In a next step it is necessary to check and verify the methods and their impact in a flexible simulation environment, e.g., the hybrid simulation environment of LUPO laboratory [20, 21], or even implement them in practice.

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## References

1. Scholz-Reiter B, Kolditz J, Hildebrandt T (2006) UML as a basis to model autonomous production systems. In: Cunha PF, Maropoulos P (eds) Proceedings of the 3rd CIRP sponsored on digital enterprise technology. Setúbal, Portugal
2. Hadar R, Bilberg A (2011) Manufacturing concepts of the future - upcoming technologies solving upcoming challenges. In: ElMaraghy HA (ed) Enabling Manufacturing Competitiveness and Economic Sustainability. In: Proceedings of the 4th international conference on changeable, agile, reconfigurable and virtual production (CARV2011). Montreal, Canada
3. Windt K, Böse F, Philipp T (2006) Autonomy in logistics—Identification, characterisation and application (in German). In: Vec M, Hütt M, Freund A (eds) Self-organisation—thinking model for nature and society, Böhlau Verlag, Köln, pp 271–317
4. Windt K, Hülsmann M (2007) Changing paradigms in logistics—Understanding the Shift from conventional control to autonomous cooperation and control. In: Hülsmann M, Windt K (eds): Understanding autonomous cooperation and control in logistics Springer Berlin, pp 1–16

5. Koch M, Richter A (2008) “Enterprise 2.0—Social software in companies” (in German), 2nd Edition, Oldenourg Verlag, München,
6. Theuer H, Leo A-K (2011) Market survey: IT in Production” (in German), in: ProductivITy Management 16(2011)4, pp 37–45
7. VDI Guideline 5600 (2007) “Manufacturing Execution Systems”
8. Theuer H, Leo A.-K (2011) “Market survey: Lean Production” (in German), In: ProductivITy Management 16(2011)3, pp 30–35
9. Hülsmann M, Windt K (eds) (2007) Understanding autonomous cooperation & control in logistics – the impact on management, information and communication and material flow, Springer, Berlin
10. Günther OP, Kletti W, Kubach U (2008) RFID in Manufacturing. Springer, Berlin
11. Syska A (2006) “Production Managemet. Produktionsmanagement: the A-Z of the most important methods and concepts for today‘s production” (in German). Edn 1. Wiesbaden Gabler
12. Becker H (2006) Phenomenon toyota: success factor ethics (in German) Berlin Springer
13. Tillenburg S (2008) The concept of a balanced production in supply chains (in German). Leuphana Universität Lüneburg, Wiesbaden
14. Shingo S (1989) Study of ‘TOYOTA‘ production system from industrial engineering viewpoint. Japan Management Association, Tokyo
15. Rother M, Shook J (1999) Learning to see: value stream mapping to add value and eliminate MUDA. Lean Enterprise Institute, Cambridge
16. Erlach K (2007) Value stream design: the way to a lean enterprise (in German). Springer, Berlin
17. Womack JP, Jones DT (2003) Lean thinking: banish waste and create wealth in your corporation, Free Press, 2nd edn
18. Theuer H (2009) Market survey: quality management systems (in German). In: ProductivITy Management 144, pp. 23–26
19. Theuer H (2012) Analysis of correlation of lean and autonomous production processes. In: Proceeding of the 22nd international conference of flexible automation and intelligent manufacturing (FAIM 2012), pp 520–530, Helsinki, Finnland
20. Gronau N, Theuer NH, Lass S, Nguyen S (2010) Productivity evaluation of autonomous production objects. In: Proceedings of the 8th IEEE international conference on industrial informatics (INDIN 2010), pp 751–756, Osaka, Japan. July
21. http://www.lupo-projekt.de. Accessed 20 Jan 2013

# How to Foresee and Measure the Real Economic Impact of a Lean Manufacturing Implementation

**Leonardo Rivera and Diego F. Manotas**

**Abstract** The academic and industrial worlds seem to agree in the convenience of implementing Lean Manufacturing. Arguments to highlight the benefits of implementing Lean usually include testimonials from successful companies, published case studies, even conference presentations, plant tours, and television programs. It is not easy to foresee the impact of a Lean implementation in strictly monetary terms. Lean is an operational philosophy that does more than saving money; it prepares companies for sustained improvement and creates disciplines and operational capabilities, yet it could be argued that these capabilities are hard to value and quantify. In this paper, we propose a flowchart-type methodology to decide if a change in a procedure, in the use of tangible resources or in the use of time brought about by the implementation of a Lean Manufacturing technique will have a measurable economic impact. The decision maker will need to know the specific circumstances of the production system, but we believe he will be able to predict the economic impact of a Lean implementation (or to evaluate the results of an ongoing Lean project) with more precision, to build a stronger and more comprehensible business case and convince upper management of the real benefits of Lean.

## 1 Introduction

Most of the practitioners of Industrial Engineering (particularly in manufacturing enterprises) and the majority of academics in related fields would agree that implementing Lean Manufacturing is a good idea for a wide variety of companies.

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Many companies are also applying the principles, tools, and techniques of Lean Manufacturing in non-manufacturing settings, such as services [1], banking [2], and healthcare [3].

However, when we ask a Lean promoter or "believer" about the right methodology to present an economic justification of a Lean implementation, we do not receive a standard answer. Some will respond that it is difficult to anticipate the resources that are freed and the costs that are saved due to the implementation of Lean. Some others will say that the evidence of successful implementers should speak for itself. Finally, some others will even look at you with the profound disdain that a firm believer on something applies to the skeptical.

The fact is that there is not a single, standard, uniformly accepted methodology to foresee, measure, and assign value to the benefits obtained by the implementation of Lean Manufacturing. We will also not provide such a methodology and contend that it will solve all problems in this regard. Rather, we will propose a thought process in a flowchart format that a practitioner will be able to use to create his own assessment of the impacts created by Lean Manufacturing in his organization.

This paper is organized in five main sections. In Sect. 2 we present some relevant previous work done for the measurement of the impact of Lean Manufacturing in an organization. Section 3 contains a discussion of the most popular Lean tools and the effects their use has on resource use and costs in a manufacturing company. Section 4 presents the flowchart of thought processes we propose a way to apply economic valuation methodologies with its outputs. Finally, in Sect. 5 we discuss our conclusions and propose future directions for research in this area.

## 2 Measuring the Impact of Lean Manufacturing

Several different points of view have been adopted when trying to measure the economic impact of Lean Manufacturing. Lian and Van Landeghem [4] report that Value Stream Mapping (VSM) in its traditional configuration is unable to incorporate dynamic elements and its static representation of processes results inadequate. They propose a new VSM simulation paradigm to incorporate the effects of changes in tools and processes into newer and more adaptable maps. However, they do not incorporate a specific measure that may be related to economic impact.

Wan and Chen [5] proposed a leanness measure based on Data Envelopment Analysis (DEA). This measure provides a score between zero and one, with zero being the lowest possible level of leanness and one the benchmark of ideal leanness. The main drivers of leanness they considered are the total time and cost a product takes to move through the system, and they compare them to the ideal state in which all time and cost used to make a product are value-adding. Rivera and Chen [6] examine the impact of lean tools on the cost-time investment it takes to make a product. The cost-time investment is a measure related to working capital, and it considers not only the costs and expenditures required to manufacture a product but also their timing and the way they are used during the movement of the product through the system.

However, these measures take a direct point of view, in which the impact of Lean tools is measured only through the changes in the time and cost required to manufacture a product. We would like to examine the impact on different types of assets and their economic possibilities, which has not been discussed in detail in the literature so far.

Apreutesei and Arvinte [7] report that the implementation of Lean Manufacturing usually brings unfavorable changes in the financial statements, due to the decrease in inventory. They also contend that operational-based measures usually improve promptly, and the financial statements start showing positive changes after an adaptation period. They also argue that due to these characteristics, the traditional financial report statements are not the best tools to measure impacts of Lean implementations. Schonberger [8] states that inventory (particularly finished goods inventory) has been used as an upper-management measurement of how lean a system is, due to its ease of understanding and *"gratifying"* nature. However, in this paper he mainly focuses on presenting actual examples of companies in which this measure is insufficient and equivocal.

In this paper we will propose a methodology to identify which changes to value, but not a complete methodology to perform this evaluation. The complexities of the construction of such a methodology are presented in the future research section, as guidelines for the type of research we believe should follow.

In Sect. 3 we will present some of the most popular lean tools and techniques and their expected impact on the use of resources and on the time it takes to manufacture a product.

## 3 Impact of Lean Tools in the Use of Resources

Rivera [9] presented the conceptual justification of a Lean Manufacturing implementation model. In this model, the most popular lean tools and techniques ("buzzwords") are presented in a structured graph, meaning that there is a structure of precedence relationships between the tools. This structure is not presented as a rigid guideline, rather, as its name implies, it is proposed as a conceptual structure. This structure will be useful to present the techniques and their impact on resource and time use. Figure 1 presents this conceptual structure.

We propose that the main categories in which Lean tools may have an impact are *the use of tangible resources* and *the use of time*. We will now present briefly each of the tools [6, 9], some easily identifiable characteristics and the impact they could have in each of the two categories presented above.

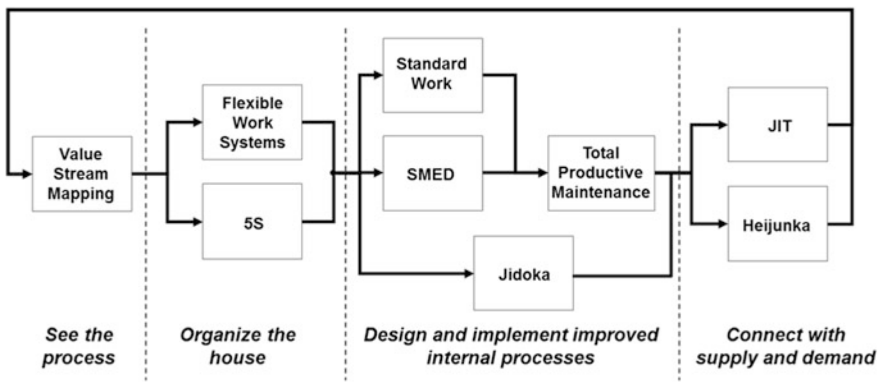


**Fig. 1** Conceptual structure of a Lean Manufacturing implementation

- *Value Stream Mapping:* VSM is a tool that presents the flow of materials and information in the production process of a product family. As such, it does not change the use of resources.
- *5S:* It is the foundation for Lean. It is the discipline of order, cleanliness, and visual control. 5S is a prerequisite for many of the more advanced techniques. It usually saves time (reduces walking and searching for tools and materials), and it also might free space (reducing clutter and removing unused items from the factory floor).
- *Flexible Work Systems:* The use of workcells, where machines used to make a product family are placed close together and a common team of people is devoted to the group of machines and the product family. Workcells usually save space and shorten the length of time the product spends in the system, thus reducing the amount of WIP required. They will also reduce material handling and walking distances.
- *Standard Work:* It refers to the documentation of operating processes in order to perform them the same way every time. The application of Standard work usually reduces the time it takes to perform operations.
- *Single Minute Exchange of Dies (SMED):* It is the systematic reduction of setup times. SMED frees time that was not available to manufacture products before. It is also the first step to reduce the product lot sizes, which decreases WIP in the factory and the lead time to customers. A decreased WIP also means less money invested in materials and less storage space requirements.
- *Jidoka:* It is the reduction of error (both from machine and human sources) to assure quality. Jidoka reduces both production time and use of materials by simplifying work processes and reducing defects and rework.
- *Total Productive Maintenance (TPM):* TPM is the transformation of a repair activity into an operator-driven set of practices to increase machine reliability and performance. Successful TPM implementation depends on 5S practices. TPM increases available time (reducing unplanned machine stoppages) and reduces operating costs (improving quality and reducing rework).

- *Heijunka:* It is the levelling of production to reflect the rhythm of the market demand. Heijunka uses smaller lot sizes, thus decreasing the WIP and therefore the investment and space required by it.
- *Just in Time (JIT):* It is the implementation of the *Pull* discipline for information and material transfer, making only what is required when it is required. JIT uses smaller lot sizes and simplified production and material movement control, reducing WIP and also in-transit inventories.

We can observe that different techniques will have different impacts on the use of time, working capital, floor space, personnel, and materials. It is difficult to standardize the impact each tool will generate in the use of resources. To gauge this impact, a systemic outlook of the production process and its resources should be applied. This is the very reason it is difficult to standardize an impact evaluation model that measures the impact every technique may have.

However, the engineers and operators in charge of the implementation of a specific Lean tool should be able to identify the changes it will bring about in their immediate working environment. The configuration of workcells will usually free some floor space and reduce movement of materials and people. It is up to the team involved in a specific work area to determine the extent of these savings. To do this in a systematic way, we propose the decision flowchart presented in Sect. 4.

## 4 Thought Process: Decision Flowchart

Every time a Lean tool is implemented, it will bring about some changes in the way things are done. Equipment will be moved around. People will be reassigned. New material handling equipment will be installed. Material containers, information systems, new manuals and tools will be needed. Floor space and storage space will be freed from previous usage. However, not all of these impacts will have an easily quantifiable impact on costs, revenues, or production times. We therefore propose the thought process presented in flowchart format in Fig. 2.

Figure 2 takes as an input the Lean tool or technique that will be implemented. The potential impacts of the implementation of the tool are then examined, basically divided into two categories: the impacts that change the use of tangible resources and those that change the use of time. They are not exclusive, as several of the Lean tools presented in Sect. 3 may have impact in both categories.

In Fig. 2 the shaded boxes represent the main stages of the evaluation. It does not mean that every tool will have impact on both categories. The main path suggests the questions that should be asked of every tool, and it also separates the impacts in Immediate Cash Flows and Intangible Impacts, which will require different evaluation techniques.

The flowchart presented in Fig. 2 comes as an idea inspired in works such as Schonberger's [8] where the most commonly used "measure of Lean" is inventory, but he goes on to show that inventory is flawed and insufficient in many

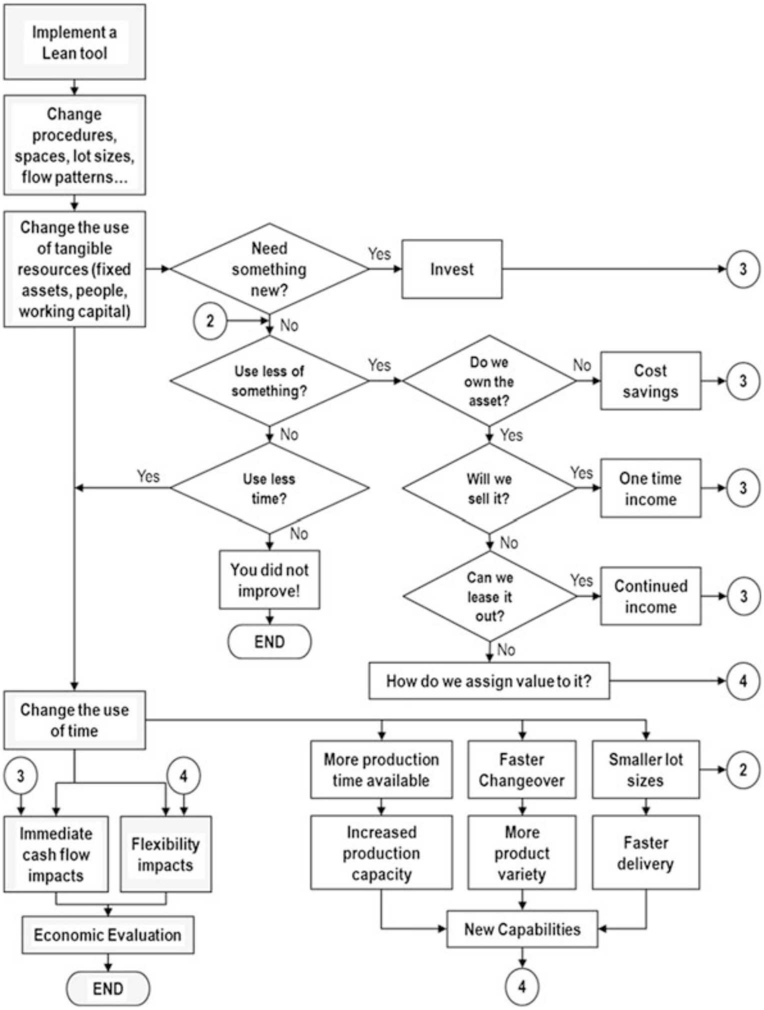


**Fig. 2** Thought process flowchart

cases. Rivera and Chen [6] also postulate some direct impacts that should arise from the application of Lean tools. However, these impacts are limited to what is expected of the tools and do not explore the relationships between functional areas and activities, nor they consider new possibilities and capabilities. This is why we considered necessary to build a flow process to identify both the impact on the use of resources and the generation of flexibility through things the company will be able to do now, that was not able to do before a Lean implementation.

## 4.1 Change the use of Resources

The first question the decision makers should ask is: "Does the implementation of this Lean tool *in this specific production process* change the amount of resources we use?". The key part of the question is the one that refers to the specific process. Not all the Lean tools will behave equally in terms of generating impact. An accurate assessment of the impact of a Lean tool will depend on many factors, such as the relationship to other processes, the physical configuration of the workspace, the material handling equipment present in the production area (including storage equipment), the level of advancement in the implementation of other Lean tools, for example. A systemic view of Lean tools is required to evaluate these impacts correctly [10]. We will illustrate the use of this section of the diagram providing a few examples.

***Need Something New:*** Many times the implementation of Lean tools will require some investment. When implementing 5S new racks, plastic bins, and storage systems are usually purchased. Also, visual boards, digital cameras, and color printers are required to keep track of production indicators. When organising workcells, oftentimes it is necessary to acquire material movement equipment, such as roller conveyors and chutes. In these cases, it is clear that this investment can be readily quantified and evaluated through its direct impact on the cash flow of the company. This one-time investment can be grouped with cash flow savings to configure an investment project that can be evaluated through traditional methods such as Net Present Value.

***Use Less of Something:*** The types of "somethings" (assets and resources) that can see their usage reduce are varied. Many kinds of resources and assets can be discussed in this section. A few of the most relevant follow:

- *Materials:* Companies can reduce their usage of materials improving their quality levels, changing their operating procedures, improving operator training, increasing the reliability of their equipment, or changing the material format with the venders, among other options. Tools such as Jidoka and TPM may have a clear impact on resource usage.
- *Floor Space:* The implementation of workcells might reduce the footprint of the production processes.
- *Equipment:* Production and material transport equipment might be rendered unnecessary by improvements in equipment reliability (TPM) or the reduction in material movement (workcells).
- *Storage Space:* Many Lean tools strive to reduce the presence of work-in-process throughout the plant. Another key aspect of Lean tools is the movement of smaller lots of materials through the process. Both these impacts have a positive impact on storage space, reducing the requirement for storage rooms, racks and other material handling equipment.
- *Personnel:* Before anything else, we must clarify that we do not contend that people should be treated as any other manufacturing asset. People deserve special consideration in Lean systems as in any other production system. Having

said that, it is also clear that an increase in the operating efficiency or a decrease in the movement of materials might reduce the personnel that are required to perform the operation of the plant. In this area we subscribe to the point of view that nobody should be let go of a company because of productivity improvements achieved in a Lean Manufacturing implementation. Therefore, when the implementation of a Lean tool causes a company to free people from an activity, special considerations should be taken to relocate them. This is, however, more economic because the human resource can be devoted to different tasks now.

When the implementation of a Lean tool causes the company to use less of some resource, there is a sequence of questions that we need to ask and decisions we need to take. Let us walk through some of these and provide examples from expected impacts from known Lean tools.

- *Use Less of Something (YES), Do we own the asset? (NO):* This question refers to the case when the implementation of a Lean tool no longer requires a resource or an asset. *If we do not own the asset* or resource, this leads to a direct realization of savings. For instance, we do not own raw materials (before we buy them from a vendor). If we need less material, immediate cost savings are obtained with a positive cash-flow impact. Another example would be when the implementation of 5S makes unnecessary the use of an externally rented storage room. The cost savings for not renting the storage room impact directly the cash flow of the company.
- *Use Less of Something (YES), Do we own the asset (YES):* If we own the asset but no longer require to use it, we need to check if it is feasible for us to sell it. Unneeded equipment or facilities might fall under this category. For example, if we configure work cells and stop using a forklift truck and replace it with a roller conveyor. *If we sell the asset*, the proceeds from the sale become a one-time income that goes into the positive cash flows of the company. *If we will not sell the asset* (for market reasons, managerial decisions or physical impossibility) we need to check *if it is possible at all to rent it out* to some other user, in which case we will receive a continued income stream from it, which will positively impact the cash flow of the company. Finally, if we cannot lease the asset, we need to find a way to assign value to it. Recently, a company in our city freed a warehouse, but it is located deep inside an industrial compound with security restrictions. The company will not need this space any longer, and they are not willing to sell it, and it is also impossible to rent it to a third party because of security concerns. We also need to assign valuable work to a person who has been freed in a certain process, through reassignment or relocation within the company. Nobody should lose their job because of productivity improvements, because if that happens people will no longer support productivity improvements to ensure their job security.
- *Use Less of Something (NO), Use Less Time (NO):* If the implementation of a Lean tool does not save in the use of resources or in the use of time, it did not generate a measurable impact on the economic results. It might be argued that

the implementation of that tool was required as a prerequisite to another, more advanced one. In that case, the economic impacts will be visible down the road, when the subsequent tool is evaluated.

- *Use Less of Something (NO), Use Less Time (YES):* In this case, we should move to the "Change the use of time" section.

All the savings in the *"Change the use of resources"* can be evaluated through the use of traditional methodologies. All of these options flow to the *Immediate cash flow impacts* process, through connector 3 in Fig. 2.

## 4.2 Change the use of Time

The other common impact of Lean tools is the reduction of the time required to operate. For example, improving manual processes through Standard Work will allow operators to finish their work earlier. Applying SMED reduces the time required for changeovers. Yet another example would be the reduction of lot sizes, which increases the frequency of material movements, reduces the accumulation of WIP and therefore reduces the lead time required to fulfill a customer order. In the case of time reduction, there is not a clear consequence that follows inevitably in terms of savings.

Time savings open a different gate for analysis, because now the thought process should not ask *how much will we save?,* rather: *What can we do with this time that we freed?*. This new question creates the need for the use of non-traditional economic valuation techniques, because the value of time as a resource *depends* on what we decide to do with it.

The implementation of a Lean tool that saves time can have an impact in more than one of the categories presented in Fig. 2. Some comments on those categories follows:

***More production time available:*** When workers and machines can finish their tasks faster, it means that they could have the time to produce more units of the same products the company makes. This leads to an increased production capacity that does not generate any economic advantage unless the company is capable of selling this newfound capacity. Opening new markets, starting export businesses, reconfiguring the product to reach new market segments would be additional actions required to take advantage of this new and increased production capacity.

***Faster Changeover:*** The application of SMED (and 5S, and TPM) could create the capability for faster changeovers. This would make possible for the company to make a wider variety of products. As with the previous issue, being able to make a wider variety of products does not mean that it will generate economic profits. The convenience of this improvements would be realized only if the company has the capability to expand its product lines and find customers for them.

***Smaller lot sizes:*** Faster changeovers enable a company to perform more frequent setups, which leads to smaller lot sizes. Smaller lot sizes reduce lead time, so customer orders can be fulfilled more rapidly. It is up to the marketing, sales and distribution areas to capitalize on this faster fulfillment speed to generate more sales and to create an advantage for the company in its marketplace.

All the capabilities and flexibilities that appear under "Change the use of time" need to be evaluated through non-traditional economic evaluation methodologies. All of these options flow to the *Intangible Impacts* section, through connector 4 in Fig. 2.

## *4.3 Economic Evaluation*

The Economic Evaluation section is accomplished through two subsections.

***Immediate cash flow impacts:*** One-time investments, cost savings and one-time revenues can be used to build a *Free Cash Flow* diagram and evaluate the improvement as an investment project, using well known techniques such as *Net Present Value (NPV)* [11]. We will not go into detail, as these techniques are well known and widely used.

***Flexibility impacts:*** The impacts that relate to the use of time configure aspects of what has been called *Manufacturing Flexibility*. As such, different methodologies to evaluate it are required. Abele, Liebeck, and Wörn [12] consider cost of purchase and operation, cycle time, and achievable work piece quality, and they use real options to evaluate manufacturing systems. Koste, Malhotra, and Sharma [13] use six dimensions with four elements each in order to measure manufacturing flexibility. Bengtsson and Olhager [14] propose a measurement of flexibility and an economic evaluation of product-mix flexibility specifically, also using real options.

Real options methods to evaluate flexibility usually produce an economic value, analogous to the *Net Present Value* of the option the company needs to take in order to realize economic benefits from the improvements. Real options literature is rich and diverse, but the area for more development at this time is the measurement of flexibility.

A basic final economic evaluation of the impact of a Lean tool would be to identify the aspects that generate immediate cash flow impacts and get their *NPV*, and then to use one of the real-options methodologies to evaluate the flexibility impacts and measure the *NPV* of the chosen option. The *NPV* of the implementation of the Lean tool would be the resulting addition of the *NPV* from the immediate cash flows and the *NPV* of the flexibility impacts.

# 5 Conclusions and Future Research

Given that the implementation of most Lean tools generates impacts on the use of resources and time, it is important to develop systemic disciplines to help in the planning of improvements. Unforeseen impacts are important, even more so those beneficial in more ways than initially planned.

It is not a simple task to develop a tool that automates the economic evaluation of the implementation of Lean tools. In this paper we presented a thought process that might be used as a guide for that purpose. Sometimes freeing an asset might not have a beneficial economic impact. Some other times the main gains of Lean tools are not immediate cash flows but rather the generation of capabilities and manufacturing flexibility that require more action from the company to be realized.

Lean tools generate different kinds of impacts, which require different tools and disciplines to be evaluated. It is necessary to train engineers and managers in systems thinking and economic evaluation tools. A traditional evaluation done without considering multiple impacts and ramifications, as well as an evaluation that does not consider the value of flexibility would probably render many Lean improvements unattractive for financially-minded managers. The value of capabilities and flexibility needs to be considered in a strategic fashion, since it will demand additional resources and actions from the company to take advantage of them.

This type of evaluation tools brings up the intuition that companies should not implement Lean tools only to reduce costs and contract the resources required to operate. That course of action brings up the question of what to do with workers that are no longer needed and the waste of new capabilities created but not used to expand the operation and generate new revenues and profits. Lean should be taken as a path for growth and success, not as one of savings, contraction and shyness.

We are planning to validate this flow chart methodology discussing it with local companies that have implemented Lean Manufacturing. We would like to build an industrial case study that is based in actual experiences. We will also start deciphering the "how" part of our proposed methodology, to determine what preparatory steps would be required to prepare a company to make accurate decisions in the characterization of impacts such as savings gained or investments needed in a Lean Manufacturing implementation.

It is necessary to study specifically the types of flexibilities that would be typical to develop when implementing Lean Manufacturing, as there is work being done to evaluate flexibility in manufacturing systems (not specific to Lean systems). If it is feasible to characterize the types of flexibility that appear when implementing lean, economic evaluation methodologies would follow logically.

A systems thinking point of view should be used to discuss Lean Manufacturing in learning environments. This would create a more interconnected understanding of the production system and the reasons why Lean manufacturing would or would not work on a certain set of circumstances. It is important to create systems thinking models with different levels of detail to address these systemic relationships between production variables and the impacts they may cause on the economic results of the company.

## References

1. Sarkar D (2007) Lean for Service Organizations and Offices: a holistic approach for achieving operational excellence and improvements, ASQ Quality Press
2. Hayler R, Nichols M (2006) Six sigma for financial services: how leading companies are driving results using lean, Six Sigma, and Process Management, McGraw-Hill
3. Graban M (2011) Lean Hospitals: improving quality, patient safety, and employee engagement, Productivity Press
4. Lian YH, Van Landeghem H (2007) Analysing the effects of Lean manufacturing using a value stream mapping-based simulation generator. Int J Prod Res 45(13):3037–3058
5. Wan HD, Chen FF (2008) A leanness measure of manufacturing systems for quantifying impacts of lean initiatives. Int J Prod Res 46(32):6567–6584
6. Rivera L, Chen FF (2007) Measuring the impact of Lean tools on the cost-time investment of a product using cost-time profiles. Robot Comput Integr Manuf 23:684–689
7. Apreutesei M, Arvinte R (2010) Financial models and tools for managing lean manufacturing. J Econ Eng 4:4–7
8. Schonberger RJ (2011) Taking the measure of lean: efficiency and effectiveness, Part I. Interfaces 41(2):182–193
9. Rivera L (2008) Justificación Conceptual de un Modelo de Implementación de Lean Manufacturing (Conceptual Justification of a Lean Manufacturing Implementation Model), Heurística, vol 15, pp 91–106
10. Dinas J, Franco P, Rivera L (2009) Aplicación de herramientas de pensamiento sistémico para el aprendizaje de Lean Manufacturing (application of systems thinking tools for lean manufacturing learning), Sistemas & Telemática, vol 7(14), pp 109–144
11. Varela R (2010) Evaluación económica de proyectos de inversión (Economic evaluation of investment projects), McGraw-Hill
12. Abele E, Liebeck T, Wörn A (2006) Measuring flexibility in investment decisions for manufacturing systems. CIRP Annals Manuf Technol 55:433–436
13. Koste LL, Malhotra MK, Sharma S (2004) Measuring dimensions of manufacturing flexibility. J Oper Manage 22:171–196
14. Bengtsson J, Olhager J (2002) Valuation of product-mix flexibility using real options. Int J Prod Econ 78:13–28

# Setup Performance Indicators: A Tool to Systematize and Standardize the Setup Process Diagnosis

**J. Morgado, P. Peças, A. Jorge, E. Henriques, R. Cernadas and S. Furtado**

**Abstract** Manufacturing industry is currently under a strong competitive pressure, not only from the developed countries, but also from countries with significantly lower labour costs. New products and processes are and will be fostered by the emergence of new manufacturing technologies, stimulated by intense competition. As complement, new management and labor practices, organizational structures, and decision-making methods will emerge. It is necessary to develop strategies that are capable of building a strong competitive position in the global market and the journey starts on the shop floor—on the capability to supply the client needs. One of the most critical point of production process in manufacturing industry is the Setup process. When companies give low attention to the Setup process or don't know that it's possible to improve it, the overall time spent on it can be really significant. Consequently, a significant percentage of production time is consumed in non-added value activities, time that could be used in actual production or to increase production flexibility. This paper is about the creation of a tool capable to diagnose the Setup process. This tool is based on a methodology that allows identification and monitor Setup's key process indicators (KPI)—i.e., total time, longer operations, waiting times, transports, handling and cleaning times. It also allows the Setup process control by assessing the KPI of consecutive Setups.

## 1 Introduction

The Setup period or activity is required to change-over the product type or component that is being produced. It lasts from the last accepted part produced in a machine to the first accepted part of the new batch. For the authors of this paper,

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the set of tasks required to complete this activity can be called the Setup Process. The time spent in this process is the Setup time. For sake of comprehension is assumed in this document that the Setup is a necessary production process and that activities such as delays, transport, cleaning, rework, etc., are considered as non-value added [1].

In some industrial realm, the Setup related tasks are considered only as a heap of jobs to accomplish out of the core processes of the production system. Accordingly, due attention with regard to performance improvement strategies is not given. This attitude contributes in general to long Setup times. Inappropriate loading and unloading systems, fixing systems and positioning mechanisms are usually found in this situation. Additionally, long Setup times can be related also with a significant percentage of Setup time consumed in non-added value activities. Absence of standard procedure, or its systematic application and the use of the Setup period to operators rest or production related issues clarifications are some of the main causes for that [2, 3].

In other type of industrial environments, more concerned with continuous competitiveness improvement, a high degree of attention is given to the Setup related tasks. Nevertheless there is lack of efficient and/or systematic and practical approaches to assess the Setup activity and compare it with other companies or competitors as occurs for a "normal" production process [1, 4].

Before introducing the approach proposed to tackle these problems, it is crucial to discuss the present state of knowledge regarding the Setup process diagnosis and its improvement methods. Using the base-line of Setup improvement methods—the work published by Shingo [5] and implemented world-wide—the tasks commonly observed in a Setup can be divided in two classes that co-exist in a non-improved Setup Process:

- Internal Operations: tasks that must be performed with the equipment idle. Examples: Positioning, Adjusting, Tool Shifting, etc.
- External Operations: tasks that can be performed before stopping the process or after initiate new process but are being done with the equipment idle. Examples: Transport, Operator Movements, Cleaning, etc.

In any action of Setup process improvement, it is crucial to identify the internal and external operations. Therefore, a procedure must be developed to assure the performance of the operations identified as external before or after the Setup (the streamlining of these operations is also important to minimize the resources waste—usually the operator). Additionally, solutions to reduce the time spent on internal operations should be developed (together with an optimized standard procedure). The new and adequate procedures developed aim to promote an organized and efficient Setup process [3, 5]. The described approach is in the core of Shingeo Shingo's SMED methodology, Single Minute Exchange of Die [5]. SMED has been at the forefront of retrospective changeover improvement activity since the mid-1980s. It has been widely acclaimed and has been widely assimilated into academic texts and industrial training material. Also several authors confirm the widespread application of the SMED methodology in industry [6, 7, 8]. This finding is reinforced by the many consultant-led changeover improvement training programmes based on this methodology [9].

It should be noted that although the major Shingo's motive in his development of the SMED methodology was the production capacity increase of a set of press machines, currently other benefits result from Setup time reduction. Continuously reducing Setup time is the most effective way to support the reduction on batch sizes, toward the vision of one-piece-flow, and without losing cost effectiveness. This batch reduction has direct effect on the stock level reduction, essential in nowadays need to decrease invested stock capital. In addition, short and standardized Setup procedures contribute to the reduction of factory variability, which is a major cause for the performance degradation in any manufacturing system [10, 11].

In the last decades, researchers have published studies related with Setup process performance and particularly with the operationalization of the SMED approach [10, 12, 13]. Those authors propose more focus on operator behavior prior and after the Setup process. It is also reinforced the importance of "beginning" the Setup process improvement in the machine/work station design phase.

The authors of this document believe the SMED approach as well as the more recent proposals to its modification should be taken into consideration in Setup process improvement. The methodology proposed in this study is mainly to be applied before the solutions design. In fact, the proposed methodology aims to facilitate the understanding of the need to improve the Setup process. Through the systematization of the Setup analysis by the use of Setup's key process indicators (KPI)—i.e., total time, longer operations, waiting times, transports, handling time, etc.—a tool to support the Setup process monitoring and control is proposed. Allowing a more agile analysis of the Setup process and identification of the critical "time consumers", the proposed methodology will contribute to a faster design of the required solutions and procedures. Furthermore, the assessment of the Setup as a process based on KPI allow for benchmarking analysis within the company, among different equipment/sectors, and with other companies using similar equipment or industrial processes.

## 2 Proposed Methodology Framework

### *2.1 Setup Process Systematic Analysis*

Assuming the Setup as a process, it is the first crucial statement of the approach. As any process, it is essential to identify and characterize the type of operations that constitute the Setup process. Performing a diagnosis based on the assessment of a set of possible operations will allow identifying the existence of inadequate tasks and/or inadequate contribution of some tasks yet necessary.

Despite the specific nature of each setup in each machine, and even in each company, the classification of the tasks required to accomplish a Setup process is

**Table 1** Type of operations proposed and its description

| Type of operations | Description |
|---|---|
| Positioning | Tasks involving parts and tools placing and removing |
| Adjusting | Tasks involving parts or special tools aligning and attaching |
| Tool shifting | Tasks involving replace or prepare the processing tool |
| Programming | Tasks involving program loading and parameters setting |
| Cleaning | Tasks involving part/special tool and/or machine cleaning |
| Transport | Tasks involving tools and material transportation |
| Operator movement | Tasks involving operator movements (no transport—free hands) |
| Final tests | Tasks involving fine tuning of process parameters by parts producing |

possible. A classification based on 8 Type of Operations (ToOP) is proposed, so anyone of the myriad of tasks required to do a Setup will fit in one (and only one) of these 8 categories [1, 2]. In Table 1, the proposed ToOP is listed and described. Its specific name and description should be adapted to each type of equipment and sector for the sake of general and practical understanding. Nevertheless, the type of action included in each ToOP should be respected to assure completeness.

The ToOP related with Positioning, Adjusting and Tool Shifting are in almost all Setups performed with the equipment idle so, these can be considered as typical and acceptable internal operations. When these ToOP are the most frequent in a Setup it usually means that prioritization should be given to the development of solutions and procedures to minimize mechanical and/or fixing related tasks time.

The ToOP related with the Transport and Operator Moving if observed during the Setup process can be considered as belonging to the external class of operations. Therefore, a Setup process in which the latter types of operations are relevant has a significant potential for improving—solutions should promote its elimination or minimization (externalization) by the development of a new Setup process procedure.

The other three ToOP, Programming, Cleaning and Final Test have no clear class definition, being sometime external, and sometimes internal. In fact, sometimes these operations include tasks that must be done with the equipment idle, depending on the type of equipment, product being process and on the Setup sequence. So, specific actions should be taken accordingly, either to externalize these tasks or to "only" minimize its duration as internal operations.

The proposed classification fosters a systematic and standard view of the Setup process. Based on the ToOP the comparison and the monitoring of the Setup process performance are possible as will be discussed in the next sub-section dedicated to the KPI. Nevertheless, the proposed analysis doesn't give any information related with the Setup process sequencing in time. Usually a Setup process is composed by several phases, so the contribution of each phase to the total time and operations done in each phase are very important information to support the definition and focus of improvement solutions.

Consequently, an additional classification based on the sequence of the Setup process phases is proposed. The Setup Phases classification depends largely on the

**Table 2** Classification and description of the setup phases

| Setup phases | Description |
|---|---|
| Finished part removing | Removing of finished part or special tool from the machine |
| Next part placing | Placing of next part or special tool on the machine |
| Part holding | Fix the next part or special tool to the machine |
| Tool changing | Replace the processing tool (the milling item) |
| Tuning | Setting programmes, adjusting process parameters and tests |

An example for CNC milling machines

type of equipment and industrial sector, so no general classification can be given. In Table 2, the set of Phases is proposed to the Setup of CNC milling machines. Based on this classification is possible to compare the Setup process on different companies and on different equipment in the same company [1, 2]. On the other hand, a proper set of Phases should be defined for distinct type of Setups, even in the same company. For example, in a plastic injection moulding company that produces its own moulds, different set of Phases should be defined for the CNC machines and for the injection moulding machines. Nevertheless, the ToOP classification can always be used to compare the general Setup process performance.

The Setup Phases classification allows the understanding of each phase influence in the Setup time. In this case, all the phases are part of the Setup process. The merging between this classification and the ToOP classification allows identifying the Operations that are performed in each Phase (Fig. 1). As an example, in the "Finished Part Removing" phase the ToOP that should be found should be related with Positioning. If a relevant percentage of other ToOP is found it means that the Setup procedure sequence should be revised (i.e., if Tool Shifting and/or Programming are relevant) or even that there is the need to externalize several tasks done during this phase (i.e., if Operator Movement and/or Transport are relevant).

Regarding the proposed classification, a remark must be made to the Setup process complexity. Depending on the product complexity and/or sequencing, the Setup process complexity in the same type of machine or even in the same machine can be significantly distinct. These differences should be taken into account when comparing Setup performances, some aspects are not comparable (i.e., Setup time, time for Positioning, time for Adjusting). Nevertheless, if a Setup has a high percentage of time on Operators Movement, Transport, Programming or even Cleaning ToOP, certainly there is space for Setup time reduction. Identifying the main causes for long Setup times and defining improvement solutions will be performed faster and more easily with the proposed classification. The next subsection will contribute to support the statements above since is dedicated to the description and discussion of the KPI proposed based on the two classifications.

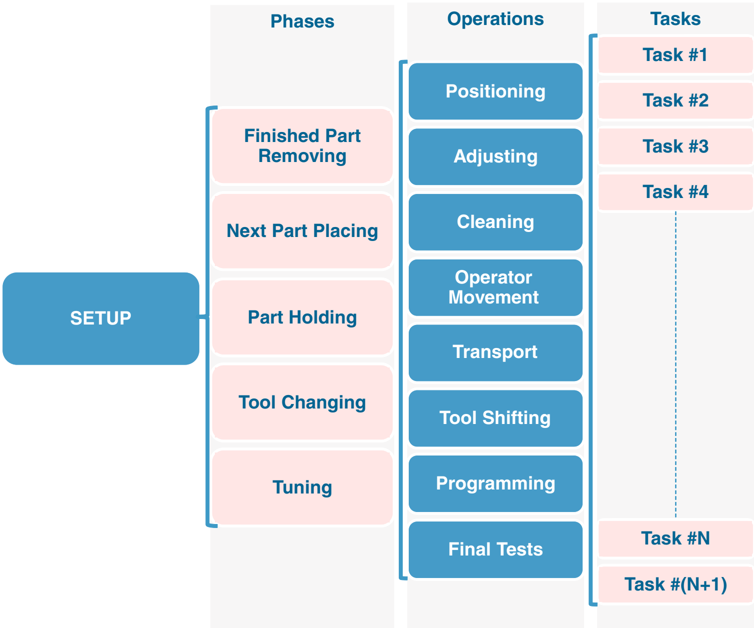



**Fig. 1** Merging between the two proposed classifications: ToOP and Setup Phases. The list of Setup measured tasks are classified in the ToOP and the Setup is divided in several Phases. The Phases here are the ones identified for the CNC milling machines (Table 2)

## *2.2 Setup Analysis and KPI*

As referred before, the intention of proposed approach is to shift the paradigm related with the Setup activities. Consider it completely as non-added value activity inhibits its total comprehension since the main aim is the total elimination, if 6-Sigma and Lean thinking principles are radically applied. Since its elimination is impossible due to the increasingly changing need of the products mix, the proposed paradigm is to consider the Setup as a process required to the overall production.

Assuming the Setup as a Process the strategies of continuous improvement can be applied by continuous analysing the Setup tasks and monitoring the process. Therefore, the successful approaches like Kaizen events, Plan-Do-Check-Act cycle (Deming Cycle) or Lean Manufacturing tools can be used to tackle the Setup as a Process. In Fig. 2, a strategy for continuous improvement is proposed for the Setup process based on an expanded Deming Cycle, similar to the one proposed by the 6-Sigma philosophy—the DMAIC cycle. As a first step of this strategy is the definition of the KPI. After its definition, should be defined the targets and objectives. The next steps are the Setup process measuring and the KPI analysis. This will allow to identify the most relevant aspects to improve (reduce time) so solutions can be developed and implemented, that should be than assessed to check its effectiveness. Typically, as bigger variability found on KPI measurement, the bigger is the improvement potential. Based on the KPI is also possible to do benchmarking analysis among different equipment in the company as well as between companies on a sectorial basis [1]. The continuous monitoring of the Setup process performance allows for continuous assessment of its performance based on the several KPIs selected.

Three KPI types are proposed for the Setup process: Overall, Partial, and Critical. The KPIs are described next, some examples are included.

The Overall KPI use production related data to give general information about the Setup process performance. Beside the Setup time measured, other data used is the manufacturing time, operator, and machine cost. The Overall KPIs proposed are the followings:

- $T_{Setup}$: Setup Time: Time measured from the last part produced of the last batch to the first accepted part produced of the new batch.
- $C_{Setup}$: Setup Cost: Production cost related with the machine stopped and operator(s) occupation during all the Setup time. Additional equipment used must also be considered.

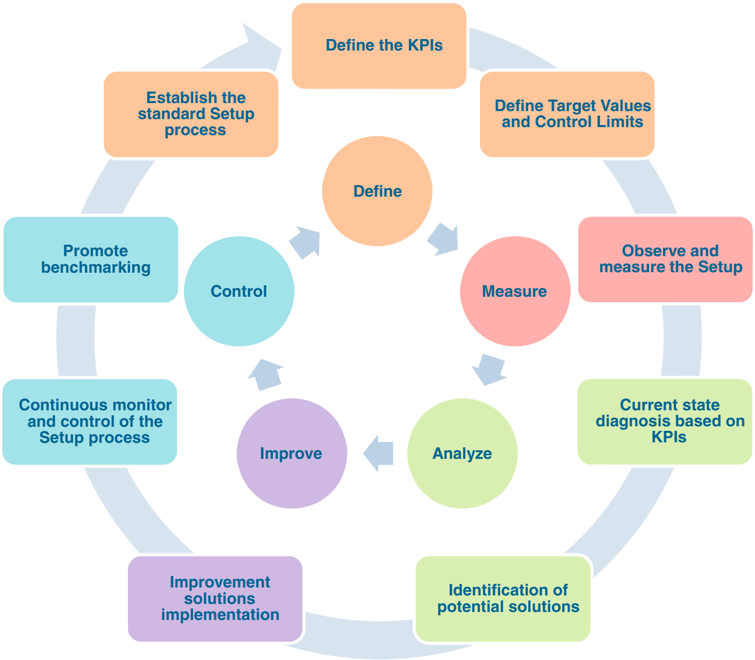



**Fig. 2** Strategy for continuous improvement of the Setup process based in the Setup KPI analysis and monitoring

- $T_{Setup}/T_{Process}$: Ratio between the Setup Time and the average production time of a batch. This KPI give information about the relevance of the Setup in the production planning.

The Partial KPIs are obtained through the use of the proposed classifications. Other than the listed ones should be used if appropriated. The Partial KPIs proposed are the followings:

- $T_{ToOP\ i}/T_{Setup}$: After the ToOP classification is possible to compute the parcel of each *i* ToOP (among the 8 ToOP). The ratio between each parcel and the Setup Time gives the percentage or the importance of this $ToOP_i$ in the Setup overall time.
- $T_{Phase\ j}/T_{Setup}$: After the Setup Phases classification is possible to compute the parcel of each *j* Phase (among the 5 Phases in the case of CNC milling machines). The ratio between each parcel and the Setup Time gives the percentage or the importance of this $Phase_j$ in the Setup overall time.
- $T_{GoOP\ k}/T_{Setup}$: The ratio between each the Time of Group of Type of Operations ($T_{GoOP\ k}$) and the Setup Time.

Here is introduced an aggregation of the ToOP to promote a more efficient diagnosis to the Setup process. There are proposed the following types of GoOP (others can and should be used accordingly):

- External type group: GoOP related with typical external operations that are in fact performed during the Setup time. Aggregation of the time of the following ToOPs: Transport, Operator Movement and Cleaning. If Cleaning is not of external type then should be removed from this GoOP.
- Internal type group: GoOP related with typical internal operations that must be performed during the Setup time. Aggregation of the time of the following ToOPs: Positioning, Adjusting and Tool Shifting. If Tool Shifting can be done externally then should be removed from this GoOP.
- Parameter Setting type group: GoOP related with typical setting operations that are usually related with communication between machines and computers and with technological know-how. Aggregation of the time of the following ToOPs: Programming and Final Tests.

The Critical KPIs intend to reveal the current state of the measured Setup. There is the need to prior specify target values aiming to identify easily and intuitively the main causes for low performance and consequently the type of improvement solutions required. The target values can be derived by production performance requirements and also by internal or external benchmarking analysis. The Critical KPIs to select depend mainly on each machine, type of Setup and company specific productivity requirements. Here are proposed some typical Critical KPIs:

- $T_{Setup}$ versus $T_{Target\ Value}$: The distance of the total Setup time to the target value aimed for the Setup time usually an important measure of performance. This distance can be measure in time difference, direct ratio or other more elaborated ratios.

- $T_{Setup}$ evolution versus Control Limits: Using the process chart logics it can be defined control limits for the Setup time. These control limits can be defined discretely as production performance bias to be kept or even statically using the approach of statistical process control. The control of the Setup process evolution along time permits to identify deviation from average performance both to promptly react to Setup time increasing either to identify good practices in the case of consistent reduction of Setup time.
- More frequent ToOP and Longest Phase: This KPIs give notice about the ToOP with a high percentage in the Setup time and the Setup Phase that has the highest parcel in the Setup time. These indicators are very important in the solutions process definition to improve the Setup process since the main drivers for an eventual long Setup time are identified.
- $T_{GoOP\ k}$ versus $T_{Target\ Value\ k}$: This or these KPI(s) give a more macro view of the Setup process performance than the KPIs related with specific *i* ToOP. Sometimes can be difficult to define target values for Operator Movements, or Cleaning or else. On the other hand using the Groups of operations is more intuitive and easy to establish target values for example for external type of operations (i.e.: Transport, Operator Movement and Cleaning) to be lower than a certain percentage or cumulative time to assure a good Setup performance.

The list of KPIs above is not exhaustive (its summary is presented in Fig. 3). Others can be used that allow for a better monitoring and control of the Setup process. The fundamental point is taking advantage of the classifications proposed in Sect. 3.1 allowing for a systematized and agile monitoring and control of the Setup process.

## 3 A Tool to Apply the Setup Key Process Indicators: SPI

To support the implementation of the proposed Setup process tasks classifications, in ToOP and Phases, and to compute and use the proposed KPIs an easy to use and adapt tool (Excel® based) was developed, tested and implemented in several industrial companies. The authors called this SPI to this tool. Several plastic injection mould making companies implemented the SPI tool to assess and improve the Setup process of CNC milling machines. Companies that use CNC milling machines to finish cast irons parts also applied it. In the former, each Setup is unique in mechanical terms and the latter there are batches of similar parts so consecutive Setups are common. In both situations, the companies' personnel accepted easily the SPI tool and began to use the tool to support the Setup process continuous improvement. The KPIs related with the Setup time evolution are used regularly and the ones related with distribution of Operations and Phases were used to initial improve the Setup process and will be used on a periodic basis (or if

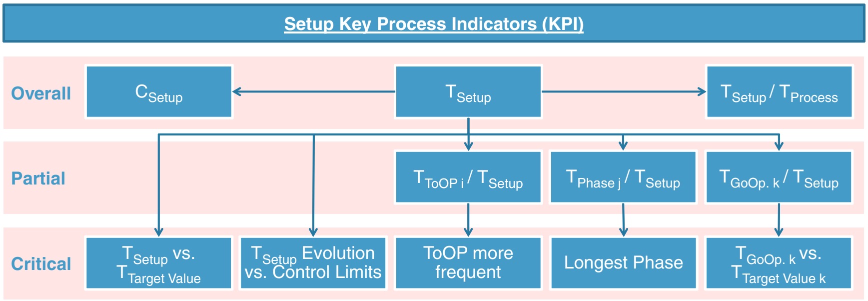
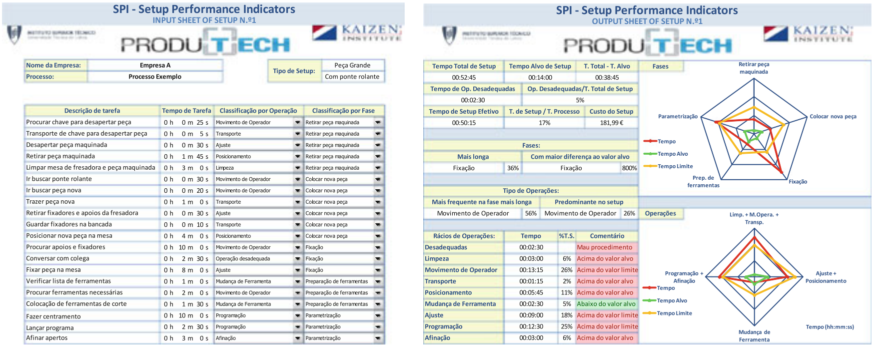



**Fig. 3** Summary of the KPIs proposed for the Setup process monitoring and control. Others can be selected if found relevant for a specific Setup process. $T_{ToPi}$ is the sum of the times of Setup tasks classified as of *i* type, among the 8 ToOp (see Table 1). $T_{Phase\ j}$ is the time of each Setup (among the 5 Phase in the case of the CNC milling machines example, see Table 2). $T_{GoP\ k}$ is the sum of the times of $_{ToOp\ i}$ included in each *k* group

an event is detected on the regular monitoring by the control limits). Two equipment manufacturers are applying the SPI tool, with specific adaptations, as an additional package to add value to the equipment. The automatic SPI tool feeding by the equipment sensors, will allow the machine user an automatic Setup time monitoring. Additionally, the target values establishment for the Setup time, specific ToOP and Phases, by the equipment manufacturers, allows its users to Setup process benchmarking and to design training programmes in order to improve continuously the KPIs.

The SPI tool was applied having in mind the philosophy presented in Fig. 2 meaning that significant data was generated and discussions occurred due to the existence of a methodology that permits to the Setup to be analysed as a process. In Figs. 4 and 5 are presented a few images of the SPI tool in use. These images don't represent all the possibilities of analysis but allows revealing the type of output available in the SPI tool. A fraction of the Setup tasks introduced and its respective times can be seen in Fig. 4a as well as the ToOp and Phase classification. In Fig. 4b, some of the KPIs are shown and its representation in a spider chart to facilitate its comprehension and discussion. In Fig. 5a the table where the user can set the target values is presented. In Fig. 5b the KPI related with the deviation from the Setup time target value, with the longest Phase and with the more frequent ToOP are showed. It is also presented graphs related with the Setup time evolution, the control limits, and related with the GoOp evolution along 10 measured Setups. The SPI tool can be easily adapted to each company needs and several designs can be used in the same company for different types of analysis and Setups. It may also be applied from time to time allowing it to audit the current state of the setup process, both method and equipment.




(a) (b)

**Fig. 4** Images of the SPI tool for the Setup of CNC milling machines. **a** Setup description and list of Setup tasks as well as its measured times and classification; **b** KPIs related with the contribution of each ToOP to the Setup time as well as spider charts for the ToOP and Phases with indication of the target values and control limits (defined specifically in this application)


(a) (b)

**Fig. 5** Images of the SPI tool for the Setup of CNC milling machines. **a** Setup targets and control limits as well as production cost relative data; **b** KPIs related with the contribution of each GoOP to the Setup time. Graphs with the evolution of the Setup time, target and control limits values as well as the evolution of the GoOP along 10 Setups

# 4 Conclusions

The ultimate aim of this paper is to contribute to the Setup related activities being considered as a process required in a production system. Assuming the Setup as a process, a list of eight Type of Operations are proposed and described together with the definition of Setup process Phases. The Operations are considered universal; the Phases are sequential and depend on each equipment, company and sector. With the proposed classifications is possible to diagnose the Setup in a systematic and standard way. Additionally, based on the referred Setup tasks classifications several KPIs are defined allowing for the Setup control and monitoring as any other production process. The use of the KPIs permits a more easy and agile identification of causes of eventual long Setup times. Therefore, the proposed approach is a valuable tool to adopt together with existent continuous improvement strategies.

This approach was applied in several companies through the use of a spread sheet based computing tool called SPI. The user introduces in the SPI tool the Setup description and the time of each elementary task measured. The following step is to classify the tasks into Type of Operations and define the Setup Phases. Also, the targets and control limits should be introduced. With the use of the SPI tool, adapted to each company requirements in terms of the most relevant KPIs, is possible to control and monitor the Setup process. Furthermore, the systematized nature of the analysis allows for benchmarking analysis within the company on several machines or sectors and on an intra-company or even sectorial analysis as well as an audit tool on a periodic basis.

Further research and SPI tool applications will be made in order to search for improvement opportunities in the Setup process diagnosis.

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## References

1. Peças P et al (2012) Collaborative model for performance improvement of non-added value activities in SMEs, 18th international conference on engineering, Technology and Innovation. IEEE Europe, Munich
2. Morgado J et al (2012) Milling machines setup process characterization in the context of mould making industry, 5th international conference on polymers and moulds innovations—PMI 2012. University College Ghent, Belgium
3. Moreira A, Pais G (2011) Single minute exchange of die. A case study implementation. J Technol Manag Innov 6:1
4. Henriques E et al. (2008) Application of quick change-over method (SMED) in the production of moulds to the glass industry, rapid product development—RPD2008. Oliveira de Azeméis: Centimfe, Cefamol, n° 8029
5. Shingo S (1986) A revolution in manufacturing: the SMED system. Productivity Press, Cambridge
6. McIntosh R et al (2000) A critical evaluation of Shingo's 'SMED' methodology. Int J Prod Res 38–11:2377–2395
7. Joshi RR, Naik GR (2012) Application of SMED methodology—a case study in small scale industry, Int J Sci Res Publ vol 2(8)
8. Ulutas B (2011) An application of SMED Methodology, World Academy of Science. Eng Tech 55:100–103
9. McIntosh R et al (1996) An assessment of the role of design in the improvement of changement performance. Int J Oper Prod Manage 16:5–22

10. McIntosh R et al (2007) Changeover improvement: reinterpreting Shingo's SMED methodology. IEEE Trans Eng Manage 54–1:98–111
11. Culley S et al. (2003) Sustaining changeover improvement, J Eng Manuf, Proc Inst Mech Engrs, 217-Part B: pp 1455–1470
12. Chakravorty SS, Sessum JL (1995) Developing effective strategies to prioritize set-up reduction in a multi-machine production system: a throughput approach, Int J Operat Prod Manage, vol 15(10) pp 103–111
13. Sugai M et al. (2007) Metodologia de Shigeo Shingo (SMED): análise crítica e estudo de caso, Gest. Prod. São Carlos, vol 14(2) pp 323–335

# Kanban Principle Training Game “Kanban Bar”

**Barbora Sramkova, Lukas Fiedler, Martin Januska, Jiri Kudrna and Lucie Stastna**

**Abstract** This paper deals with introduction of Kanban principles in the form of social group game. The game was prepared for the course of operational management at the University of West Bohemia. The goal of the game is to show participants how Kanban works at the simulation of bar. In the first round participants can see problems connected with wasting due to unfinished production. In the second round Kanban is implemented. Participants then can see the results and benefits of Kanban. The whole game is introduced in paper and benefits of the game based on students evaluation after course are discussed.

## 1 Introduction

Within the lessons at the University of West Bohemia in Pilsen students of Faculty of Mechanical Engineering created new manager game to explain the Kanban principle. Impulse for creation of a completely new game was a need for comprehensive visual teaching method usable at Faculty of Economics. The goal of game is to simulate production line and methods used to optimize production on example even students without technical background can fully understand and imagine.

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The game was tested during the lessons at the Faculty of Economics. There were three two-hour games with a total of about 100 students involved. Based on the experience gained during these pilot games basis for teaching in the next term were created. The game is especially suitable for educational purposes within the University, but can be modified for use on training in enterprises.

## 2 About kanban

Kanban system is based on the principle of pull. This change in management material flow is based on a very simple principle: the manufacture and assembly is divided into cycles of self regulating and defining the relationship "supplier customer" in the manufacturing process. Command variable is the size of the buffer stock (tank, storage) after sales department. Kanban system works on principle of strength (in English = pull). This means that it is raised, or produced only the material shipped, the customer removes it from the buffer. Absence requirement for material, there is no activity. Kanban contains information needed for production control and material flow. Contains information, what to produce, where to produce, how much the produce and where to deliver the product after manufacture or move. The material has defined container transport units (e.g., pallets, boxes, crates, etc.) and Number pieces in packaging of these units. Principle for Kanban Management production is that it can not produce or move material in the absence of request in the form of free Kanban card. These cards circulating in the material flow—Kanban in the circuit—in a predefined amount. This will determine the amount of material in the circuit and is thus controlled by the amount of material held in the string [1].

## 3 About the Game

Games have demonstrated to provoke active learner involvement through exploration, experimentation, competition and co-operation. They support learning because of increased visualization and challenged creativity. They also address the changing competences needed in the information age: self-regulation, information skills, networked co-operation, problem solving strategies and critical thinking [2].

The game has been named Kanban Bar Game and is intended for any number of teams with seven players. The game is controlled by the moderator, who is cooperating with needed count of supporters. Same as in number other management games players are not informed about principles of particular method—here Kanban. Purpose of the game is gradual uncovering of the method and explanation in the course of the game rounds.

Name of the game gives the hint that team simulates workers in the bar. Every Bar has assigned one player as customers. The game moderators with his assistants are investors who decided to open a bar. Investor's gives support to the bar workers such as material needed, supplies and know-how. Investors expect that bar workers will attract and maintain customers provide high-quality services and earn as much money as they can.

Game should be played in four rounds where each round is evaluated and teams receive points. After every round results are being evaluated and discussed. Therefore, more than one team is needed to create competitive environment. Same time between rounds discussion will be setup to demonstrate principles of production. Teams are discussing with the moderator about highs and lows of theirs decisions. Players and moderator are finding the best path how to eliminate wasting which happened in the round (game). It is expected that moderator will explain the method to the players (students) in this phase.

## 3.1 The First Round

First round is about introduction of the bar products. The products which are presented in the bar are being introduced to the players (bar workers). Products are 3 different cocktails to each recipe and the production process is introduced see Fig. 1.

All of the products are in fact created from the paper by cutting coloring and bonding. The formula has been created in the way which makes possible to give to every player specialization to just one operation. Bar is in fact simulation of

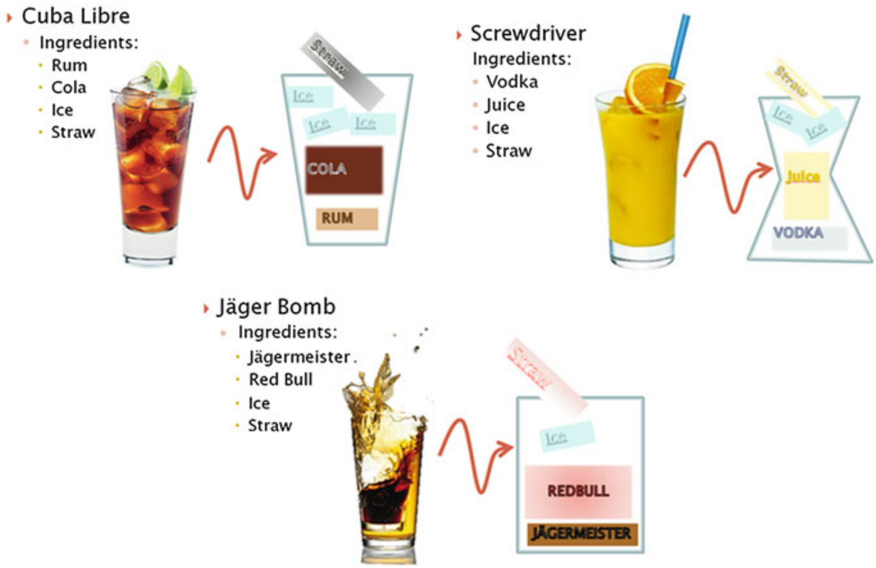



**Fig. 1** Bar products

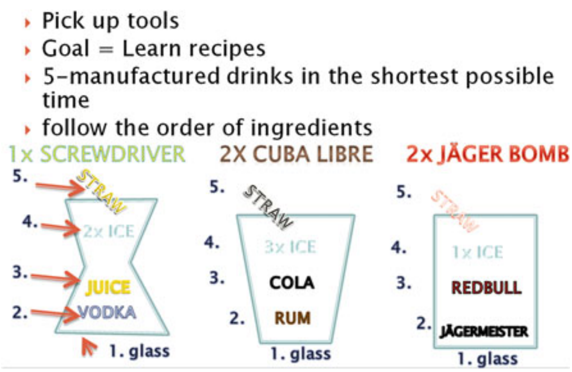



**Fig. 2** First round

production line which is easier for participants without technical practice to imagine. Operations on the production line are for example preparation of the glasses, pouring the liquors, adding ice and preparation of the straws. The last worker is the waiter who takes orders from customers and serves them. Every operation place receives visual instructions.

The goal of the first round is to divide tasks between the players and master the production processes. Players are tasked to make five selected drinks and deliver them to the customer. Customer's task in this round is quality control of the products and recipe. Customer controls if shapes of cut of paper are being followed, if right color have been used, if full areas have been colored etc. Customer returns product to the waiter if not satisfied. Waiter should take the returned product to the bar where mistake will be removed and customer will receive repaired product. See Figs. 2, 3, 4, and 5.

Moderator marks time for creation of the 5 drinks to the particular box of the result table. In the discussion phase moderator notify players if they notice that drinks have the same operation plan. Teams will find out that players should be linked in way that operation will follow in right order. Theory about terms layout and operation line will be explained.

## *3.2 The Second Round*

Story that is being told by moderator about the second round is following: investors are satisfied how teams created 5 testing drinks. All workers know the operation process which they are supposed to do and line is well assembled. It is possible to open bar to the public. Opening party starts and investors expects the great deal of customers to come. The bar's goal is to finish as much orders as possible in one shift. Players are not familiar with length of the shift. Moderator tracks time and make approximately 8 min long round.

Second round starts and teams receives orders via projector. In one order is different number of different drinks and waiters goal is to bring to the customers all

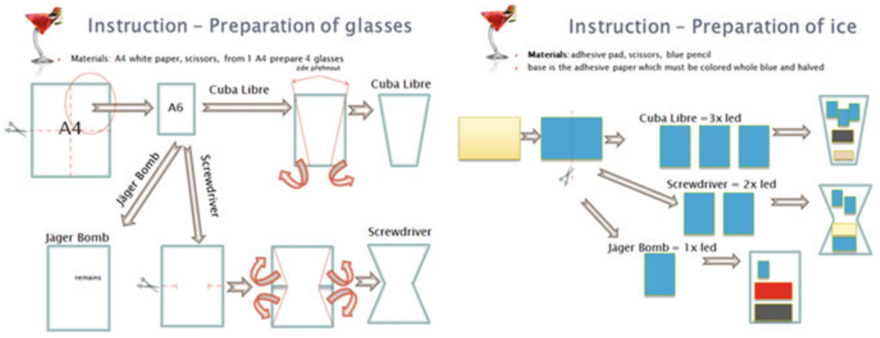



**Fig. 3** Preparation of glasses, preparation of ice

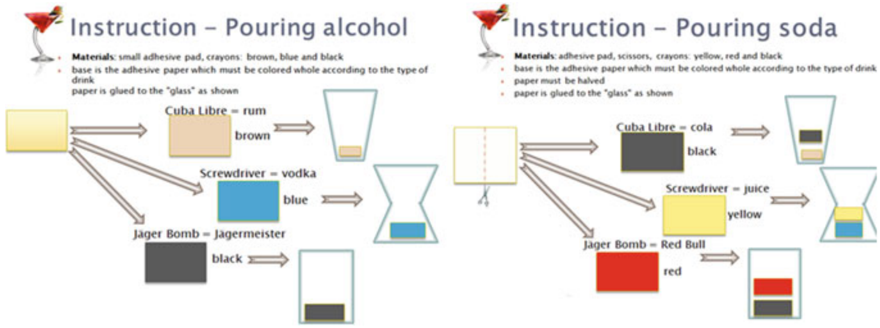
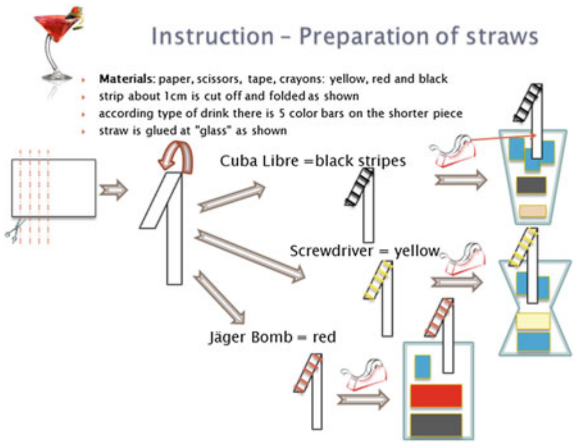



**Fig. 4** Pouring alcohol and soda

**Fig. 5** Preparation of straws




the products from the order at once. Customers have to be served in the order in which order took place. Large number of orders takes a place and bar's goal is to finish as many orders as possible.

After some time in the environment which have been established and which is very similar to the production line every operation place starts to make stockpile with intermediate products which uses for production. Player's notice that some parts are being used more often and start to create stock in order to not to make products piece by piece. Between stockpiled pieces cut of papers, colored papers etc. can be found. This stockpiles then worker stocks in his workplace which is starting to be messy.

After certain time which has been selected by moderator as time of the shift all bars are ordered to stop working and second round is finished. The end will happen regardless to the situation of the orders in production line. Moderator's assistants counts points for finished orders. Points are being putted in the table projected on board. Moderator now makes emphasis on fact that this is not the final count of the points for the round. Players will be informed about size of the stockpile and that they can't use it anymore. On this situation will be shown that large stockpile is undesirable. Shift ended and for example ice will melt and lose value. In the same time is necessary that all stockpiles have to be stocked and warehouses takes place. Other thing is that stock makes workplace cluttered. From all these reasons teams will lose number of points for every prepared but unfinished or semi-finished product. Score for the second round is result of the finished (sold) products subtracted by semi-finished (wasted) products. It is appropriate to tell players that score for finished drink is higher than score for components (added value).

Participant will find out that unfinished production significantly affects their score gains. The team that sold the same amount of drinks but did not make the stockpiling of semi-finished products is now at an advantage. Sponsors now have a speech to their bartenders: We all recognize the need to improve the working lines especially to reduce inventories. It is necessary to establish limits and rules. Bar sponsors therefore directs bars to implement Kanban. Now players will be first introduced to the concept of Kanban and theory will be explained in detail. Kanban is a tool for process optimization through its visualization and serves to eliminate wasting in form of unnecessary stocking. Goal of Kanban is to try to limit the amount of work in progress, to measure and optimize the average production period. Another advantage of Kanban is that narrow place in production is exposed.

### *3.3 The Third Round*

In the third round the Kanban principle is implemented in all bars. Kanban cards, boards, and trays become novelty in the bar. Moderator explains all the new rules and tools using illustrations. The Kanban cards are prepared for ordering. These cards have prepared fields that waiter fills according to customer requirements. Fields such as: number of table, number of card, ordered items, quantities and etc.

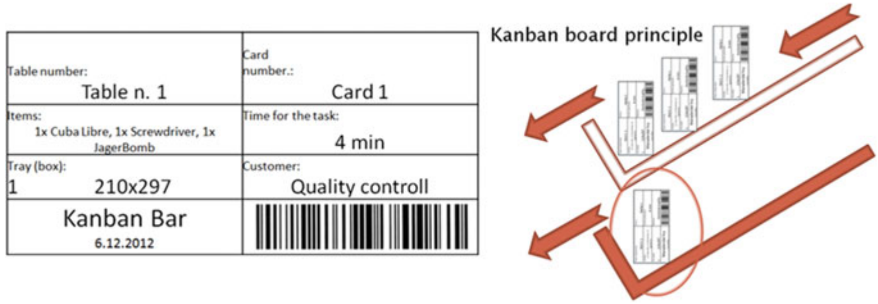



**Fig. 6** Kanban card and Kanban board

Waiter places the fully and properly completed card to the Kanban board next to the first work place—in our case the glasses preparation. Kanban board has two shelves—white and red. Regular orders are placed on a white shelf and are processed according to the principle of FIFO.[1] If order with high priority or reclamation of previous order shows up it has to be processed with highest priority. Therefore is placed to the red shelf. Any card on the red shelf has to be processed first see Fig. 6.

First in line is now starting its operation that he picks up the first card from the board in the order and places it on the Kanban tray. Tray is represented by colored paper and supposed to simulate real pallet or crate in production. The idea is that all the pieces of unfinished production orders travel together with the card on the one tray. It is forbidden to transport any parts between sites without the tray or card. At the end the waiter brings the tray with everything ordered to the customer along with disposed card. Every workplace produces only what is written on the card—order and nobody is allowed to stockpile himself without knowing what to produce. Each team member thus produces only what the customer actually requires which significantly reduces unfinished production. At the end of the round the points are evaluated again. There will be just minor improvement in points for finished products but the penalty for impaired inventories and work in progress will be dramatically lower. Total score for all teams will be considerably higher. Again there has to be discussion of what has been achieved in this round, what problems the teams faced, and where there are opportunities for improvement.

[1] FIFO is an acronym for First In, First Out, which is an abstraction related to ways of organizing and manipulation of data relative to time and prioritization. This expression describes the principle of a queue processing technique or servicing conflicting demands by ordering process by first-come, first-served (FCFS) behavior: where the persons leave the queue in the order they arrive, or waiting one's turn at a traffic control signal.

### 3.4 The Fourth Round

The last round is just an extension of the previous rounds. Teams make a brief meeting at the beginning of the round. Every team assesses where their bottleneck in the chain is and how it can be eliminated. Teams will try to figure out what could be improved while maintaining all the rules that were set out in the previous round. Each bar is trying to get the best result of all rounds and gain advantage over other teams.

## 4 End of the Game

After the last round the points are counted and the winning team is announced. At this moment it is up to moderator to summarize all demonstrated principles and theories demonstrated by the game and compare all the phenomena to the reality which occurs in actual production. Then is time for questions and for the final discussion.

There is also possible to include whole theoretical seminar with pictures and case studies of good practice. Summarize the types of waste which are in production and explain what methods can be used to remove wasting.

To create a competitive atmosphere is good to announce some kind of reward for the most successful bar. According our experience at the university simple pack of candies will do the trick.

## 5 Summary

The Kanban Bar game is supposed to demonstrate number of lean principles in manufacturing. Bar is simple simulation of production line. Mainly the benefits of Kanban principle are explained and secondary effect of wasting reduction due to elimination of unfinished production. Need for effective layout and one piece flow is also demonstrated in this game together with the push and pull principles. Game is originally designed to be done in 1.5 h to allow to play it during the regular lesson. But the game can be expanded and wider range of lean methods can be demonstrated. Participants can see that usage of Just in Time production principle is limited and there is certain need of operational stock to be in place to allow continuous production to be able to react on certain kind of special situations.

The game was used during one practical lesson in subject Operational Management at Faculty of Economics. Game was created because of need to explain lean principles to students of Faculty of Economics which are not familiar with real experiences from production companies and real production processes. Therefore, the bar theme witch all students are familiar with and it is easy for them to imagine was chosen. Feedback from students was entirely positive. During these subject two games was used as practical lessons. According to students the games was welcomed enriching change in lessons and many lean principles in further lessons were referred to the game. There were 12 theoretical and 12 practical lessons so the games were not the major part of education. Based on results at the exam 90 % of students understand and remembered the principles of Kanban because of the game.

## References

1. Mašín I, Vytlačil M (1996) Cesty k vyšší produktivitě. Institut průmyslového inženýrství, Liberec. ISBN 80-902235-0-8
2. Prensky M (2006) Digital natives: learning in the digital age, 63:8–13

# Using the Six Sigma DMAIC Methodology to Improve an Internal Logistic Process

**Luís Miguel D. F. Ferreira, Cristóvão Silva and Carolina Mesquita**

**Abstract** Six Sigma is a data-driven approach using specific tools and methodologies that lead to fact-based decisions. It employs a well-structured methodology to reduce process variability and eliminate waste within the business processes by applying statistical tools and techniques. This paper presents a case study highlighting how a manufacturer of domestic water heating equipment has used the Six Sigma Define-Measure-Analyze-Improve-Control (DMAIC) methodology to improve one of its internal logistical processes; the replenishment of supermarket in production lines. The paper describes how a company can use a systematic methodology to improve an internal logistical process, moving it toward a world class quality level. The application of the Six Sigma methodology resulted in a reduction of those routes taking more than 30 min to be completed from 25 to 3 %; a reduction in the coefficient of route time variability from 40 to 14 % and a reduction of the mean route time from 31 to 24 min. These results had a significant financial impact, allowing the elimination of one of the three existing routes—without any negative impact in the supermarket replenishment process—leading to a drop in man hours and costs through the elimination of two milk runs.

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## 1 Introduction

Six Sigma is a highly disciplined method of data collection and treatment that makes use of statistical tools, and requires a significant involvement of senior management and a hierarchy of workers with the necessary training. In technical terms, Six Sigma signifies a defect level below 3.4 defects per million opportunities (DPMO), where sigma is the term used to represent the variation of a process around its mean [1]. As such, the principal objective of the Six Sigma methodology consists of the reduction of the variability associated with products/processes, drawing on a continuous improvement methodology known as DMAIC and composing five phases: define; measure; analyze; improve; control.

Today Six Sigma is viewed not only from a statistical perspective, but also from the perspective of business strategy, as is particularly evident in the definitions that appear in the literature. The definition of Six Sigma provided by [2], describe it as "a business improvement strategy used to improve business profitability, to drive out waste, to reduce costs of poor quality, and to improve the effectiveness and efficiency of all operations so as to meet or even exceed customers' needs and expectations" while [1] see it as "an organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates". For the interested reader, good literature reviews are available regarding the Six Sigma methodology; see, for example, [3] and [4].

This article intends to show the application of the DMAIC methodology to the internal logistics of a company that manufactures domestic water heating equipment. The application of the Six Sigma project is intended to improve the performance of the process ensuring the supply of materials to the production cells. This process, in the company that served as a case study, is carried out using a milk-run system. A milk-run system is composed of a logistical train that starts from the warehouse, visits the work stations associated with its route, distributing the required material, and periodically returns to the starting point [5].

In the following sections the milk-run process for the company is presented in detail, describing the Six Sigma project put in place to improve its performance. Thus, this paper intends to present an application of the six sigma methodology to a logistical process, a functional area for which there is a lack of in-depth six sigma studies [6].

## 2 Case Study

This case study was conducted in the logistics department of a company that produces domestic water heating equipment. One of the logistical areas in this company is that of internal logistics, that determines, among other functions, the movement of materials within the company. The internal logistics function is fundamental to the success of the business, given that it is responsible for the delivery of materials in the right quantity, at the right time and in the right place. If this does not happen, lost production can result, or delivery deadlines may be missed, impacting upon the satisfaction of the client. In order to ensure that it met its functional obligations, the logistics department implemented a concept for internal supply that would be able to guarantee the delivery of smaller sized lots with increased frequency. As such, milk-runs, Point of Use Providers (POUPs), and logistical trains were all created. The milk-runs are the operators responsible for controlling the logistical train. They follow fixed paths, designated as routes. They deliver all the materials located in the warehouse to the supermarkets of the internal clients. The POUPs are the operators responsible for the movement of the materials from the supermarkets, close to the point of use, to the final point of use. The process starts with the requests from the POUPs for replacement material, that, after collecting a supermarket box, makes an electronic request for restocking their consumption. This electronic request is made using a barcode reader and creates a stock picking label for the component warehouse. Every 15 min the information system processes the electronic requests for the whole factory. The warehouse operators receive these requests and carry out all the picking operations that result in the placement of the necessary material to fulfill the requests in the logistical train. The milk-run operator, according to the route which was allocated to it, couples up the various carriages to form a train which is then coupled to the traction device and the defined work sequence is started. At every stopping point, the milk-run delivers the full boxes and retrieves the empties from the supermarket return ramp. After delivering all of the requests the train returns to the warehouse, uncouples the empty carriages, couples up the carriages filled by the warehouse operators, and starts a new route.

In the section of the factory analyzed in this case study; there exist three routes for the delivery of materials to the workstations that will be defined as routes A, B, and C. The routes A and B are carried out in a cyclical fashion and their duration was fixed at 30 min. The route C is different from the others in that it supplies a sector of the company that necessitates passing outside of the building, requiring different traction equipment from that used for the routes A and B. Apart from this, this route does not run cyclically, is of less duration than the other two and is carried out by the milk run which is associated with Route A. In the case of the routes A and B, it is considered that the routes which run for more than 30 min constitute a defect, as they can lead to materials at the workstations to run out, causing a production stoppage. Frequently this can only avoided by relying on an emergency restocking from the POUPs, short circuiting the milk-run. Besides this, it was found that the variability associated with the time of the routes lead to a necessity to carry a safety stock in the supermarkets, which could be reduced if it were be possible to reduce the uncertainty around the delivery time.

# 3 The Six Sigma Project

The decision was made to implement a Six Sigma project to improve the internal supply process for the company, as described in the previous section. In a first phase the time required to carry out the routes A, B, and C was measured over a period of 2 months of activity. Route A was the route found to have the most variability in the time of execution and that resulted in the greatest percentage of defects (durations larger than 30 min). As such, it was decided that the project would, in a first phase, be limited to improving Route A. The DMAIC methodology followed in this project is defined in detail in the following points.

## *3.1 Define*

In this phase the objective consists in defining the limits and objectives of the improvement project considering the requirements of the client and the processes that ensure the fulfillment of these requirements [6]. The project charter is produced to provide support for this phase. It formalizes the project start and facilitates the alignment of the team members. This document is probably the most important of the project [7], as it is here that the project management is laid out. Below a brief description of the case study project charter is presented.

The project was developed for the Internal Logistics area, centering on Route A of the process covering the internal supply of materials. The team was made up of a Champion, the director of the Logistics department, by one Master Black Belt, by Green Belts—mainly workers from Internal Logistics and the Warehouse—and had the support of a Black Belt, the group coordinator for the area of Quality. The scope of this project is limited to the cyclical process of the internal restocking of materials for the workstations associated with Route A. The objective is to control the duration of this process. From observing the process it was possible to identify it major steps: (1) couple full carriages to the traction device, (2) cover the trajectory warehouse–workstation, or that between two consecutive workstations, (3) unload material in the supermarket for the workstation and collect empty boxes, (4) return to the warehouse, and (5) uncouple the carriages with the empty boxes from the traction device.

The problem was defined in the following way:

> Between January and February 2011, approximately 50 % of the routes were found to have an execution time above the maximum allowed time, defined as 30 min. This delay in the delivery time negatively affects system confidence and increases the necessary safety stock in the supermarkets of the internal clients.

The objectives defined for the project were: (1) to reduce the number of defects per million (DPMO) and consequently increase the Sigma Level for the process; (2) to reduce the variability and the average times of the route (3) to eliminate the time in the warehouse with the train stopped for coupling and decoupling of the

**Table 1** Definition and quantification of the project objectives

| Objective—Route A | January | February | Objective |
|---|---|---|---|
| Reduction of the DPMO | 345,238 | 551,020 | 10,000 |
| Increase in the sigma level | 0.4 | 0 | 2.3 |
| Reduction in the coefficient of variation (%) | 44 | 36 | 11.5 |
| Reduction in the average time (min) | 27 | 34 | 25 |
| Coupling/decoupling (min) | 12 | 12 | 0 |

**Table 2** Client requirements

| | Voice of costumer |
|---|---|
| Must have | 0 % of production stoppages due to stock outs in the supermarkets |
| More is better | 50 % reduction in stock safety margin in the supermarket |
| Delighter | 0 % of area occupied by the supermarkets. Direct delivery to the point of use |

carriages. These objectives were quantified, as laid down in Table 1, identifying the initial situation and the objectives to be reached.

It was decided that the project team would meet weekly to analyze the results achieved, discuss improvements to be implemented and define actions and timeframes. It was moreover decided that the monthly meeting of the Logistics Department would be used to present the results achieved and the actions in progress.

The definition of the objectives of this project took into consideration the expectations of the clients served by Route A. At the beginning of the project a workshop was held with all of the Production and POUP Managers served by the route, leading to the requirements detailed in Table 2.

To respond to these client expectations it was found that the parameter critical to quality (CTQ) should be the duration of the Route A. This variable has an obvious impact, both over the production stoppages due to parts stock outs in the supermarkets, and the safety stock necessary in those same supermarkets.

## *3.2 Measure*

In this phase, the objective consists of measuring the actual performance of the process so as to define its actual state. It is moreover necessary to establish the measurement system that allows the monitoring of the process evolution under analysis with respect to the objectives established in the previous phase.

For this case study it was necessary to measure the duration of the routes A made by the milk-run, with the following process having been installed to collect the relevant information. At the beginning of each milk-run a magnetic card is passed through a machine located at the exit of the warehouse, registering the time of exit. At the end of the route this process is repeated in another machine that can be found at the entry to the warehouse. These data are stored in a database, where it is possible to create a report for each route carried out, with the start time, end time, and the duration of the stopping time in the warehouse between two consecutive routes. The Total Cycle Time for route A can, as such, be divided into two cycle sub-times: (1) 'route-time'—the time that elapses between the exit and the return to the warehouse, that represents the time necessary for the journeys, delivery of the requests to the supermarkets and collection of the empty boxes, and (2) 'stopping time in the warehouse'—the time necessary for the exchange of the carriages from the previous route (with the empty boxes) for the carriages with the material for the new route.

To analyze the performance of the actual system, 148 routes were analyzed for the month of March. The recorded data clearly showed the need to improve the process under consideration. Of the 148 routes that were run, 77 ran over the limit of 30 min, representing a defect level of 52 %, or a DPMO of 516,779. This indicates a sigma level of 0, while the desired objective is a sigma level of 2.3.

## 3.3 Analyze

This phase has as its objective the identification of the causes that could be at the root of the problem and identify the relations of Cause—Effect, i.e., how is it that one of more independent variables affects the dependent variable. In this problem, the dependent variable is the time of the route measured in minutes and the independent variables are the various factors that contribute to that time. To achieve this objective the team started by analyzing the process in detail. It was seen that the milk-run responsible for carrying out route A was also responsible for route C. From the observations made it was found that 25 % of the routes carried out by the milk-run are C routes which are not cyclical and have an average duration of 12 min.

A Cause—Effect diagram, or Ishikawa diagram, was developed, to proceed with the identification of the factors that potentially can impact on the time required for the route. This diagram can be seen in Fig. 1. The potential causes were identified in a brainstorming session that involved the members of the project team.

In order to understand the extent to which a run of route C had a negative impact on the running time of the following route A, it was decided to conduct a hypothesis test. The hypothesis test was conducted with a significance level of 5 %. As the *p* value obtained was well below the chosen level of significance, it was concluded that there exists a significant difference in the time taken to run route A when it is preceded by a run of route C. This difference can be explained by the fact that runs of route A that follow a run of route C have the tendency to include more boxes to be delivered. This occurs because the operators of the warehouse have more time to load boxes onto the logistic train.

To be able to quantify the impact of the cause of 'N° of boxes to deliver by route', on the route time, a Linear Regression Test was carried out between the

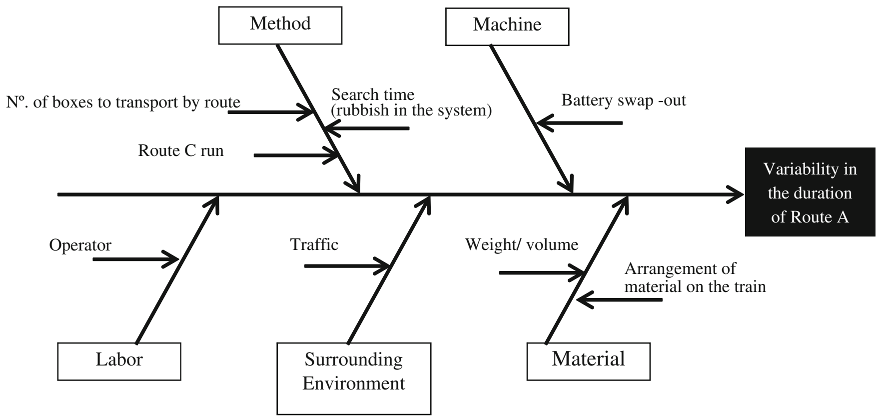


**Fig. 1** Machining features and their tool access directions

independent variable (N) 'Number of boxes loaded onto the logistic train' and the dependent variable (X) 'Time necessary to run the route'. A positive relationship between these variables was found, in other words, the time taken to run the route increases with the number of boxes to be delivered. The value of the coefficient of determination ($r^2$) obtained from the linear regression model indicates that approximately 75.6 % of the variation in the time to run the route relates to the variation in the number of boxes delivered.

With respect to the other causes identified in the cause-effect analysis, it was not possible to collect quantitative data. As such it was necessary to resort to direct observation of the process to gauge its impact on the duration of the route. It was found that the milk-run loses some time in restocking the material in the supermarket due to inconsistencies in the information regarding parts localization—cause 'search time'. It was also found that some of the heavier material was located on the upper shelves of the supermarket—cause 'weight/volume'. All the other causes were considered as having an insignificant impact on the running time of the routes.

## 3.4 Improve

The objective of the Improve phase consists in finding and implementing solutions that eliminate the causes of the problems identified in the Analyze phase, preventing a re-occurrence or reducing the variability of the process. While there may exist various possible solutions for the same problem, the best, or top two should be selected to be applied. Ideally, these identified solutions should not imply such large investment costs and they should be tested before being implemented such that their efficacy can be checked and to avoid wasting time on solutions that require a great deal of effort for little benefit.

**Table 3** Evaluation of the impact and effort of the various solutions proposed

| Solutions | Impact | Effort | Observations |
|---|---|---|---|
| 1 The milk-run covers only Route A | 9 | 4 | Allocate Route C to another operator |
| 2 Delivery of a fixed number of boxes per route | 8 | 7 | Necessity for a 3rd train |
| 3 Relocate the heavy and outsize materials | 3 | 4 | Analyze in what location the heavy materials are to be found. Locate them as close as possible to the milk-run stop |
| 4 Eliminate the obsolete parameterizations from the information system | 2 | 6 | Analyze piece by piece the parameterizations in the system that are no longer used. Eliminate contradictory information |

The project team held a workshop to propose solutions to the problem being studied, using the data collected in the 'Analyze' phase as a basis. The solutions proposed were evaluated having defined, on a scale of 1–10, the expected impact from their application and the amount of effort required for its implementation. The resulting matrix Impact-Effort can be seen in Table 3.

Following on from the evaluation, it was decided to test out the solution 'The milk-run covers only Route A'—and the solution for the—'Delivery of a fixed number of boxes per route'—as these solutions maximize the impact.

### 3.4.1 Solution: The Milk-Run Covers Only Route A

To test out this solution a pilot test was carried out over a period of 15 days, named as 'Process Route A w/o C'. During this period the milk-run ran only route A, while the runs of route C were allocated to another worker of the company. The test period saw 79 routes completed. The improvements made relative to the initial process are notable. Of the 79 routes run, 12 took longer than the 30 min stipulated, which represents a defect rate of 15 %, or a DPMO of 151,899, implying a sigma level of 1.03. A reduction in the variability of the route running times can also be seen, as shown by the reduction in the coefficient of variation (CV) that reduced from 37 % for the original process to 26 % for the process 'Route A w/o C'.

The implementation of this solution did not bring significant alterations to the stopping time in the warehouse, which continued at 12 min. This time is used essentially for the decoupling and coupling operations of the carriages. As would be expected, by eliminating the runs of Route C by the operator the number of runs of route A carried out per shift increased, allowing deliveries to be both more frequent and of smaller quantity.

### 3.4.2 Solution: Delivery of a Fixed Number of Boxes Per Route

Having tested Route A as a cyclical and unique process, without being combined with any other task, and having experienced positive results, it was decided to test a solution ‘Delivery of a fixed number of boxes per route’. This was to be done not with the conditions of the initial process, but using the evolved process ‘Route A w/o C’. This test was called ‘Fixed-load test’.

By fixing the objective for the route time at [25; 30] minutes, the interval for the number of boxes to transport was calculated using results from the linear regression test developed in phase Analyze. Accordingly to these results, to achieve the pretended route time, the number of boxes to transport per route should be located in the interval [55, 65].

The implementation of the solution ‘delivery of a fixed number of boxes per route’ shows considerable improvement over the solution ‘Route A w/o C’. Only one of the 30 routes run during the test took more than 30 min, representing a defect rate of 3 % or a DPMO of 33,333, implying a sigma level of 1.83 %. A reduction in the variability of the time taken for the routes run is also evident, visible in the reduction of the CV from 26 to 14 %. The average time taken to run a route remained stable at 24 min.

The implementation of this solution, however, brought with it a negative effect on the stopping times between routes. This value rose from 12 to 30 min, on average, resulting from the time that the milk-run waits for a full load before departing, on top of the time necessary for uncoupling and coupling the carriages.

### 3.4.3 Comparison of the Proposed Solutions and Improvements Implemented

The solution ‘Route A w/o C’ produces a significant improvement, both in terms of the average time a route takes and the variability in the times of the routes. When this solution is combined with the ‘fixed load’ solution, it is possible to reduce the variability of the time that the routes take even more, without negatively impacting the average time for a run. Taking these results into account, it was decided to implement 3 proposals for improvement.

*Proposal 1: ‘The milk-run covers only Route A’*

The Route C, without a defined frequency, which was initially combined with Route A, was integrated into the work of the POUP associated with the workstations serviced by Route C. The tasks of that POUP were redefined so as to eliminate wastage identified, allowing the time necessary for it to service Route C to become available. The main advantage of this integration is that the control of the whole supply process is controlled by one person.

*Proposal 2: Supply a fixed quantity of boxes per route*

One of the objectives of the normalization of the tasks—executing tasks in repeatedly the same way—is that this allows for comparisons, easy identification of divergences, and their elimination. The implementation of this solution allowed

**Table 4** Client requirements

| Objective—Route A | January | February | Goal | Achieved | Status |
|---|---|---|---|---|---|
| Reduction in the DPMO | 345,238 | 551,020 | 10,000 | 33,333 | ☹ |
| Increase in the sigma level | 0.4 | 0 | 2.3 | 1.8 | ☹ |
| Reduction in the coefficient of variation (%) | 44 | 36 | 11.5 | 14 | ☹ |
| Reduction in the average time (min) | 27 | 34 | 25 | 24 | ☺ |
| Coupling/decoupling (min) | 12 | 12 | 0 | 0 | ☺ |

inefficiencies that existed in the process to be uncovered, as for example, the wastage associated with the transport of small loads.

*Proposal 3: Quick change of carriages*

To eliminate the 12 min of stopping time in the warehouse associated with the coupling and uncoupling of carriages on every route run, a solution of entry and exit rails was implemented. The milk-run moved to a system of uncoupling only the first carriage from the train, leaving the whole train lined-up on the rails, ready to be loaded by the warehouse. Only the first carriage of the full train need then be coupled-up. To avoid time maneuvering, these rails were moreover lined-up with the exit and entry gates.

The results obtained from the tests, as presented in the previous sections, show that the implementation of the proposed solutions could allow the objectives laid down for the project to be achieved. This comparison can be seen in Table 4.

The objective of reducing the average time of the route was achieved as a result of the introduction of Proposals 1 and 2. The stopping time in the warehouse was eliminated as a result of the improvements associated with Proposal 3. The other goals were not reached, while it is, however, notable that very significant improvements were made in all of the performance measures under consideration in this process.

The results of the tests show that the implementation of these three proposals could, however, result in an increase in the stopping time in the warehouse, considered to be time wasted. These results also show that the methodology proposed cannot be followed rigorously, given that during some periods the waiting time for a complete load could be unsupportable, leading to production line stoppages due to stock outs. In these cases the logistic train ended up leaving with a load below the minimum level defined.

### 3.4.4 New Proposal for Improvement

The project team found that the stopping time in the warehouse could allow Route B to be integrated; this route did not initially make up part of the analysis for this project, for Route A. This signifies the elimination of Route A and B, creating a new route, called ‘Single Route’ that would account for all the deliveries to all the workstations previously visited by the eliminated routes. In this situation, a full load will be achieved more quickly, as there are more stations to visit on the route.

This adaptation guarantees a reduction in the waiting time in the warehouse and avoids trains leaving without a full load. This solution could, however, have the effect of eliminating/reducing some of the gains achieved with the previous proposals. A new test was carried out to be able to evaluate this proposal, called 'Single Route test', during which the times associated with 74 route runs were recorded.

The results of the 'Single Route test' show that the amalgamation of the Routes A and B into one route can be considered viable. There is a slight degradation in the average time for the routes; however, this continues to be below 25 min. The variability of the times of the routes increased slightly, showing an increase in the coefficient of variation from 14 to 16 %. Three of the routes ran took more than 30 min, translating to a sigma level of 1.74, slightly below the level of 1.8 that was achieved for the 'fixed load' test. This slight deterioration in the performance measures occurs due to the fact that the single route is slightly longer and visits more workstations. However, there are positive facets that make this solution interesting. The substitution of two routes by a single route contributes to the reduction in costs associated with the internal restocking process. The stopping time in the warehouse between two route runs reduced from an average value of 30 to 6 min. All the routes run complied with the criterion defined for the number of boxes to be transported, i.e., for all the routes under analysis, the logistical train carried more than 55 and less than 65 boxes.

## *3.5 Control*

In this phase the improvements implemented are controlled, or in other words, the new system. Actions should be defined so as to guarantee that the process is continuously monitored, so as to assure that the key variables maintain within specified limits. This can imply the definition of new standards and procedures, training of workers in the new process, and the definition of new measures to ensure the sustainability of the gains.

In the case study under analysis, new working procedures were established, both for the picking operators, and for the milk-runs responsible for carrying out the single route. The automatic card system for registering the entry and exit of trains from the warehouse, installed as part of the tests, was maintained. The data collected for the process are held in a company information system and analyzed at the monthly meeting of the logistics department.

Three months after the implementation, the data collected over the period of one month, corresponding to 190 routes run, showed that there were 7 routes run lasting more than 30 min. As such, with this project it was possible to reduce the defect rate from 50 to 3.6 %. The sigma level, starting at 0, raised to 1.79, representing a significant improvement both in terms of the sigma level and the percentage of defects. The average duration of the routes run was 24.4 min. The fact that these results, that are close to those seen during the test phase, were verifiable 3 months after the implementation show that the new process of internal restocking is stabilized.

## 4 Results Achieved

Besides the improvements in the performance of the internal restocking process previously referred to, that allowed the reduction of the safety stock in the supermarkets of the shop-floor, this project had other positive results for the company.

Moving from two supply routes (A and B) to a single route allowed the reduction of one milk-run per shift, or in other words, two operators per day. Besides this, it was possible to eliminate one traction device, rented from an external company for logistics trains. These two consequences together represent a reduction in costs associated with the process of internal restocking of around 100,000€ per year.

The reduction of two milk runs also represents the reduction of 15 h of work per day (7.5 h per shift) associated with the internal logistics of the company, having contributed to the increase of its efficiency indicator. Finally, the elimination of one route reduced the internal traffic, with the consequent increase in security for the workers of the company and the reduction in the stoppage time due to congestion in the corridors.

## 5 Conclusions

Six Sigma centers on the measurement of defects and is normally applied to specific parts and processes, with the objective of understanding the origin of those defects and what the possible solutions are for systematically eliminating them and getting as close as possible to 'Zero Defects'. It is one of the possible strategies for process, product, and service improvement. By way of its systematic and project orientated methodology, DMAIC allows cost reduction by eliminating waste, and variability, and defect reduction. This systematic approach showed itself to be extremely important in the implemented project, principally for having divided the process in two—route run time and stopping time in the warehouse—allowing the hidden waste to be uncovered.

The implementation of the project described in this article resulted in a reduction in the cycle time of a route for internal restocking from around 31 to 24 min, and the reduction in the number of route runs over 30 min from around 517,000 routes per million routes run to 33,333 at the end of the project. This translates to an increase in the sigma level from around 0–1.8, in the elimination of the time wasted in the warehouse coupling, and uncoupling the train carriages, in the reduction of the transport wastage by integrating Routes A and B in a single route and, finally, an increase in the satisfaction of the client.

These improvements in the process moreover translated into a financial benefit of around 100,000€ yearly. For the company, this methodology showed itself to be an excellent complement to the Lean methodology already in place, given that by using appropriate statistical tools and techniques it was possible to analyze the data rigorously and propose solutions to reduce the divergences from the pre-defined standards.

Even though the level of sigma for the studied process was slightly under 2, and as such outside of the interval [2, 4] where most of the world's companies are to be found, it is necessary to take into account the fact that Six Sigma should be seen as a program for continual improvement over the long term.

Finally, it should be noted that the involvement of participants from various levels of the organization in carrying out the project contributed decisively to its success. The very positive results achieved created a climate of confidence in the DMAIC methodology that led to its adoption for resolving new quality problems identified in the same company.

## References


1. Linderman K, Schroeder RG, Zaheer S, Choo AS (2003) Six Sigma: a goal-theoretic perspective. J Oper Manage 21(2):193–203
2. Antony J, Banuelas R (2001) A strategy for survival. Manuf Eng 80(3):119–121
3. Nonthaleerak P, Hendry L (2006) Six Sigma: literature review and key research areas. Int J Six Sigma Competitive Adv 2(2):105–161
4. Brady J, Allen T (2006) Six Sigma literature: a review and agenda for future research. Qual Reliab Eng Int 22:335–367
5. Husseyin K, Durmusoglu M, Baskak M (2012) Classification and modeling for in-plant milk-run distribution systems. Int J Adv Manuf Technol 62:1135–1146
6. Wei CC, Sheen GJ, Tai CT, Lee KL (2010) Using Six Sigma to improve replenishment process in a direct selling company. Supply Chain Manage: Inte J 15(1):3–9
7. Pande P, Cavanagh RR (2002) The Six Sigma way team fieldbook: an implementation. McGraw-Hill, Guide for Process Improvement Teams
8. Porter L (2001) Six Sigma excellence. Qual Word 1:12–15

# Lean Six Sigma Supply Chain Case Study: Aircraft Shipment Improvement in a Pharmaceutical Company

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**Abstract** Distribution is an important activity in the integrated supply-chain management for pharmaceutical products, especially when these goods have to travel long distances from manufacturing facilities to the consumer markets. This paper presents the case of a pharmaceutical company in which the quality assurance and the management teams set an objective of reducing their distribution costs to less than 0.16 Euros per unit. The quality assurance (QA) team has decided to optimize sample shipments as a high priority in order to reduce costs. The methodology used in this study was supported through a series of experiments using a Lean Six Sigma approach that implemented the Define Measure Analyze Improve Control (DMAIC) phases. The QA team analyzed the previous state of sample shipments and then suggested improvements based on an optimized process. The results showed a set of non-value added activities specifically in transportation, motion, waiting, defects, and the sub-utilization of people. Based on Lean tools, the improvements achieved a 26 % reduction in the cycle time spent and no complaints from customers have been reported since implementation of the new process. In addition, a control plan was also developed to track shipments and maintain open and close communication with the customer. Finally, the resulting processes that have been implementation have a significant impact on reducing distribution costs.

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# 1 Introduction

Supply chain management (SCM) is the integration and coordination of a set of processes that involve delivering a product or service from suppliers to customers. In the manufacturing process, an effective SCM is crucial to achieving high levels of competitiveness [1]. There is evidence that shows that organizations have reduced cycle times and costs by improving their SCM [2–4]. According to Blanchard [5], over the past 30 years, in countries such as in the US, the percentage of the GDP devoted to logistics costs has dropped from 17.9 % in 1980 to 8.3 % in 2011. This suggests that organizations have been investing and refining their SCM to optimize processes and reduce cost significantly. In the pharmaceutical industry, SCM plays a key role since the counterfeiting of products is a real threat to public health and safety. Consequently, it is essential to protect the pharmaceutical industry against the penetration of such products as well as illegal products that are imported, stolen, and lacking in the quality standards these products require in order to be distributed and consumed [6].

In this context, this paper presents an empirical study on a leading pharmaceutical company that applied the Define Measure Analyze Improve and Control (DMAIC) phases of the Six Sigma methodology in order to improve its supply chain (SC) process. The study focuses on the company's goal of reducing the cost of sample shipments. To achieve that aim, the paper reviews some of the relevant literature related to Six Sigma and Lean manufacturing, as well as the sample shipment process associated with the SC problem faced by this company. It then describes the application of the DMAIC process to this case and presents the different situations that the company went through during each stage of the improvement process. Finally, it comments on the results that were achieved after the DMAIC phases were implemented and draws conclusions about the use of the Lean Six Sigma method as it was applied to the SC.

## *1.1 Supply Chain Management*

According to Jayant et al. [1], one convenient way for a single company to view the SC is to divide the company's logistics system into inbound logistics (material management and procurement) and outbound logistics (customer service and channels of distribution). As such, Jayant et al. [1] suggests that inbound logistics is a matter of perspective; that is, if someone is the receiver of a shipment, the shipment is categorized as inbound. On the other hand, if someone sends a shipment—as a raw materials supplier, manufacturer, or vendors—then the shipment is considered to be outbound. From this point of view, the process under study (sample shipments) belongs to the category of outbound logistics. Companies typically have reduced their manufacturing costs by implementing improvements in activities related to operational logistics, but inbound and outbound logistics seems to be effective ways to further reduce cycle times and costs and they also can improve customer service and satisfaction [1].

### 1.2 The Six Sigma Approach

Six Sigma was a strategy developed by Motorola in the 1980s and popularized by General Electric and others in the 1990s [7]. Six Sigma is a metric that determines how well a process performs against a standard of excellence at only 3.4 defects per million opportunities [8]. A defect occurs when a measured attribute is outside the tolerance limits, which typically results in customer dissatisfaction [4]. The Six Sigma quality concept recognizes that variations or defects are inevitable due to insufficient design margins, inadequate process controls, imperfect parts, fluctuations in environmental conditions, and operator variations, among other variables [9]. However, as product and process defects are driven out, the company captures market share by providing higher quality at a lower price, while maximizing profits and company stakeholder value [10]. In addition to the financial benefits of cost reduction and revenue growth, Six Sigma also helps improve what it may be considered one of the most important metrics of performance for any organization: customer satisfaction [7].

Six Sigma is supported by quality tools that enable an organization to make correct decisions based on scientific facts through data collection and analysis. According to Jacobsen [11] and Fine [12], some of the quality tools that support Six Sigma projects are: statistical process control (SPC); the Define Measure Analyze Improve Control (DMAIC) process; the eight disciplines problem-solving process (8D); the Shainin System; Poka-yoke; Failure Mode and Effects Analysis (FMEA); and process capability (Cpk). The decision about which improvement techniques and methods to choose is based on a variety of factors, such as cost, time, training, and suitability.

### 1.3 Lean Manufacturing

Lean manufacturing (Lean) is derived from the Toyota Production System introduced by Toyota's Taiichi Ohno in the 1950s as a response to competition from larger car manufacturers [13]. Lean is focussed on the reduction of waste and different types of non-value added activities [14]. Some of the types of waste are due to over production, conveyance, inventory, unnecessary motion, processing failure, space, among others [15]. Lean operations eliminate obvious waste, reduce variability, reduce inventory and, thereby, reduce costs. Lean manufacturing has been defined as an 'integrated manufacturing system intended to maximize capacity, reutilization and minimize buffer inventories through the minimization of system variability' [16]. The essence of leanness is focused on the efficient use of resources through the minimization of waste. Some of lean manufacturing tools and techniques include value stream mapping (VSM), 5S, Kanban, Kaizen, Total Quality Management (TQM), Total Productive Maintenance (TPM), and Quality Function Deployment (QFD) [17–19].

Several large pharmaceutical organizations, such as AstraZeneca, Johnson and Johnson, and Pfizer, have simplified their operations and processes, and have reduced their costs via Lean and Lean Six Sigma. Thus, Pharmaceutical Technology's QPEC [20] indicates other pharmaceutical companies and suppliers within the industry have followed those steps to benefit from those practices.

When lean manufacturing practices are properly deployed, an organization can realize several benefits including cost savings, better quality-products, lower impact on the environment, and higher customer satisfaction. On the other hand, some disadvantages and risks may include lack of stock when products are needed, the possibility of distribution problems due to natural or other disasters and the potential for ineffectiveness, unless suppliers are also practicing lean strategies. However, in a general sense, the advantages of lean manufacturing outweigh the disadvantages [21].

## 2 Description of the Problem

This study was conducted on a leading pharmaceutical company in Mexico City responsible for manufacturing medicines for the European market. The company satisfied international regulations, e.g., those imposed by EudraLex, which state 'samples from each batch should be tested in the European Community before a certification of the finished product batch is issued by a Qualified Person (QP)'.[1] Another EudraLex regulations states: 'when any samples are taken in the manufacturing country, they should either be shipped under the same conditions as the batch which they represent. If they are sent separately, it should be demonstrated that the samples are still representative of the batch', for example, by 'defining and monitoring the shipments and its storage conditions'. Another EudraLex regulations states that 'a retention sample should represent a batch of finished products as distributed in the European Economic Area (EEA) and may need to be examined in order to confirm non-technical attributes for compliance with the marketing authorization or EU legislation'. Therefore, in all cases, retention samples should be located within the EEA. These should preferably be stored at QP's site in order to certify the finished product batch is located.

Since the company in this study has decided to send samples of each batch separately and the QP is located in Germany, this paper focuses on the problem of improving the sample shipment process. This process has reported high operation costs due the company's need to re-send samples if the first shipment is damaged.

[1] The QP is responsible for releasing the product to the European market.

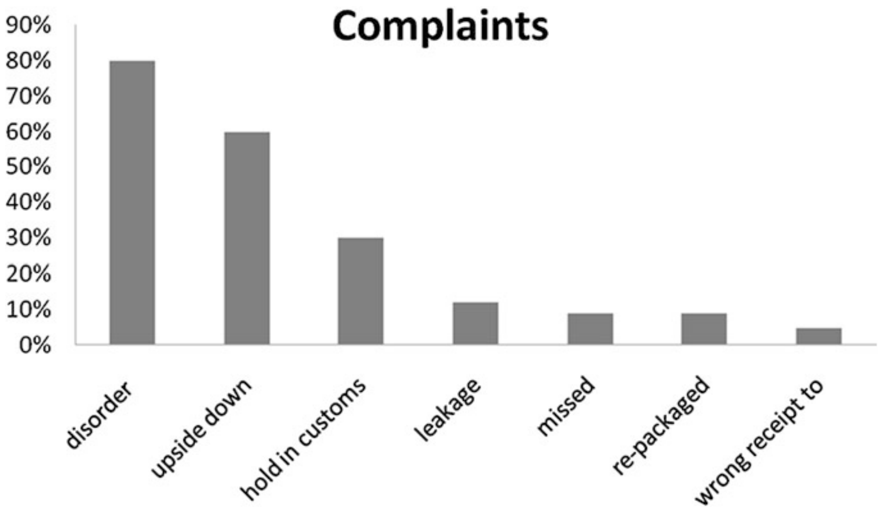


**Fig. 1** Complaints in sample shipments from the company's manufacturing site to Europe during 2012

The QP reports issues related to each shipment to the Quality Designee (QD) at the manufacturing site, and the frequency of damaged samples has resulted in several complaints.

Figure 1 shows an analysis of issues in 48 sample shipments during 1Q 2012 revealed that the main reason for the customer complaints was due to the disorder in the samples of the finished product that involved bottles being out of their individual boxes and samples of boxes that did not contain any leaflets or syringes. This issue arises because a loss of traceability occurs in regard to the product's non-technical attributes, such as the appearance of the finished products as distributed in the EEA. The second reason for complaints is due to the placement of the bottles, which are very frequently found in an upside down position. The severity of this complaint is high due to the fact that medicines that are exported to Europe are done so in an oral suspension presentation, and this suggests that the inappropriate handling of these bottles impact the product's performed tests. When this kind of complaint is reported by the customer, the company replaces the damaged samples, causing an increase in costs due to the cost of the rework, but a decrease in the size of the original batch as well. The third issue for complaints is due to the length of time the shipments spend in customs when there is a need to provide more information about the origin of the material or packaging material, which are subject to other tests, since packaging will represent waste at some point. As a consequence the complaints reported seem not only to have a cost impact, but also low productivity, and lack of availability to process urgent demands. This generates losses of potential customers, management loss of confidence, and has a direct impact on current customer satisfaction.

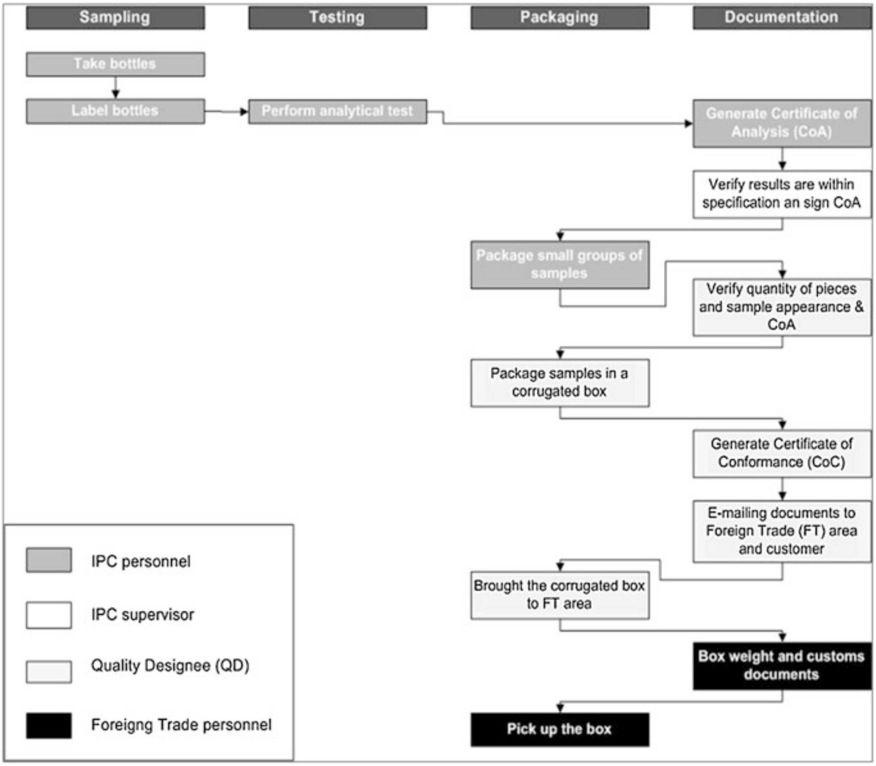


**Fig. 2** The sampling shipment process

In essence, the stages for the sample shipment process of each batch are defined by (1) sampling, (2) testing, and (3) packaging and document fulfillment. The stages are strictly dependent upon each other and each stage involves minor activities that are performed by different areas (Fig. 2).

The sampling stage is carried out by the In Process Control (IPC) team. This team takes some samples during processing and labels each of them in order to identify which will be analyzed at the manufacturing site prior to sending the batch to the European site. Once the samples are tested, the results are registered in a Certificate of Analysis and that document is review by the IPC supervisor. When the results comply with the regulations, IPC packs bottles into small groups according to the quantities required for the tests. The samples are then delivered to the Quality Designee (QD), who is responsible for verifying the number of bottles as well as their batch size and their appearance. The QD must also verify that the test results are within the required specifications.

In this way, the QD generates the Certificate of Conformance and packages the samples into a corrugated box attaching the proper identification. The next step is to send all the information by e-mailed to the Foreign Trade Area so that documentation for delivering the shipment to customs can be prepared. The QD also takes the corrugated box to the Foreign Trade office to weigh it and places the exact value of the box's contents into the shipping format. Finally, the courier service picks up the box to ship it to Europe.

The sample shipment process described above usually takes from 7 to 9 days after the manufacturing process is completed. This shipment process is usually performed twice a week, depending on the product demand. If all the documentation is in order and no further information is required by customs, the courier service delivers the box to Europe within 3 days. Historical data show that in Europe it usually takes 7 days to analyze the samples and provide the test results. Considering these activities, the cycle time for the sample shipment process takes 19 days to complete. Due to the length of this cycle time, when one or more of the shipped batches is part of an urgent order, 'urgent analysis' is also required, which increases the cost of the analysis by 12.5 % per batch.

The complaints related to long delivery shipment times as well as issues with the quality or consistency of the samples, have a direct impact on the distribution costs of the product. The pharmaceutical company has established its standards for distribution costs to be less than 0.16 Euros per unit, where sample shipments should represent no more than 15 % of that total cost. Nevertheless, those issues have increased the estimated cost, which can reach as high as 30 %. Consequently, the quality assurance team set an objective of reducing their costs.

## 3 Methodology

This research aims to determine the root causes related to the three main customer complaints shown in Fig. 1, and to propose an improvement strategy. Toward that end, a team was created that included two QDs, one Foreign Trade specialist, one supervisor from the IPC area, one supervisor from the warehouse area, one supervisor from the logistics area, and two technicians. This project was developed under the company's quality approach that was introduced in October 2009. This approach has enabled the company to implement the Six Sigma methodology in-house. This project strictly implemented the methodology by using the DMAIC process.

The first step of the DMAIC process entails *defining* the customers' needs and the project's scope. To achieve this, complaints reported during 2012 were used as the Voice of the Customer (VOC). Bear in mind that a good project is one that will have a measurable impact on Critical to Quality characteristics (CTQ) [22] if the right CTQ characteristics are defined. In the second step of the *measurement*, team members were asked to indicate the potential root causes of errors or variations in the process. In addition, for the *analysis* phase, the activities conducted during the sample shipment process were identified in order to describe the process 'as is' into a Value Stream Map (VSM) and Cross Functional Diagram (CFD). Some authors, such as Lummus et al. [14] and Abdulmalek and Rajgopal [18], have reported that only the use of the VSM tool has allowed the process to achieve significant efficiency. Furthermore, a fish-bone diagram and an FMEA were useful for deeply understanding the causes of failure. Therefore, at the *improvement* step, a Kaizen blitz was conducted for each area involved in the sample shipment process. In this way, each small group was focused on improving their own work. Finally, all aspects of the process were streamlined by implementing roles and responsibilities, establishing parallel operations between the technicians and the Foreign Trade specialist and writing guidelines in order to standardize the process. For the *control phase*, some documents were officially implemented in order to clarify job profiles and identify the allowable materials for the samples packaging. Moreover, the manufacturing site's Customs Application Forms were developed for all product ranges in order to avoid holding times. A shipment database was shared between both parties (the company's on-site team and the receiving company) in order to follow up on the current status in real time. Furthermore, pictures of each shipment were shared before the shipments were sent to Europe. Finally, the QD took on the responsibility of tracking shipments and reporting to other areas if something went wrong.

# 4 Results and Discussion

## *4.1 Define*

At this stage, data were collected through complaints sheets using the Voice of the Customer (VOC). In addition, a survey was sent to those customers in order to obtain more information about their unstated needs and requirements. Due to customer satisfaction requirements, these attributes have a linear impact on the level of sufficiency [22], and a critical-to-quality tree (CTQ-Tree) was designed to convert the customer needs into CTQs requirements, which were defined as follows:

1. Insure that 100 % of the samples arrive at the customer site in optimal condition so they can be analyzed (i.e., no disorder in the final product, no bottles shipped upside down, etc.).
2. Reduce the of cycle time of the sample shipment process by 20 %.
3. Eliminate urgent analysis orders due to the holding time at customs.

Based on the historical data of the sample shipment during the 1Q 2012, the Cost of Poor Quality (COPQ) was calculated. It is important to reduce the cost that results from COPQ. As such, Crosby [23] argues that those 'visible' internal costs are the result of failing to meet requirements before the product or service is delivered to the external customer, and that this problem must be tackled before this failure occurs. Therefore, COPQ deficiencies are caused both by errors in the products and inefficiencies in the manufacturing and shipping processes. The long cycle time for the sample shipment process was placed into this category. On the other hand, external 'visible' costs are caused by deficiencies found after the product is delivered to the external customer. Those costs involve the reshipment and replacement of samples and losses due to the need to process urgent analysis orders. Additional costs were also identified as those related to the loss of confidence by corporate governance, the need to handle complaints and time spent with customers to sort out problems. Finally, an SIPOC diagram was designed, focusing on the sample packaging and fulfillment documentation for customs.

## *4.2 Measure and Analyze*

According to the literature, value stream management is a process of planning and linking lean activities through systematic data capture and analysis [24]. Furthermore, a Value Stream Map (VSM) is a visual representation of information and material flow, so it can be a crucial tool to document processes and eliminate waste [25]. In fact, at the measure stage, the VSM developed for the packaging and documentation stages, which belongs to the sample shipment process, revealed that 22 minor activities were required in the cycle, but only two activities were Value Added Activities (VAA), five were Non-Value Activities (NVA) and, therefore, they were unnecessary and could be eliminated.

Two other activities were inappropriately processed because the work of the responsible specialist was unnecessary; the help of a technician was sufficient. In addition, five other activities were identified that could be improved in order to meet the CTQs. In order to identify more points in the process that could have a broad impact on timeframes, the process was determined through a Cross Functional Diagram (CFD). The CFD revealed process deficiencies, such as frequent downtimes and inequitable workload. The decision point analysis demonstrated that the sample shipment was mainly a push system. After developing the CFD, all people involved in the stages participated in a brainstorming session. They were asked to identify the root cause of the three main complaints reported in Fig. 1. Then, the ideas were transferred to an Ishikawa's diagram for each complaint. Many potential causes were identified, and when the diagrams were put together, it was identified that at least four reasons were similar. The first issue was an inappropriate way to handle the samples during their inspection at customs. This issue was related with lack information about the origin and content of the bottles. Additionally, it was identified that instructions and warnings located in the corrugated boxes were not "visible" and the language used on the labels was in English instead of Spanish and German. Finally, in order to prioritise the root causes for each complaint based on their impact on the customers' expectations, a Cause and Effect Matrix was developed. Then, an FMEA was conducted to include an appropriate depth of information on the causes of failure based on experience with similar products and processes. For example, the potential failure of disorder in samples was attributed to different sizes and materials of corrugated boxes that could contribute to a complicated configuration of the bottles. The upside down position of the bottles was attributed to wrong packaging, in that moment the control performed was to use bags fixed to the bottles with adhesive and any dividers to limit each package into the box were used. Finally, the holding time in customs were difficult to analyze since according to the specialist the unknown content of bottles and a slow communication flow between customs-courier-office-customer delayed deliveries.

## 4.3 Improve

At the improvement stage, team members worked separately according to the area to which they belonged. This approach was necessary in order to suggest viable and quick improvements in their own workload. Highlights from the Kaizen results follow.

The QD implemented the packaging of small groups of bottles using wrapping material instead of bags in order to prevent shifting of the product arrangement during transport. The challenge was to standardize the configuration of those small groups so as to avoid empty spaces using a corrugated divider and a top pad to assure easy manipulation when the samples were required by customs. The team placed the shipping label—written in English and German—on the top of the box to avoid any confusion. At the same time, the team was authorized to use quality corrugated boxes as a unique material for the sample shipments. In order to avoid lengthy customs holding times, a letter was addressed to the personnel at the manufacturing site's customs area. This letter included relevant information about the product's composition, packaging materials and dosage per unit forms, allowing for easy identification of the box content in the event that a customs inspection was required.

For the improvement stage, it was also determined that shipments that involved a unique box were more frequently inspected than those placed into an exportation pallet. Furthermore, the courier service allowed the pharmaceutical company to ship packages weighing up to 200 kg at a discounted rate, which had no significant impact on the distribution cost. Hence, a warehouse technician was required to put the corrugated box onto a pallet. As a result, elimination of inappropriate processing waste was accomplished when the responsibility for bringing the box to Foreign Trade office was transferred from the QD to a technician. The time the technicians spent in unnecessary motion was avoided by creating a specific schedule and designating a place to pick up the box. Since the new process involves the pallet shipment, the activity related to weighing the boxes was eliminated from the Foreign Trade specialist's task load. Now, that person only waits for the information shared by the QD and a warehouse technician to prepare the export bill and the documents required in customs.

Finally, the courier service is now responsible for picking the pallet up at the warehouse, which results in conveyor waste reduction because the warehouse is closer to the courier service station than the Foreign Trade office is. All those

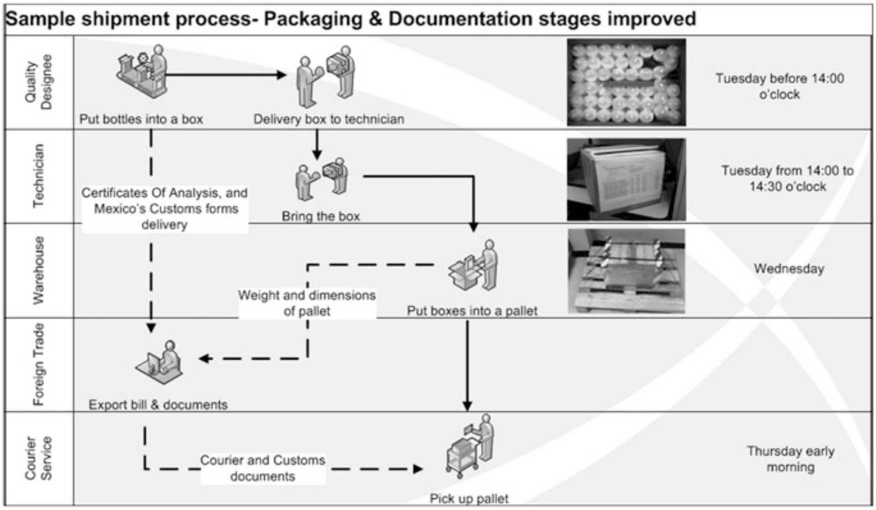


**Fig. 3** Cross functional diagram for the packaging and documentation stages

improvements were well executed at the end of 2Q 2012 and they allowed for a reduction in the sample shipment time from 19 to 14 days, which represents a 26 % reduction in the cycle time (Fig. 3).

## 4.4 Control

In order to specify the roles and responsibilities in the improved process, job profiles, and procedures were updated. The manufacturing site's Customs Application Forms are now always attached to all shipments to avoid holding times. A database was generated at the beginning of 3Q 2012 in order to track all shipments in real time. That file includes pictures of the boxes before they are shipped and after they have arrived in Europe to maintain detailed track of every batch. Until now, no urgent analysis orders due holding times at customs have been reported, and 100 % of the shipments have arrived at the customer's site within specifications. Furthermore, a cost-benefit analysis of the project, based on the investment of human resources and new equipment (like a hand wrapper packaging machine), revealed that distribution costs during 3Q 2012 were reduced from 30 to 17 %, which represents a reduction of 26 %. Until the QA managers achieve those results, it is suggested that the target established by the company (15 %) has not yet been completely fulfilled. Nevertheless, there are more opportunities for improvements, like decreasing the bottleneck in the warehouse, because the warehouse workers spend a day-and-a-half preparing the pallet. Further studies could provide improvements at this stage of the process.

## 5 Summary

The aim of this paper was to propose and implement a process strategy in order to improve productivity in a leading pharmaceutical company. The Six Sigma methodology allowed the investigators to determine the root causes of customer complaints. Using Lean manufacturing tools, the project implemented optimal standard procedures for a sample shipment process. The improvements obtained were significant, allowing for a decrease in the company's distribution costs (from 30 to 17 %), and reducing the company's process cycle from 19 to 14 days. This was an achievement since the process under investigation had previously reported low efficiency that was resulting in waste and high distribution costs.

It is important to mention that the results derived from this project cannot be generalized to similar aircraft shipments since the working and environmental situations, among other factors, may be different. However, they may help other supply chain and quality assurance managers and directors replicate good practices and avoid bad practices, which can sometimes resulting in pitfalls. For the case of this company, further research and projects may include the implementation of the DMAIC phases into the other stages involved in the process, which involves specific challenges such as a reduction analysis. In addition, further projects can include studies related to the Theory of Constraints in order to suggest a solution for decreasing the bottleneck that was detected in the warehouse. Similarly, careful registration and tracking of key variables of shipments through trend analysis could improve the shipment process. In conclusion, it can be stated that Six Sigma methodology and Lean manufacturing were useful methodologies and tools that provided positive results for reducing this company's distribution costs. However, in order to accomplish those objectives, it is recommended that any improvement methods and techniques be carefully selected, based on an organization's needs and experience and that the attention be paid to the regulations enforced within an organization's industry.

## References

1. Jayant A, Gupta P, Garg SK (2009) An integrated approach for performance improvement in supply chain: a case of manufacturing unit. Int J Bus Insights Transform 3(1):62–73
2. Rossetti CL, Handfield R, Dooley K (2011) Forces, trends, and decisions in pharmaceutical supply chain management. Int J Phys Distrib Logistics Manag 41(6):601–622
3. Shang J, Yildirim T, Tadikamalla P, Mittal V, Brown L (2009) Distribution network redesign for marketing competitiveness. J Mark 73(2):146–163
4. Huehn-Brown W, Murray S (2010) Are companies continuously improving their supply chain? Eng Manag J 22(4):3–10
5. Blanchard D (2012) Lean Six Sigma keeps cardinal's supply chain healthy. Industry Week/ IW 261(10):54
6. World Health Organization (2010) Good distribution practices for pharmaceutical products. Annex 5, WHO technical report series, no 957

7. Pande P, Neuman R, Cavanagh R (2000) The Six Sigma way: how GE Motorola and other top companies are honing their performance. McGraw-Hill, New York
8. Picard D (2002) The black belt memory jogger: a pocket guide for Six Sigma success. GOAL/QPC and Six Sigma Academy, USA
9. Narahari Y, Viswanadham N, Bhattacharya R (2000) Design of synchronized supply chains: a Six Sigma tolerancing approach. In: Proceedings of the IEEE international conference on robotics and automation, ICRA '00, 2 Apr 24–28, pp 1151–1156
10. McCarthy B, Stauffer R (2001) Enhancing Six Sigma through simulation with IGRAFX process for Six Sigma. In: Proceedings of the 2001 winter simulation conference, pp 1241–1247
11. Jacobsen J (2007) Siemens VDO optimizes processes using Six Sigma. American Society for Quality, USA, pp 1–4
12. Fine E (2000) Choosing the right SPC tools for quality problems. Ind Pain Powder Mag 11(00):28–30
13. Womack JP, Jones D, Ross D (1990) The machine that changed the world. Rawson Associates, New York
14. Lummus RR, Vokurka RJ, Rodeghiero B (2006) Improving quality through value stream mapping: a case study of a physician's clinic. Total Qual Manag 17(8):1063–1075
15. Connaughton S (2008) Lean manufacturing. Lean Manufacturing Research Starters Business, Toyota
16. Narasimhan R, Swink M, Kim SW (2006) Disentangling leanness and agility: an empirical investigation. J Oper Manage 24(5):440–457
17. Doolen TL, Hacker ME (2005) A review of lean assessment in organizations: an exploratory study of lean practices by electronics manufacturers. J Manuf Syst 24(1):55–67
18. Abdulmalek FA, Rajgopal J (2007) Analyzing the benefits of lean manufacturing and value stream mapping via simulation: a process sector case study. Int J Prod Econ 107(1):223–236
19. Vinodh SS, Chintha K (2011) Application of fuzzy QFD for enabling leanness in a manufacturing organisation. Int J Prod Res 49(6):1627–1644
20. Pharmaceutical Technology's QPEC (2008) Quality and process excellence conference, VA, USA
21. Houborg C, Lundbeck H (2010) Implementing a successful lean programme: where do you begin? Pharm Technol Eur 22(9):52–57
22. Lai HJ, Wu HH (2011) A case study of applying Kano's model and ANOVA Technique in evaluating service quality. Inf Technol J 10:89–97
23. Crosby P (1979) Quality is free: the art of making quality certain. McGraw-Hill, New York
24. http://asq.org/learn-about-quality/lean/overview/value-stream-mapping.html
25. Tapping D, Luyster T, Shhuker T (2002) Value stream management. Productivity Inc, New York

# A Comparative Study of the Implementation Status of Lean Six Sigma in South Korea and the UK

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**Abstract** Fierce competition and more complex customer needs and demands have forced organizations to continuously improve their operations and the quality of their products and services. Over the last decades, two of the most popular and effective strategies used by organizations to achieve such improvements have been lean manufacturing and Six Sigma. However, as competition and costumer needs and demands evolved and increased, the quest for even more efficient operations and higher quality products and services resulted in the integration of these two strategies to form an improved approach known as Lean Six Sigma. This paper investigates and compares the implementation status of Lean Six Sigma in South Korea and the UK. To do this, an empirical and exploratory study was conducted based on the design, validation, and random distribution of a survey questionnaire in various South Korean and UK industries. The data was analyzed using descriptive statistics. The study results revealed that Lean Six Sigma has been more widely adopted in the UK than in South Korea and that some other operations and quality improvement strategies are also a popular choice among organizations of these two countries. The results also provide evidence about different aspects of the implementation of Lean Six Sigma in South Korea and the UK. This

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study offers academics, researchers and practitioners interested in Lean Six Sigma with some preliminary evidence of the adoption of this approach in two industrialized nations such as South Korean and the UK.

## 1 Introduction

It has now been several decades since lean manufacturing and Six Sigma were introduced to the world. Nowadays, these two strategies are the most well-known and recognized improvement approaches in operations and manufacturing management [1, 2]. Due to their success, lean manufacturing and Six Sigma principles and tools have not only prevailed in the manufacturing industry, where they originated, but also expanded to other sectors such as construction, healthcare, telecommunications, education, fast food restaurants, education, and lately to the municipal sector [3, 4]. Such have been the benefits that lean manufacturing and Six Sigma have brought to many organizations that their principles and tools have been combined under the umbrella of a unified improvement approach known as "Lean Six Sigma". According to Sheridan [5], the term Lean Six Sigma is utilized to indicate the integration of both lean manufacturing and Six Sigma philosophies. Lean Six Sigma is a relatively new business improvement methodology created to improve "speed", through the elimination of waste, and "quality", through the reduction of process variability, at the same time [6]. Some studies suggest that the implementation of Lean Six Sigma in some developed countries has contributed to enhance the efficiency of organizations and the quality of their products and services [7–9].

According to a study conducted by Lee and Lee [10], the philosophies of both lean manufacturing and Six Sigma have been employed by South Korean organizations since the mid 1990s. This study indicates that this initially occurred in large organizations and branches of foreign companies in the automotive and electronics/electrical industries. However, as the time went by, the number of companies using these approaches increased and thus their principles and techniques expanded to other industries and sectors. In terms of lean manufacturing, it has now been applied in South Korean industries that include services [10], steel [11] and IT [12], among others. In the case of Six Sigma, it has been implemented in various South Korean sectors such as IT [13, 14], healthcare [15], government [16], and service [17]. Park [18] comments that approximately 600 companies of different sizes and various industries in South Korea are now utilizing Six Sigma to improve the quality of their products, services and/or processes.

Although various studies in the academic literature show a wide application of lean manufacturing and Six Sigma in South Korean organizations, no research has been carried out to investigate the extent to which companies in this country have adopted Lean Six Sigma as an integrated approach. For this reason, this research investigates the degree of awareness and adoption of Lean Six Sigma in South Korea, the reasons behind its implementation, the issues faced during its deployment, the results achieved, and possible future, in South Korea, of Lean Six Sigma. Besides this investigation, a similar study was also conducted in the UK, where the use and application of lean manufacturing and Six Sigma principles is well documented. This provided a platform to compare and contrast different aspects between the adoption and use of Lean Six Sigma in South Korea and the UK.

## 2 Literature Review

Six Sigma concentrates on decreasing variation from a process as a main strategy to pursuit customer satisfaction and financial betterment [19]. On the other hand, lean manufacturing attempts to streamline the flow of a process by identifying and eliminating waste, or non-value added activities, that may be present in it. Despite the benefits that many organizations have attained by employing lean manufacturing and Six Sigma principles and techniques, Devane [20] insists that there are three features that lean manufacturing does not have but Six Sigma principles do, and vice versa. According to him, a pure lean manufacturing approach has the following shortfalls: (1) it does not control and monitor a process using statistical data, (2) it does not scrutinize variations in processes, which are utilized for making decisions, and (3) there are no practices associated with the use of quality and advanced statistical/mathematical tools to identify further problems still remaining in the process after waste is eliminated. In the case of Six Sigma, Devane [20] further expresses that it does not (1) directly concentrate on enhancing the speed of a process, (2) attempt to directly reduce the amount of inventory, and (3) secure better financial results in a short period of time. In order to compensate for the shortcomings of each approach, Lean Six Sigma was proposed by combining the two methodologies. Other obstacles in the Six Sigma approach that include (1) big size of jobs and a number of roles within the Six Sigma structure, (2) lots of training that should be provided, and (3) a long period of time to generate outputs also lead organizations to the adoption of Lean Six Sigma [21]. According to Gershon and Rajashekharaiah [21], the Lean Six Sigma approach does not take much time and other resources to be operated while offering a visible outcome in a relatively short period of time.

In terms of the role that lean manufacturing and Six Sigma play within the Lean Six Sigma integrated approach, Spedding and Pepper [22] comment that lean manufacturing supports the conceptual structure, supplying an operational direction and a ground for business improvement. This, according to them, aids in recognizing the main areas for enhancement, which they call “hot spots”. Once these “hot spots” are identified, Six Sigma provides the techniques and tools to tackle/improve them in a focused and project based manner, which results in achieving the desired future state in the business case. Similarly, Bhuiyan and Baghel [23] argue that by mixing the two approaches, waste is first eliminated and then variations from the process are easily identified and reduced because lean manufacturing attempts to eradicate waste while Six Sigma pursues the reduction of variation in the process. More specifically, Laureani et al. [7] mention that lean manufacturing would improve the speed and efficiency of processes and performance whilst Six Sigma would seek a precise and accurate performance. In other words, lean manufacturing would make sure that resources are operating on the right actions whereas Six Sigma would be able to have the activities carried out right the first time without scrap or rework [7].

In reference to the benefits, Mader [24] insists that Lean Six Sigma is beneficial to both manufacturing and service industries for the following reasons: (1) it ensures that products and services are in accordance with customer's requirements (i.e., voice of the customer), (2) it eliminates the non-value added activities (i.e., waste) in a process, (3) it decreases the rate of defective items and transactions, (4) it makes the lead time shorter, and (5) it provides the right items and services in the right place at the right time. According to Harry [25], Lean Six Sigma projects generate considerable and positive financial performance, which has contributed to raise the interest of top management, in different industries and countries, on Lean Six Sigma [26]. Therefore, it was the aim of this paper to investigate whether that interest on Lean Six Sigma exists in South Korea and how it compares to the interest shown by UK organizations.

## 3 Research Methodology

Data collection is an essential part in the conduction of any research as it dictates the quality of the analyzes and conclusions drawn from them. Since this research aimed at firstly investigating the degree of application of Lean Six Sigma in an unlimited boundary of industries in two countries, and then examining people's opinions and attitudes about the implementation of this approach, it used an exploratory and descriptive survey as its data collection strategy.

### *3.1 Survey Questionnaire: Construction, Structure and Content*

The survey questionnaire was developed and adapted taking into consideration the research instruments previously used in similar studies carried out by Garza-Reyes et al. [3] and Antony and Desai [4]. The questionnaire was electronically created employing the services of an online company that provides a website for on-line surveys. Nesbary [27] states that a web-based survey is an easier and faster way to gain data than other type of surveys such as face-to-face, telephone and mail surveys, assuring informed consent, confidentiality and anonymity. In addition, online surveys are more easily distributed to access a number of respondents from widespread locations and specific groups.

The questionnaire developed for this investigation consisted of five sections. Section 1 contained three questions that were intended to collect general information about the organization's profile, for example: size, industry where it competes, and the position of the respondent within such organization. Collecting profile related data allowed the researchers to explore if the respondents differed in behaviors, attitudes and/or believes in relation to different aspects of Lean Six Sigma. In the case of Sect. 2, three questions aimed at obtaining information about what approaches the participant organizations utilize for improving operational/quality performance (the results of this were later correlated with the organizations' size and industry), the degree to which companies were aware of Lean Six Sigma, and the sources through which they have obtained this information from. Some logic in terms of the questions' sequence was embedded within the questionnaire, which automatically opened or skipped questions depending on the respondent's answers. This made the questionnaire easier to follow and less time consuming to respond, which helped to increase the overall rate of response. On the other hand, Sect. 3 only applied to respondents of the organizations that had already or were in the process of implementing Lean Six Sigma. Five questions about possible reasons for and barriers found when implementing Lean Six Sigma were asked in this section of the questionnaire, as well as about the benefits of adopting this approach. Additionally, this part also asked the participants to answer in which area of the operational process Lean Six Sigma had been applied and which of its tools were particularly used. In the case of Sect. 4, it only applied to the respondents of the companies that had not or were not currently applying Lean Six Sigma in their operational processes, it consisted of two questions. These questions were aimed at finding out which other strategies (i.e. ISO, Total Quality Management, lean manufacturing, Six Sigma, etc.) they were using, if any, for the improvement of their operations and the possible reasons for not implementing the Lean Six Sigma approach. Finally, Sect. 5 consisted of an open question that intended to investigate the views and feelings of the respondents regarding the future of Lean Six Sigma and its possible adoption in the investigated countries.

## *3.2 Survey Questionnaire Validation*

Evaluating the validity of the data collection instrument is vital in the process of a questionnaire based research. Robson [28] suggests the validations of a questionnaire through a small scale pilot study before distributing it to sample subjects. Thus, after the questionnaire was created, it was e-mailed to several academics in various UK universities. The motives underlying this pilot study were:

- To remove irrelevant questions from the survey.
- To improve/re-write any question(s) that were difficult to read and/or understand.

- To refine the language of the survey questions in order for the respondents to gain an easier and better comprehension of the idea asked.
- To have a general feedback from the respondents of the pilot study with regards to the questionnaire's structure, logic and language.

### *3.3 Survey Questionnaire Distribution*

The questionnaires were distributed via e-mail attachments, together with a cover letter introducing the main researchers and explaining the objective of the investigation, to middle level managers or engineers involved in the company's operations (i.e., production, quality, operations, etc.). The e-mail included a web link for a participant to access the survey's website. The organizations were selected on a random basis from the Internet, and they covered a variety of industries that included chemical, electronics/semiconductor, automotive, construction, service, textile, food, retail, etc., regardless of their size.

From the questionnaires distributed, 50 responses where received from South Korean organizations and 48 from UK based companies. Although the number of responses obtained is obviously not representative of all companies in both countries, they provided sufficient data for an initial and general exploratory analysis of the implementation status of Lean Six Sigma in South Korean and the UK.

## 4 Results, Analysis and Discussion

The first section of the survey provided an overview of the profile of the responding organizations and individual respondents. In this case, almost half of the responding South Korean companies (48 %) were large organizations with over 1,000 employees while 20 % were small organizations with less than 50 staff. Medium size organizations with between 50 and 300 people accounted for 18 % while 14 % of respondents worked in medium size enterprises with between 300 and 1,000 employees. In the UK, on the other hand, about 70 % included small companies and large scale firms, with 37 and 33 % respectively. Medium size organizations with between 50 and 300 and 300 and 1,000 employees accounted for the rest 30 % with relatively similar percentages (14.6 and 15.4 % respectively).

As for the industry of the organizations surveyed in South Korea, manufacturing represented the largest industrial sector with 60 %. Specifically, the electronics and semiconductor industry included 28 % of the manufacturing industry, followed by mechanical (14 %) and food (10 %). Textile, automotive, chemical, pharmaceutical, and electrical sectors accounted for the rest 8 %. For the rest of the industries, construction was 14 %, followed by service (12 %), others (6 %), retail (4 %), and education (4 %). In the UK, construction represented 21.8 % of the organizations surveyed, followed by specific industries of the manufacturing sector such as electronics and semiconductor (11.5 %), mechanical (10.4 %), automotive (9.3 %), and chemical (7.3 %). Other sectors that included textile, pharmaceutical, food, electrical, printing, service, retail, and education represented 6.7 % while "others" accounted for 33 % of the organizations surveyed. "Others" included organizations from the stationery, sheet metal, boat, and furniture industries.

Madu et al. [29] comment that middle level managers are one of the most effective and important sources of information related to quality issues in any organization. Arguably, this is also the case in the provision of information related to the implementation, management and sustainment of operational approaches such as lean manufacturing, Six Sigma and Lean Six Sigma. Thus, whenever possible, middle level managers were sought as the main source of information for this research project. Among South Korean companies, approximately 45 % of the questionnaires were filled out by operations, quality and production managers. The rest of the survey questionnaires were completed by human resources managers (11.4 %), engineers/supervisors (10.3 %), and others (33.3 %), which included project, sales and marketing team managers, as well as office and service staff. On the other hand, in the UK about 42 % of the respondents were operations, quality and production managers. The rest of the questionnaires were filled out by directors (31.3 %), engineers/supervisors (5.8 %), and others (20.9 %). "Others" included staff in the role of office managers, acquisition and risk managers, marketing executives, a head of corporate affairs, a recruitment administrator, etc.

### *4.1 Operations/Quality Improvement Approaches Used, Awareness and Sources of Awareness of Lean Six Sigma*

In the second part of the questionnaire, the respondents were asked to comment about what operations or quality improvement approaches their organizations were currently utilizing. Figure 1 shows a comparison between the operations and quality improvement approaches employed by the surveyed South Korean and UK organizations. Figure 1 shows that the application of Lean Six Sigma in the UK is three times higher than in South Korea, which is in line with the fact that UK is the second country, after the USA, from where more research publications about Lean Six Sigma have been produced [30]. Figure 1 also indicates that in the UK Lean Six Sigma is nowadays a more popular alternative to operations and quality improvement than lean manufacturing and Six Sigma, while in South Korea Six Sigma is still the most popular approach. If Lean Six Sigma is considered the latest "evolutionary stage" of lean manufacturing and Six Sigma, it can be concluded that only very few South Korean organizations have embraced this latest trend. In terms of organizations' size, 80 % of the South Korean companies that had

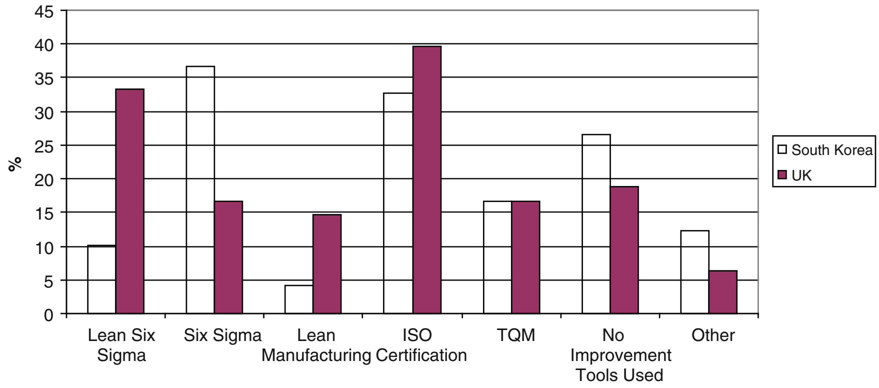


**Fig. 1** Main improvement approaches used by South Korean and UK organizations

implemented Lean Six Sigma were large organizations with over 1,000 employees, while in the case of the UK this organizational size accounted for 68.8 %. This clearly indicates that due to the availability of resources, knowledge, and expertise, large enterprises have a fastest access to the implementation of the latest technological developments, including Lean Six Sigma. This study also shows that the spread of Lean Six Sigma to smaller size organizations is occurring faster in the UK than in South Korea.

When analyzing the implementation of Lean Six Sigma in reference to the industry where it has been implemented, this study indicates that in South Korea, the electronics and semiconductor industry accounts for 60 %, followed by the automotive and service sectors with 20 % each. In the UK, this research shows that the application of Lean Six Sigma occurs in a wider spectrum of industries, for example: electronics and semiconductor (25 %), mechanical (25 %), construction (18.7 %), chemical (12.4 %), and automotive, service and others with 6.3 % each. Although the application of Lean Six Sigma is relatively high in the UK's construction industry, the manufacturing sector still remains as the most prominent "ground" for the application of this improvement approach.

In reference to the awareness of Lean Six Sigma, 64.6 of the South Korean organizations surveyed were not aware at all of this improvement approach, 35.4 % had some degree of awareness while no organization was completely aware of it. Those participants that responded that they had some degree of awareness of Lean Six Sigma were also asked what the source from such awareness was. From the 35.4 % that were aware of this approach, 18.8 and 8.3 % mentioned that they obtained this knowledge from professional societies/publications and top management respectively. In addition, few respondents were made aware of Lean Six Sigma through customers (2.1 %), consultancy agencies (2.1 %) and others (4.1), which included manuals and personal studying. On the other hand, 33.3 % of the UK organizations responded that they were not aware at all of Lean Six Sigma, 60.4 % had some degree of awareness and 6.3 % were completely aware of it. From the 66.7 of the participants who were aware of Lean Six Sigma, the majority (24.4 and 21.2 % respectively) had obtained such awareness from top managers and professional societies/publications. The awareness of Lean Six Sigma for the rest of the respondents came from business partners (8.7 %), consultancy firms (7.4 %), personal education and training (3.7 %), and costumers (1.3 %).

### 4.2 Lean Six Sigma Implementation

Organizations that had implemented Lean Six Sigma were asked in what area(s) they had applied such improvement approach. In reference to this, 80 % of the South Korean organizations surveyed had implemented Lean Six Sigma in their production processes, 60 % in their entire operations, and 40 % had applied it at a supply chain's level. Similarly as in South Korea, the implementation of Lean Six Sigma in UK companies finds its main application in production, entire operations and supply chain, with 75, 62.5, and 37.5 % respectively. However, the study shows that unlike their South Korean counterparts, UK companies had expanded the application of Lean Six Sigma principles to other departments that included sales (12.5 %), finance (6.5 %), human resources (6.5 %), and service and facilities (6.5 %). This indicates that similarly as with what occurred with lean manufacturing, which application grew and spread to other functional areas, the application of Lean Six Sigma is evolving to be adapted and employed in functional areas other than production and operations only.

As for the reason to implement Lean Six Sigma, about 83 % of the South Korean companies expressed that they utilized the approach to raise profits and reduce unnecessary expenses. Also, 67 % launched Lean Six Sigma to improve their operational performance. Few companies implemented the initiative to be globally competitive (33.3 %), become a world-class organization (16.7 %), create a better image for their products or services (16.7 %), and enhance customer satisfaction (16.7 %). In terms of UK organizations, all of them commented that they had implemented Lean Six Sigma with the objective of improving operational performance, increase profit and reduce unnecessary expenditure. About 43 % of these companies also thought that it would help them to enhance customer satisfaction while 37.7 to become a world-class organization. Some other reasons as to why UK organizations had decided to implement Lean Six Sigma were to be globally competitive (31 %), solve chronic problems (18.8 %), and to create a better image for their products and services (6.3 %).

Figure 2 presents some of the most commonly used Lean Six Sigma tools according to the responses obtained from the South Korean and UK organizations surveyed. As Fig. 2 indicates, UK organizations employed a wider number of Lean Six Sigma tools than their South Korean counterparts. Some of the tools that none of the respondent companies surveyed employ include SIPOC diagrams, poka-yoke, design of experiments (DOE), and simulation. In terms of the main benefits

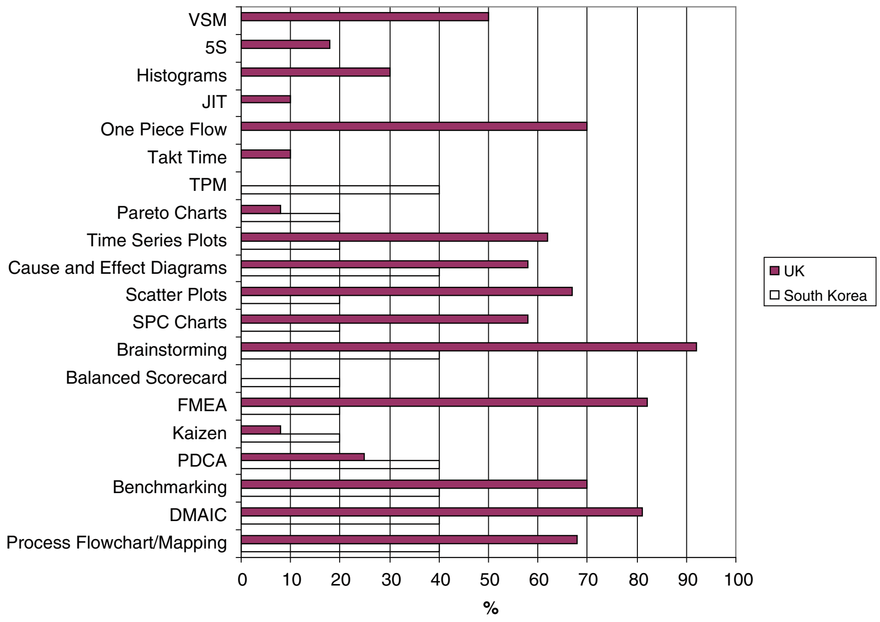


**Fig. 2** Lean Six Sigma tools used by the surveyed organization

obtained from the implementation of Lean Six Sigma, the results are very similar. The South Korean and UK organizations surveyed agreed that it has helped them to increase profit and productivity, as well as to reduce operational cost. Some other benefits include reduction of scrap/rework and delivery time.

The participant organizations were further asked to mention the possible barriers they confronted during the adoption of Lean Six Sigma in their operations. Figure 3 indicates the various impediments the South Korean and UK organizations faced during the implementation of Lean Six Sigma. As illustrated in Fig. 3, the main barrier the surveyed organizations found when implementing Lean Six Sigma was the lack of technical knowledge on such approach. Thus, most of the organizations surveyed provided extensive training to their employees during the implementation of this approach while some others employed the support of consultants. Lack of fast tangible results was the second highest barrier encounter by the South Korean and UK organizations when implementing Lean Six Sigma. This shows the immediate positive effect on organizational performance that companies expect after have dedicated time and resources to the implementation of Lean Six Sigma. Some other important barriers found by the respondent organizations included lack of HR and financial resources. In general terms, it seems to be that UK organizations find the implementation of Lean Six Sigma more difficult than their South Korean counterparts.

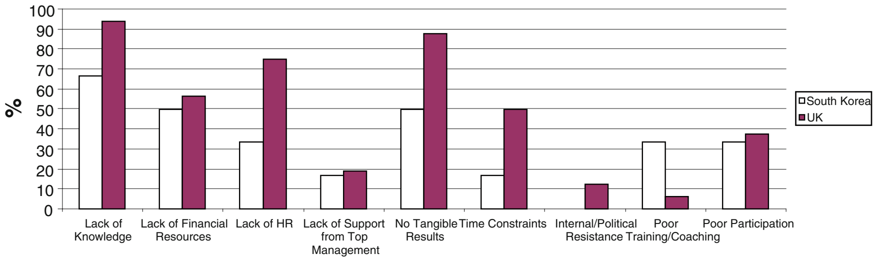


**Fig. 3** Barriers faced by the surveyed organizations during the implementation of Lean Six Sigma

## *4.3 No Lean Six Sigma Implementation*

In this section of the survey questionnaire, the respondent organizations that had not implemented Lean Six Sigma were asked to state the alternative tools and techniques they were employing, if any, for operations and quality improvement. In terms of the South Korean organizations, Six Sigma was found to be the most popular choice, followed by, in that order, ISO 9000, Total Quality Management (TQM), and lean manufacturing. Sixteen South Korean companies had not implemented any operations or quality improvement approaches. On the other hand, most of the UK organizations that had not implemented Lean Six Sigma used ISO 9000 as the main operation and quality improvement approach, followed by, in that order, Six Sigma and TQM, and lean manufacturing. Nine of the UK organizations that had not implemented Lean Six Sigma were not using any other approach to improve their operations or the quality of their products and/or services.

The top five reasons as to why South Korean companies had not implemented Lean Six Sigma included: lack of knowledge to "kick it off" (48.7 %), lack of availability of human resources (30.8 %), have implemented or plan to implement other improvement initiative (28.2 %), cost implications (25.6 %), and lack of assistance from top management (17.9 %). On the other had, the top five reasons in UK organizations were lack of availability of human resources (43.8 %), lack of knowledge to "kick Lean Six Sigma off" (37.5 %), had never hear about it (34.4 %), cost implications (25 %), and have implemented or plan to implement other improvement initiative (21 %). Lack of technical knowledge about Lean Six Sigma has created a barrier to implement Lean Six Sigma in both countries, this corroborates the finding discussed in Sect. 4.3, where organizations indicated this as the main barrier when deploying this approach. As empirical evidence suggests that Lean Six Sigma helps organization to be more competitive, the South Korean and UK governments should create strategies to aid organizations with its implementation. Cost implications and the future use of other improvement strategies were found to be common factors for not implementing Lean Six Sigma in both South Korean and UK companies.

### 4.4 Future of Lean Six Sigma

This last part of the survey questionnaire was based on an open question which intended to investigate the future of Lean Six Sigma as perceived by the respondents. In this context, a South Korean respondent using Lean Six Sigma commented that Lean Six Sigma projects are widely spread these days, but that it is not easy to find companies focusing on post-project activities, which according to him could maximize the effects of Lean Six Sigma. Another respondent mentioned that the use of Lean Six Sigma will increase in South Korea since organizations are always eager to find appropriate ways to improve quality and reduce costs. On the other hand, for those who indicated that they were not using Lean Six Sigma in South Korea, they expressed that the approach has not been widely promoted so they considered it needs to be more widely spread.

From the survey performed in the UK, a participant using Lean Six Sigma commented that “it has been proven that this methodology can help to effectively produce goods”. Thus, he believes that many companies in the UK will embrace this initiative too in other areas (e.g., cleaning services) besides manufacturing. Participants in the UK who were not employing Lean Six Sigma commented that “it is more beneficial to large scale companies as small size organizations are in their cost base for survival”. Also, according to them, it still needs to be more strongly promoted as very few small size organizations know about it.

## 5 Conclusions

This paper has presented a study where the implementation status and some other factors related to the adoption of Lean Six Sigma in two counties, South Korea and the UK, have been investigated and compared. In general terms, the study revealed that Lean Six Sigma has been about three times more widely adopted by UK organizations than their South Korean counterparts. In the UK, although ISO 9000 still remains as the most popular approach for operations and quality improvement, Lean Six Sigma has now positioned itself as the second most popular option, which is not the case in South Korea, where other approaches such as Six Sigma, ISO 9000, and TQM are still preferred over Lean Six Sigma. Lack of awareness of Lean Six Sigma seems to be the main cause for South Korean companies not adopting this approach as 60 % of the organizations surveyed had not hear about Lean Six Sigma. In this context, the South Korean government and professional institutions must develop appropriate strategies for their organizations to come to know and adopt the latest improvement approaches and thus keep internationally competitive.

The paper has also explored, in more detail, different aspects related to the adoption of Lean Six Sigma. These include, for example: the type of industry and organization functions where it has been implemented, reasons behind its deployment, most commonly Lean Six Sigma tools used by organizations, barriers encountered during its deployment, among some other aspects that have contributed to enrich the knowledge on this relatively new improvement methodology. Although this study has presented some interesting initial findings with respect to the implementation of Lean Six Sigma in South Korea and the UK, these findings need to be interpreted with caution due to the survey's sample size studied and response rate obtained, as well as the data analysis method employed (i.e., descriptive statistics). Therefore, it would fall to a future research agenda to expand this investigation by increasing the number of organizations surveyed, the response rate and by analyzing the data collected using inference statistics.

## References

1. Truscott W (2003) Six Sigma: continual improvement for businesses. Butterworth-Heinemann, Oxford
2. Trent RJ (2008) End-to-end lean management: a guide to complete supply chain improvement. J. Ross Publishing, FL
3. Garza-Reyes JA, Parkar HS, Oraifige I, Soriano-Meier H (2012) An empirical exploratory study of the status of lean manufacturing in India. Int J Bus Excellence 5(5):395–412
4. Antony J, Desai DA (2009) Assessing the status of Six Sigma implementation in the Indian industry: results from an exploratory empirical study. Manag Res News 32(5):413–423
5. Sheridan JH (2000) Lean Sigma' synergy. Industry Week 249(17):81–82
6. Corbett LM (2011) Lean Six Sigma: the contribution to business excellence. Int J Lean Six Sigma 2(2):118–131
7. Laureani A, Antony J, Douglas A (2010) Lean Six Sigma in a call centre: a case study. Int J Prod Perform Manag 59(8):757–768
8. O'Rourke P (2005) A Multiple-case comparison of Lean Six Sigma deployment and implementation strategies. ASQ World Conf Qual Improv Proc 59:581–591
9. Timans W, Antony J, Ahaus K, Van Solingen R (2012) Implementation of Lean Six Sigma in small and medium sized manufacturing enterprises in the Netherlands. J Oper Res Soc 63(3):339–353
10. Lee KI, Lee SS (2012) A case study on the lean management activity in business-service industry. Asia-Pac J Bus Ventur Entrepreneurship 7(1):189–206
11. Kim JH, Nam HG (2008) A lean logistics model for improving the port logistics in the steel industry. J Inf Sec 8(1):101–108
12. Hwang SS, Kim SK (2011) How to implement lean principles into software development practice?: visualization of delays and defects. Inf Sys Rev 13(1):61–74
13. Ko SG (2010) A study on evaluation indices for testing PoP of mobile phones. Korean J Appl Stat 23(6):1035–1045
14. Lee KC, Ro TS (2006) Application of quality management in telecommunication service industry: a case of applying Six Sigma in KT. Korean Soc Qual Mana 08:227–235
15. Lee KB, Kim Y, Chung KS (2009) Improvement of hospital sickroom thermal environment through reestablishment of fiducial temperature. Soc air-conditioning Refrigerating Eng Korea 25(June):573–578
16. Cho IH, Yoon SP, Chung KH (2008) A study on the success factors for Six Sigma in public corporations. J Korea Saf Manag Sci 10(3):183–191
17. Ahn YJ (2008) Six Sigma review on service. J Korean Prod Oper Manag Soc 19(4):81–106
18. Park YH (2004) Six Sigma in Korea with case studies. In: Proceedings of the IIE annual conference, Houston, Texas

19. Gitlow H, Levine D (2004) Six Sigma for green belts and champions: foundations, DMAIC, tools and methods, cases and certification. Prentice-Hall, Upper Saddle River
20. Devane T (2004) Integrating Lean Six Sigma and high-performance organizations: leading the charge toward dramatic, rapid, and sustainable improvement. Wiley, New York
21. Gershon M, Rajashekharaiah J (2011) Double LEAN Six Sigma: a structure for applying Lean Six Sigma. J Appl Bus Econ 12(6):26–31
22. Spedding TA, Pepper MPJ (2010) The evolution of lean Six Sigma. Int J Qual Reliab Manag 27(2):138–155
23. Bhuiyan N, Baghel A (2005) An overview of continuous improvement: from the past to the present. Manag Decis 43(5):771–781
24. Mader DP (2008) Lean Six Sigma's evolution. Qual Prog 41(1):40–48
25. Harry MJ (1998) Six Sigma: a breakthrough strategy for profitability. Qual Prog 31(5):60–64
26. Snee RD (2003) Lean Six Sigma: getting better all the time. Int J Lean Six Sigma 1(1):9–29
27. Nesbary D (2000) Survey research and the worldwide web. Allyn & Bacon, Upper Saddle River
28. Robson C (1993) Real world research: a resource for social scientists and practitioner researchers. Blackwell, Oxford
29. Madu C, Kuei C, Jacob R (1996) An empirical assessment of the influence of quality dimensions on organisational performance. Int J Prod Res 34(7):1943–1962
30. Zhang Q, Irfan M, Khattak MAO, Zhu X, Hassan M (2012) Lean Six Sigma: a literature review. Interdiscip J Contemp Res Bus 3(10):599–605

# The Application of a Lean Philosophy During Manufacture of Advanced Airframe Structures in a New Product Introduction (NPI) Environment

**Darren Winter, Chris Jones, Carwyn Ward, Paul Gibbons, Chris McMahon and Kevin Potter**

**Abstract** The manufacture of primary structural wing components from high-performance composite materials is a relatively new technique. GKN Aerospace faces the challenge of manufacturing complex large-scale aero-structures by the 'Automated Fibre Placement' (AFP) process whilst transitioning from the 'new product introduction environment' to meet contractual production rates. This paper reports on the adoption of the Lean philosophy within a 'value stream' by capturing staff perceptions to gain an understanding of the success levels and areas of concern. The research is of particular importance since the 'barriers of resistance' in manufacturing environments can be high if Lean is not introduced in a fashion production staff can relate to. Therefore, the research conducted offers GKN the opportunity to focus on the specific areas to realise continuous improvement through the adoption of Lean. The research investigation consisted of a questionnaire employed to gauge staff perceptions from the end of operations at Year 1. At the end of Year 2, the questionnaire was repeated to broaden the cross-sectional study over a longitudinal time horizon. The results were subject to statistical significance testing which showed the differences in staff perceptions were evident. These differences were attributed to the overall level of Lean understanding and appreciation within the facility. The novelty of this research is manifested in how well Lean practice has been adopted in a large-scale aerospace manufacturing facility transitioning from the NPI environment to serial production. Other Lean practitioners and academics will be able to apply the approach in their work, especially those looking to incorporate a Lean philosophy in a NPI environment.

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## 1 Introduction

The Lean philosophy has been widely employed in the automotive sector and provided cost savings through greater production efficiency [1]. From this success, other industries such as aerospace have adopted Lean with a view to achieving similar improvements [2]. The GKN Group Plc have deployed Lean amongst their manufacturing sites and as of recently, adopted the philosophy within their Aerospace Division (GKNA). GKNA is a leading tier one supplier to the worlds OEM's and have achieved competitive advantage by specialising in manufacturing technologies utilising high performance carbon fibre materials. This strategy led to their selection as risk-sharing partners with Airbus for manufacture of the 'Fixed Trailing Edge' for the A350-XWB airliner. However, production of high value low volume components from carbon-fibre materials differs from high volume production scenarios found in other industries i.e., Automotive. The low volume production rate for A350 Wing Spars is a function of scale, complex part geometry and fabrication method i.e., smaller, simpler parts with known methods and materials would yield a higher volume output. The success of the Lean adoption in this non-traditional environment was therefore under closer scrutiny. To meet contractual manufacturing rates, GKNA invested £170 M into a 'state of the art' manufacturing facility specialising in Wing Spar manufacture through automated composites deposition technologies. Figure 1 shows the 'Automated Fibre Placement' process (AFP) depositing material in 0.25 mm thickness increments onto bespoke mandrel tooling.

Wing Spars form the primary structural element of the 'Fixed Trailing Edge' by providing spanwise stiffness in traditional wing-box structures. Each Wing Spar is comprised of three C-sections for port and starboard wings; see Fig. 2. On assembly, the Spars are fastened 'end to end' by joint plates to form a component spanning 30 m; the largest structural component the UK has produced from high performance carbon fibre materials. The GKNA manufacturing facility has been in operation for two years, and at the time of writing, was transitioning from the 'New Product Introduction' environment (NPI) towards 'Steady State

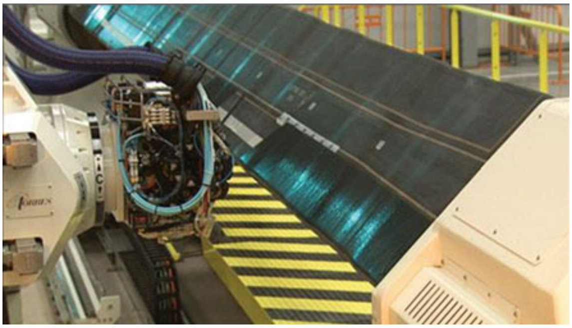

**Fig. 1** Automated fibre placement of wing spar

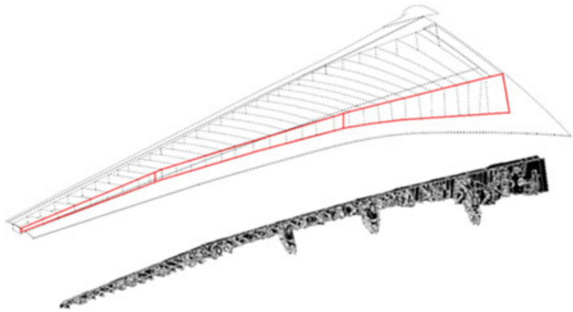

**Fig. 2** Fixed trailing edge in wing attitude

Manufacture' (SSM). To smooth the transition from NPI to SSM, GKNA have relied on a 'Continuous Improvement' methodology (CI) for improving production efficiency.

## 2 Literature Review

### *2.1 The New Product Introduction to Steady State Manufacture Transition*

Figure 3 shows the NPI to 'steady state' production scale modified from Saaksvuori and Immonen [3].

Viale [4] agrees with Saaksvuori and Immonen, defining NPI as a series of planned phases that comprise of technology development and design activity where manufacturing process maturity must reach an acceptable level in the pre-production phase prior to delivery. Kumar and Wellbrock [5] present a number of challenges that exist when working in NPI, ranging from compressed design lead times and the need for manufacturing quality improvement; these often stem from a condensed 'time to market'. With an understanding of these challenges, GKNA function as risk sharing partners with Airbus and having secured the production contract, strive to meet production targets to fulfill their role in the supply chain. Additionally, GKNA have also faced the added complexity of introducing a brand new manufacturing technology: the 'Automated Fibre Placement' Process. Oppenheim [6] and James-Moore [7] argue that 'low maturity' technologies can pose work flow related problems as opposed to existing 'known' technologies during the NPI phase. In this instance, efforts in production operations at GKN have focused on 'proving out' and stabilising manufacturing capability as quickly as possible before ramp-up to facilitate a smoother transition to SSM. Haller et al. [8] also argue that production ramp-up (or time to volume) directly affects the financial success of a product. For example, if production ramp up is delayed, expected revenues are not achieved. Therefore, shorter ramp-ups can improve financial indicators such as return on investment and return on assets. To meet this

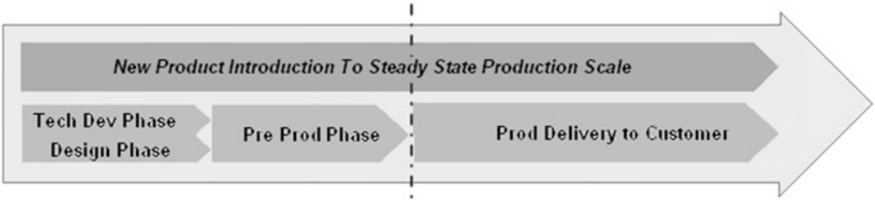


**Fig. 3** 'New product introduction' process with respect to the product lifecycle

challenge, GKNA has adopted a 'Lean Philosophy' to aid in the 'Continuous Improvement' of work flow and the ramp-up of production rates to meet contractual obligations.

## *2.2 Genealogy of Lean and Continuous Improvement*

The use of continuous improvement (CI) techniques in production operations gained momentum in Western nations during the early 1980s [9]. Methods such as 'Just in Time' (JIT) and the Toyota Production System (TPS) have been extensively been reported on; Schonberger [10]. However, as Western manufacturers began to adopt CI tools and TPS methods within their respective organizations, they quickly realized certain barriers to implementation existed, Womack and Jones [11]. Bessant et al. also provides reasons why CI initiatives can fail to take root and sustain themselves in practice [12]. Hines et al. [13] also provide historic and genealogical accounts of increased competition from the Japanese automotive industry. Their work emphasises the effectiveness of the TPS as a manufacturing philosophy that not only improved quality, but also efficiency during production operations which led to the emergence of Lean as a CI philosophy. The Lean philosophy came to the fore during the 1990s through the collaboration of Womack, Roos and Jones who authored 'The Machine that Changed the World' [1]. This seminal work paid homage to the TPS and their subsequent publication built on their original work by reorganising and reforming previous CI methods and rebranding them as 'Lean Thinking'. This new philosophy set out Lean 'Central Tenets' with the purpose of easing adoption and diffusion in Western manufacturing. The tenets of 'Lean Thinking' focus on the removal of 'waste' in manufacturing processes and can often be applied with a 'Resource-Based View' (RBV) of the firm [14]. By applying the Lean, waste is identified and removed from the 'bottom up' in production operations by constructing a 'current state' 'Value Stream Map' of each successive stage. The first step in value stream mapping is to understand what is 'value adding' in the eyes of the customer. For A350 Wing Spars, the value adding elements are production of the 'Key Characteristics' within designed tolerances. With this in mind, the value stream map can be developed to identify waste and develop the 'Future State' scenario [15].

With respect to the GKNA manufacturing facility, its VSM was conceptualized at the start of the A350 project as lessons learned from prior aircraft programs had shown issues with logistics, stability, and flow. Efforts have focussed on gradually implementing Lean whilst transitioning from NPI to SSM.

### *2.3 The Challenge of Implementing Lean During the 'NPI to SSM' Transition*

Crute et al. [2] investigate the transferability of the Lean philosophy from automotive to aerospace, acknowledging the differences between high and low volume manufacturing. The driver for the adoption of Lean into Aerospace was attributed to the shift in market conditions during the 'Mass Production' era due to increasing overseas competition. The case studies presented show a Lean adoption during 'Steady State' manufacture rather than NPI. In the same year, Oppenheim [6] also reported on 'Lean Product Development Flow' (LPDF). A higher level generic framework for the adoption of LPDF is provided based on the central tenets set out by Womack and Jones [16]. However, Oppenheim states *'LPDF is more suitable for smaller design programs with a high degree of legacy knowledge, with technologies mature enough so that program feasibility is not in question'* i.e., low levels of disruption and high legacy knowledge is assumed, thereby reinforcing the case for smoother flow in the NPI environment. Haque and James-Moore [7] also report on the application of Lean in NPI as part of the UK Lean Aerospace Initiative (LAI). Their review states the importance of 'Capability Management', 'Technology Readiness' and 'Design for Manufacture'. The research is also supported by two case studies addressing Lean in NPI from two mature manufacturing operations. Similar to Oppenheim [6], a high level of manufacturing maturity is assumed and is therefore able to cope with changing conditions. Both case studies reveal the success of Lean adoption with meaningful returns in terms of time reduction and cost savings. In 2008 Oppenheim et al. published 'Lean Enablers for Systems Engineering' [17] utilising the tenets set out by Womack and Jones [16]. Oppenheim presents a series of important 'Enablers' when implementing Lean in a production scenario. Perhaps not Lean but holistic, some 140 Lean Enablers were constructed and sent to individual aerospace companies for assessment. Each company scored the Lean Enablers based on their usefulness when applied to their respective aircraft programs. Analyzing the results of the assessments, Oppenheim presented the ranking for each Lean Enabler in tabular format as categorized by the 6 central tenets originally presented by Womack and Jones. These enhanced Lean Enablers were found to be of particular relevance to GKNA and were identified as a method for conducting a cross sectional analysis of the 'Current State' of the value stream and a format for gauging the level of the Lean adoption within the facility.

## 2.4 Summary of Literature Review

A review of the antecedent Lean conceptual literature has shown how the philosophy has been adopted with considerable success. However, amongst the success the review has identified obstacles that exist when applying the six Lean tenets and 140 Lean Enablers in a NPI and non-steady state environment. The case studies reviewed were fairly cross-sectional in nature and produced results for the 'single setting' in which they were applied. The review has revealed Lean frameworks can be applied but support the notion that no single solution exists for the implementation of CI or Lean in differing 'real world' manufacturing scenarios, Childerhouse and Towill [18]. The application of Lean in a non-steady state production environment as part of a NPI project has not been fully captured before perhaps identifying a gap in the body of Lean knowledge. Also, a longitudinal investigation of a Lean application from the very outset of an aircraft program would be valuable for GKNA and would reveal blockers and enablers as the program progressed. Of particular relevance would be the central tenets of Lean and those Lean Enablers set out by Oppenheim that ease an introduction to Lean when transitioning from NPI to steady state manufacture. A longitudinal study of an implementation of Lean whilst transitioning from NPI to steady state is therefore proposed taking into account the Lean Enablers.

# 3 Research Methodology

This paper employs a survey based research strategy by adopting a questionnaire as its primary method of data collection. For a fuller appreciation of the 'Lean Enabler' questions, the reader is referred to 'Lean Enablers for Systems Engineering'; Oppenheim et al. [17]. The final part of the questionnaire is further complemented by asking open questions in the style of a semi-structured interview. The data was acquired at the end of business operations Year 2; during the early stages of transition from NPI to SSM. Data from the same questionnaire is also incorporated from an earlier study conducted at the end of operations from Year 1 where GKNA were operating purely in the NPI phase. The comparison of data from end of Years 1 and 2 converts the initial cross-sectional study into one conducted over a longitudinal time horizon. The business strategy is to continually re-deploy the questionnaire at the end of operations each successive year for the first five years. The five year time span will cover the adoption of Lean plus any further CI methods; their success will be gauged quantitatively in this respect. The questionnaire was deployed vertically within the organization across 5 tiers of hierarchy:

Tier 1: Vice President of Manufacturing Facility
Tier 2: Value Stream and Manufacturing Management
Tier 3: Engineers

Tier 4: Lean Enterprise Team
Tier 5: Customer Interface for Airbus contract.

For each Lean Enabler, the interviewees were asked to assign a value from (1) to (5) for the metric questions MQA and MQB below:

Q1. MQA: How important is this enabler to your role?
Q2. MQB: How well do you implement this enabler in your role?

By ranking the metric questions from (1) to (5), each Lean Enabler established the 'perceived importance' and level of implementation where (1) equaled 'unimportant' and (5) equaled 'very important'. The analysis ascertained the delta value between **|MQA—MQB|** for each enabler giving a priority for the metrics of perceived importance versus implementation. The **|MQA—MQB|** data was then used to draw a comparison for Lean adoption between Years 1 and 2 by Pareto analysis. The data was then subject to significance testing ascertaining the differences in staff perceptions between tiers 1–5 above. A one-way 'Analysis of Variance' (ANOVA) was then performed by plotting the means along with 'least significant difference' error bars at the 5 % alpha level. Gaps between the error bars were considered significant and overlaps insignificant.

## 4 Results and Discussion

The delta values from each **|MQA—MQB|** metric were summed i.e., the actual number of 0, 1, 2, 3 and 4s were added. The contribution of 3 and 4s was observed to be lower for Year 2 than Year 1 of operations. A Fisher's exact test was performed where the null hypothesis was that 'no difference' in perception existed for operations between Years 1 and 2. The $p$ value was observed to be $<0.05$, therefore the null hypothesis -that no difference existed- was rejected.

A Pareto analysis was then conducted by summing the delta values for each tier by their individual enabler, i.e., for Lean Enabler 1, the delta values across tiers 1 through 5 were summed. This gave a 'ranked sum', plus the percentage contribution for each Lean Enabler. Four of the Lean Enablers were observed to be above the 80 % level giving an indication as to how the business adopted Lean during Year 1 (NPI environment):

1. Enabler 5: Do we plan to prevent potential conflicts with suppliers?
2. Enabler 15: Have we built an organization based on respect for people?
3. Enabler 25: Do we promote complimentary continuous improvement methods?
4. Enabler 11: Do we make program progress visible to all?

The Pareto Analysis was then performed for Year 2 operations. The results showed Lean Enablers 5 and 25 contributed the least when compared to Year 1. Lean Enablers 15 and 11 also appeared to be below the 80 % level.

The Lean Enablers above 80 % for Year 2 operations were:

**Table 1** One way ANOVA was then performed for years 1 and 2

| ANOVA: single factor for years 1 and 2 of employee lean implementation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Year 1 | | | | Year 2 | | | |
| | n | Sum | Mean | Variance | n | Sum | Average | Variance |
| Tier 1 | 15 | 16 | 1.1 | 0.5 | 15 | 27 | 1.8 | 0.5 |
| Tier 2 | 15 | 46 | 3.0 | 0.2 | 15 | 24 | 1.6 | 0.8 |
| Tier 3 | 15 | 12 | 0.8 | 0.7 | 15 | 14 | 0.9 | 0.4 |
| Tier 4 | 15 | 39 | 2.6 | 1.5 | 15 | 13 | 0.9 | 0.7 |
| Tier 5 | 15 | 18 | 1.2 | 1.0 | 15 | 21 | 1.4 | 0.7 |
| | Between groups | | Within groups | Total | Between groups | | Within groups | Total |
| SS | 61 | | 56 | 117 | 10.1 | | 42.3 | 52.3 |
| Df | 4 | | 70 | 74 | 4 | | 70 | 74 |
| MS | 15.2 | | 0.8 | | 2.5 | | 0.6 | |
| F | 19.1 | | | | 4.2 | | | |
| F crit | 2.5 | | | | 2.5 | | | |
| *P* value | 1.12E-10 | | | | 4.41E-03 | | | |
| 5 % LSD | 0.69 | | | | 0.60 | | | |

1. Enabler 1: Do we establish the Value of the end product to the Customer?
2. Enabler 4: Have we developed 'only what needs developing'?
3. Enabler 7: Do we clarify, derive and prioritise requirements early enough?
4. Enabler 6: Have we planned indicators and metrics to manage the program?

Table 1 shows the ANOVA performed on the **|MQA—MQB|** metrics. The F/Fcrit ratio implied a strong dataset for Year 1 and the $p$ value of $<0.05$ indicated significance. Figure 4 shows a perception that Lean is well implemented for tiers 1, 3 and 5, whereas tiers 2 and 4 show significant difference. This implies that for Year 1, the view between Operations management and the Lean team are in agreement but not with other tiers in the organization. The F/Fcrit ratio for Year 2 is much weaker yet the $p$ value is still $<0.05$; this indicated the data must be treated with caution. The LSD error bars at alpha 5 % highlight a consistent overlap suggesting no significance between tiers.

The datapoints for Year 2 in Fig. 4 show a marginal downward trend for tiers 1–4. This implies that as by progressing vertically down through the organization, Lean implementation is perceived to improve. That is until the customer at tier 5 is reached whose opinion is more in line with the VP and management tiers. Importantly, tiers 2 and 4 for Year 2 operations are now more in line with the perception of the remaining tiers and generally, the average delta is lower than Year 1 operations. Regarding the open questions at the end of the interview, a strong perception of Lean and other CI tools was evident. These encompassed

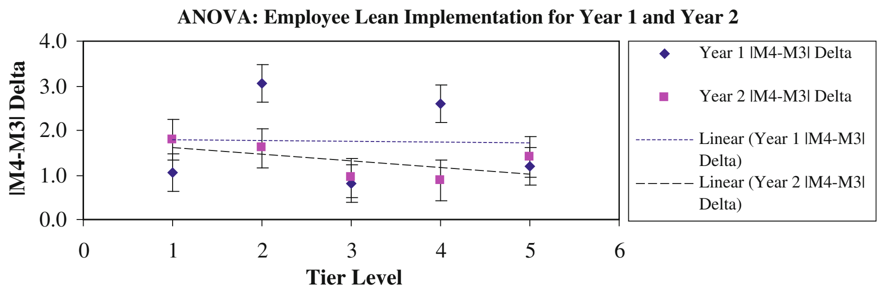


**Fig. 4** ANOVA table for years 1 and 2 employee lean implementation

**Table 2** Staff perception of NPI versus steady state

| Analysis of question 31: NPI versus SSM | |
|---|---|
| Where would you position GKNA Western approach on the scale of NPI to SSM? | |
| VP: tier 1 | 15 |
| Management: tier 2 | 30 |
| Engineer: tier 3 | 32.5 |
| Lean lead: tier 4 | 55 |
| Customer: tier 6 | 60 |
| **Mean:** | **38.5** |
| **Max:** | **60.0** |
| **Min:** | **15.0** |
| **Range:** | **45.0** |
| **SD (Pop):** | **18.7** |

Statistical Process Control (SPC), Six Sigma, Theory of Constraints and other project engineering techniques. The overall feeling was that GKNA are adopting Lean whilst SPC is currently trialed across production cells within the facility; also this feeling was supported by the roll out of a 'Lean fundamentals' course for all production staff at the end of Year 1 operations. However, none of the interviewees could provide results outlining how either Lean or other CI tools have benefited the business. Question No. 31 of the questionnaire requested staff to gauge between 0 and 100 % where they perceived GKNA to be with regard to the 'NPI versus SSM' scale. The mean result gave a perception that at the end of Year 2 operations, GKNA resided within the NPI environment with a mean at 38.5 %. The ±1.0 standard deviation of 18.7 indicated a broad spread between the tiers with a noticeable downward trend from the VP to the customer (Table 2).

## 5 Conclusions

The results from the **|MQA—MQB|** exercise show high variability for Year 1. Year 2 shows less variability and no gaps between the adjacent LSD bars between tiers. This is indicative a greater degree of agreement exists for Lean implementation at end of Year 2 in comparison to Year 1. The Pareto results for Year 1 showed strained relationships with suppliers, poor communication and a lack of respect for each other within the organization. Noticeably, CI methods were also not promoted at this early stage. The business focus was purely on the manufacture of acceptable components rather than improving the flow of manufacturing processes. The Year 2 Pareto results showed altogether different Lean Enablers than for Year 1. Establishing value to the customer was something that both management and the customer felt was of great importance. This evidence suggests that since acceptable parts have been delivered, the focus should be drawn more towards customer requirements; this view is supported by the Lean Enabler 'prioritising requirements'. 'Developing only what needs developing' also demonstrated GKNA have greater familiarity with the processes employed in wing spar manufacture. Staff can readily assess the suitability and value that new processes could potentially bring as presented to manufacturing operations. The 'Performance Indicator' enabler also supports the notion that focus should now be on manufacturing performance over NPI. Regarding the transition from NPI to SSM, the average of 38.5 % showed a progression away from NPI towards SSM. A noticeable trend was observed where senior management to engineer level (Tiers 1–3) believe GKNA are still in NPI (15–32.5 %) but the Lean team and customer perceive we have comfortably reached the early stages of SSM (55–60 %).

Overall the results have shown a greater degree of success in the uptake of the Lean philosophy at the end of Year 2 operations. The work has also contributed to the body of knowledge by demonstrating how Lean can be adopted in a low volume, high value production scenario. In the case study presented there was particular recognition of the cultural change achieved over the two year time horizon. From a customer perspective, there is now a requirement to understand where the value lies during component manufacture and that requirements are better prioritized quantifying the impact of the Lean adoption.

## 6 Limitations and Future Work

Since the interviewees could not quantify how the current CI methodology has benefitted the business, future research during Year 3 of operations should not only address the Lean philosophy but the operational effectiveness of the facility. Quantifying operational effectiveness should be supported by the roll-out of meaningful indicators across the site allowing staff to have direct visibility in accordance with the Lean central tenets. Engineering staff should also be provided with a more detailed insight of how CI methods can benefit the facility. The current mismatch in Lean implementation between the management and engineers also needs to be resolved. A greater appreciation of CI would mean philosophies such as Lean would be designed into operational methods and processes as they are introduced and would highlight how they are of benefit over and above the 85 % 'learning curve' adopted by the business. Further, during the Year 2 survey, production staff perceptions were also taken into account. Therefore, on presentation of the Year 3 results, a comparison of production staff perceptions between Year 3 and Year 2 will be incorporated.

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## References

1. Womack JP, Jones DT, Roos D (2007) The machine that changed the world: the story of lean production–Toyota's secret weapon in the global car wars that is now revolutionizing world industry. Free Press, New York
2. Crute V, Ward Y, Brown S, Graves A (2003) Implementing lean in aerospace—challenging the assumptions and understanding the challenges. Technovation 23:917–928
3. Sääksvuori A, Immonen A (2008) Product lifecycle management. Springer, Berlin
4. Viale JD (1998) New product introduction : a systems, technology, and process approach. Crisp Publications distribution to the U.S. trade: National Book Network, Menlo Park, California, Lanham, MD
5. Kumar S, Wellbrock J (2009) Improved new product development through enhanced design architecture for engineer-to-order companies. Int J Prod Res 47:4235–4254
6. Oppenheim BW (2004) Lean product development flow. Syst Eng 7
7. Haque B, James-Moore M (2004) Applying lean thinking to new product introduction. J Eng Des 15:1–31
8. Haller M, Peikert A, Thoma J (2003) Cycle time management during production ramp-up. Rob Comput Integr Manuf 19:183–188
9. Monden Y (1983) Toyota production system: practical approach to production management. Industrial Engineering and Management Press, Institute of Industrial Engineers Norcross, GA
10. Schonberger RJ (1982) Japanese manufacturing techniques: Nine hidden lessons in simplicity: Free Press, New York
11. Womack JP, Jones DT (1996) Beyond Toyota: how to root out waste and pursue perfection. Harvard Bus Rev 74:140–172
12. Bessant J, Caffyn S, Gilbert J, Harding R, Webb S (1994) Rediscovering continuous improvement. Technovation 14:17–29
13. Hines P, Holweg M, Rich N (2004) Learning to evolve: a review of contemporary lean thinking. Int J Oper Prod Manage 24:994–1011
14. Wernerfelt B (1984) A resource-based view of the firm. Strategic Manage J 5
15. Rother M, Shook J (1999) Learning to see: value stream mapping to add value and eliminate muda. Productivity Press
16. Womack JP, Jones DT (2003) Lean thinking: banish waste and create wealth in your corporation. Free Press, New York
17. Oppenheim BW, Murman EM, Secor DA (2011) Lean enablers for systems engineering. Syst Eng 14:29–55
18. Childerhouse P, Towill DR (2002) Analysis of the factors affecting real-world value stream performance. Int J Prod Res 40:3499–3518

# Applying Value Stream Mapping to Identify and Evaluate Waste in a Company of the Ceramic Sector

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**Abstract** Small and medium-sized companies today need to maintain or increase their competitiveness, and this is necessary for effective production with the least amount of waste. This paper seeks to use Value Stream Mapping (VSM) to identify waste within a company in the red ceramic sector. It should be mentioned that there are few studies in the literature describing the application of lean production tools in companies in the red ceramic sector. Through the knowledge of the production process of the company, followed by a subsequent data collection, we built the current state value stream map of the company. With the analysis of this map, several improvements aimed at reducing waste in the production process were proposed, which are depicted in the future state value stream map. With the proposed improvements, we expect a 69 % lead time reduction, as well as reduction in raw material, in-process and final inventory levels.

## 1 Introduction

According to data from ANICER for the year 2008, the red ceramic industry in Brazil was responsible for approximately 0.6 % of the Gross Domestic Product of the country, with revenues of about US$ 9 billion. According to [1], in 2010 the state of Santa Catarina had 710 companies in the ceramic sector employing 18,700 workers.

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However, due to low modernization of production processes in this type of industry, control of waste (activities that do not add value to the final product) is poorly applied, thus hampering production that could be more efficient and profitable. Moreover, according to [2], construction, main customer of the red ceramic requires maximum use of material.

Lean Production, in turn, originated in Japan when Toyota Motor Company needed to increase its productivity and become competitive in the automotive industry worldwide. The main objective of lean production is the continuous elimination of waste [3]. Value Stream Mapping (VSM) is a tool to aid lean production, and it is an important tool to identify waste.

Following the trend of market competitiveness of the industries and the need to identify waste in order to reduce the lead time and costs, to overcome its competitors [4], this study seeks to identify wastes of Lean Production through VSM in a red ceramic company located in the state of Santa Catarina, in southern Brazil. The VSM methodology presented by Rother and Shook [5] was applied, which is composed of the following steps: (a) choice of product family, (b) development of current value stream map of the company, analyzing its production processes and thus identifying the points of waste, (c) development of future value stream map, and (d) implementation schedule of the proposed improvements in order to eliminate waste.

## 2 Brief Literature Survey

### *2.1 Lean Production*

The Toyota Production System, now known as Lean Production System, was born in Japan after World War II. According to [3], at that time Japan was experiencing a crisis in the auto industry. Important market requirements, such as low demand and large product variety, demanded that industries did not mass produce anymore, trying to be more responsive to the realities of the market. A consistent and complete elimination of waste was the solution found by Toyota, which applied this thinking on its production line.

Lean Production is defined by Womack and Jones [6] as a way of organizing and managing manufacturing to produce more with less and less, i.e., less human effort, equipment, time, and space, while increasingly offering customers exactly what they want.

The basis of the concept of lean thinking is the elimination of waste within companies [7]. Waste, according to [3], is all that is part of production that increases cost, but does not add value to the final product. Shingo [8] classifies seven types of waste: overproduction, waiting, excessive transportation, inadequate processes, unnecessary inventory, unnecessary movement, and defective products.

### 2.2 Value Stream Mapping

According to [5], the tool of value stream mapping provides a view of all the steps of a given process, building a path from raw material to final product to the customer. For this it is necessary to consider the perspective of flow stream in the entire system, not just individual processes, thus resulting in improved of the whole. It is essential to understand the functioning of the sectors and how they all relate, seeking, through the design of each one of them, to investigate the points of waste, or that do not add value to the chain as a whole.

Ferro [9] defines Value Stream Mapping as "a tool capable of looking at the processes of adding value horizontally". Similarly, Womack and Jones [6] define Value Stream Mapping as a process of identifying all the specific activities occurring along the value stream regarding a product or family of products. Rentes et al. [10] consider this as an important tool because it illustrates how the flow of information within the work places showing the relationship with the material flow, making it easier to identify and eliminate waste.

Moraes et al. [11] used the VSM and the principles of Lean Production in a clothing factory. After identifying and analyzing the seven wastes of Lean Production, it was possible the elaboration of the future value stream map. It was expected a reduction of 68% in lead time of the production process of the company. Salgado [7], with the application of VSM, identified waste in the process of developing products in an enterprise. With the deployment of the future map, a lead time reduction of 8 h was achieved, one hour reduction in the final product manufacture, and an increase from 28.1 to 47 % in production process efficiency.

Fernandes et al. [12] deal with the analysis of technical feasibility for the deployment of lean manufacturing tools in one of the leading manufacturers of refractory products in the global market.

Lima and Zawilasky [13] analyzed seven small and medium enterprises in the state of Rio Grande do Sul (southern Brazil), suppliers to the automotive industry (rubber, iron, etc.). With VSM, the result was a 23 % reduction of inventory time, and also a 65 % reduction of added value time.

## 3 Methodological Aspects

The methodology discussed in this research was presented by Rother and Shook [5], which is composed of the following steps:

1. *Selection of the family of products*—in the beginning of the mapping process the family of products must be identified, considering the costumer side of the value flow, based on products which undergo similar processing steps using common equipment in later processes.

2. *Mapping the current state*—after the families of products are identified, the "door to door" flow mapping is started, using a set of icons to represent the processes and flows.
3. *Mapping the future state*—from the map of the current state, a map of the future state is generated, seeking to eliminate all waste that was identified before.
4. *Plan of improvements*—based on the waste found on the map of the current state, an action plan is developed to achieve the future state developed by VSM.

For primary data collection, informal interviews were conducted with people involved in the manufacturing process and with members of senior management. In addition, secondary data were collected through document analysis in administrative reports presenting supply and demand data. The data obtained were both quantitative (e.g., inventory, demand) and qualitative (e.g., process viability, comments).

This research, with regard to its objectives, has an exploratory emphasis, since there are few studies on Lean Manufacturing on the red ceramic industry.

## 4 Description of the Company

The company considered in this study consists of a brick factory for slabs (red tile), and it is their only product. The company was founded in 1953, and it produced initially French style tiles. The initial installations relied on a few small sheds and equipment and, at the time, used a lot of heavy labor and animal power for material handling as well as small machines.

In 1990 the factory had its production focused on bricks for slabs, producing around 700,000 pieces/month. Currently it works with a capacity of about 1,500,000 bricks/month. Its production process is largely mechanized and continuous, unlike small businesses in the region. The factory has a modern large capacity dryer, gaining competitive advantage over their competitors, since most of them carry out drying outdoors.

The company also has a mining field, extracting the raw material (clay) for the remainder of the process. For this reason, the company does not need to deal with many suppliers. The company only seeks external suppliers for the purchase of sawdust (furnace fuel), or when the clay becomes too wet because of rain.

70 % of the transport of finished brick is done by the customers themselves, while 30 % is performed by the company itself, or outsourced hired by the company considered.

The company's product, referred to as H7, has the following dimensions: 7 cm wide, 30 cm long, and 20 cm in height. It occupies a volume of 0.00188 $m^3$.

The company does not have a very accurate control of its waste, not knowing where they are located in its production process, or what is the amount of waste along the manufacturing lead time, and the costs of the final product. Thus, a significant opportunity for improvement in the processes of the company was envisaged.

In the red ceramic industry there are some paradigms related to the company's customers. The construction depends on various natural factors (e.g., rain), social and political factors (growing economy, financing facilitated by the government, etc.). Changes in these factors cause variations in the construction market and, consequently, sales of ceramic industry. Therefore, measures to strengthen the company are necessary, so that it does not influenced deeply by variations in the market. Strong relationships with customers seeking an effective programming schedule of production can be important for obtaining an end product with higher quality and on-time delivery.

## 5 Value Stream Mapping

### *5.1 The Family of Products*

Since the studied company manufactures only one product, this product was the focus of this product, i.e., the H7 brick. Then it was sought to understand the production process in order to map it and start to identify the waste present there.

### *5.2 Current State Mapping*

A good understanding of the production process is essential for the elaboration of the current map, as well as for further diagnosis and improvement proposals. Therefore, visits were made to the company, where the operations were observed. Early on some of those visits waste was identified, these being perceived visually and through conversations with engineers and technicians. There were many defective products at the end of the production process and also in-process, a large inventory of end products and work-in-process.

Rother and Shook [5] established a sequence for the construction of the current map, identifying which data is required and indicating that they must be collected from the end of the production process toward the beginning. Mapping should start by customer demand, and then data should be collected. Thereafter, the cycle time, the number of people needed to operate it, the available work time per shift, the operation time, and the size of production batches should be obtained for each process. In addition, the initial, in-process and final inventories must be determined, besides determining the flow of information on the shop floor.

The studied company has always worked with large inventories due to the difficulty in predicting sales, and it keeps a record of the inventory amount, which corresponds to a few months. This caused some difficulty in mapping of the current state. In times of increased amount of constructions, with government incentives and dry climate, sales increase considerably. On the other hand, raining seasons and low government incentives cause sales to decrease.

Another important factor is that the studied company does not have a Production Planning and Control department, and therefore it does not have a well-structured information flow. The products are pushed to the customer, moving in an uninterrupted manner. Thus, the communication between administration and manufacturing is unidirectional.

The production process is divided basically into two stages, an initial that operates with higher productivity, but in only one shift, and a second phase of lower productivity, operating in three shifts. In the first phase the processes of disintegration and extrusion of the raw material (clay) take place.

In the disintegration the clay is prepared for extrusion, passing through a few steps of grinding or enhancement. Impurities are removed and dry materials are added if necessary. This process is important for ensuring the necessary properties to the mud so that the final product has no defects.

Extrusion is the stage where the raw material acquires the shape of the final product, while still moist and without resistance. At this stage the product is cut to size and is stacked automatically on drying shelves. The first stage of the production process is finished, having only one shift, which generates a daily inventory to be consumed by the next phase in the next two shifts.

The second phase comprises the processes of drying, burning and expediting the bricks. In the drying process, which has a longer cycle, the stacked bricks (still wet) move through a corridor a pathway where they are dried. After being dried, the bricks are stacked manually and prepared for the next process.

Burning is the last step before the product reaches the customer. In this process, the bricks reach the necessary strength, getting ready to be sold. Burning is carried out in a large furnace fueled by sawdust through which the bricks move on pallets, each containing 860 bricks. A pallet leaves the furnace every 24 min. After firing the bricks are stacked in an inventory of end products and loaded on trucks for delivery to customers.

The processes are depicted in the current state map of the company, which is shown in Fig. 1.

Through the analysis of the current map, some waste was identified in the production system of the considered company:

- High inventories, both final (900,000 bricks) and in-process (e.g., 130,000 bricks between Disintegration and Extrusion), which significantly increase the manufacturing lead time (e.g., 18 days of inventory of the final product);
- Pushed production, limiting communication between processes, contributing to an increase in inventory;
- Absence of a well-structured Production Planning and Control department, which leads to manufacturing that does not follow the demand variations;
- Unnecessary waiting time, approximately 10 % of the total working time, caused by lack of preventive maintenance.

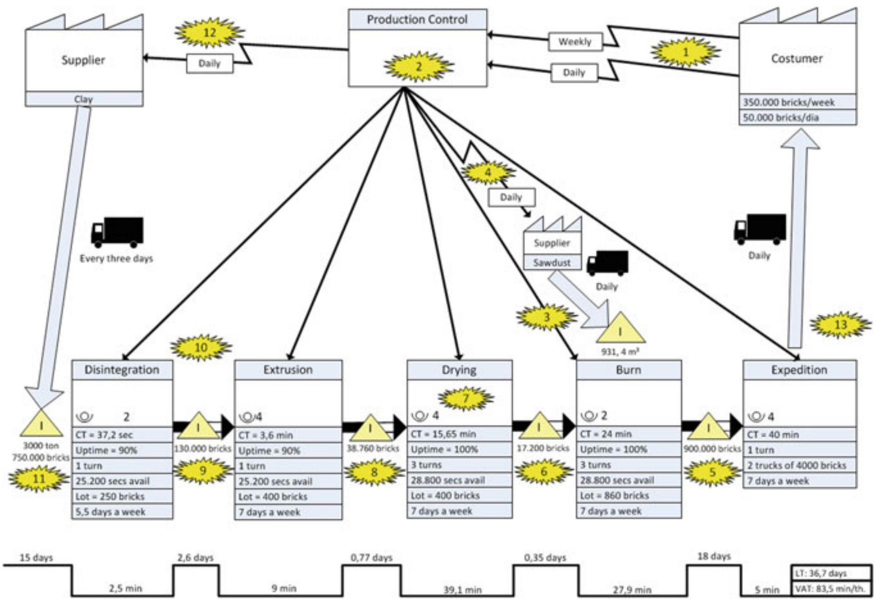


**Fig. 1** Current state map

## 5.3 *Improvement Proposals and Future State Mapping*

In order to eliminate the waste that was identified, the following improvements have been proposed:

Improvement Proposal 1: Eliminate emergency orders from the customer, asking him for at least one week in advance in order to produce a weekly schedule of sales.

Improvement Proposal 2: It is seen as necessary to create a Production Planning and Control (PPC) department, which will be responsible for preparing the weekly schedule, either through customer orders or demand forecast. The PPC also will be responsible for issuing orders for raw materials and control production to meet customer demand.

Improvement Proposal 3: With the weekly schedule completed, it is possible to issue a production order to the pulling process (i.e., Burning), so it has a target production for the current week. Therefore, all processes prior to Burning should produce to meet it.

Improvement Proposal 4: Perform a weekly schedule for sawdust orders, keeping an inventory of seven days to feed the furnace.

Improvement Proposal 5: Reduce finished goods inventory. It is proposed that production seeks to always keep an inventory of 100,000 bricks, sufficient to cover the production of the furnace in two days, without exceeding this amount.

Improvement Proposal 6: Inventory in supermarket that does not exceed 9,000 bricks, which is the required amount due to the difference in cycle time. The drying process takes longer than the burning process.

Improvement Proposal 7: Analysis of the stacking station (drying for the furnace) according to Methods Time Measurement (MTM) with an ergonomic analysis. Moreover, it would be necessary training of employees and greater production control in order to reduce the stacking time. On the future map it was established a target of 50 % reduction in stacking and 13 % of the total added-value time of the drying process.

Improvement Proposal 8: Decrease in inventory between the extrusion and drying processes to 33,000 bricks, needed to make up the difference of two shifts of both processes.

Improvement Proposal 9: Reduce inventory of benefited clay after Disintegration. Like the rest of production, disintegration must work to supply the following process, so that in the end burning meets weekly schedule. However, beyond meeting the schedule for the week, the disintegration should keep an inventory of 75,000 bricks (or 150 $m^3$), enough to meet the rest of the process on the days it does not performed.

Improvement Proposal 10: Increase the time for the processes of disintegration and extrusion through scheduling preventive maintenance on machines outside of their operation shift. These processes operate only one shift, and during 10 % of their time they are stopped so that the machines undergo maintenance.

Improvement Proposal 11: Reduce the initial inventory of raw material to meet the maximum capacity of the furnace, which is 50,000 bricks / day.

Improvement Proposal 12: Based on the sales scheduled for the week, we suggest the development of a weekly schedule also for the extraction of raw materials, removing only enough material for production to meet customer demand during that week.

Improvement Proposal 13: Create an area responsible for periodic quality control of finished products. It is frequent the occurrence of many bricks with fractures, since the company does not analyze often the composition of bricks.

Through these proposed improvements the future state map was elaborated, and it is shown in Fig. 2.

## 6 Expected Results

Both maps and suggestions of improvements were presented to the company's management so that they are implemented in the near future. It is expected that after the future map is implemented, the results listed in Table 1 will be achieved. After the goals are achieved, we suggest the development of a new map, seeking continuous improvement.

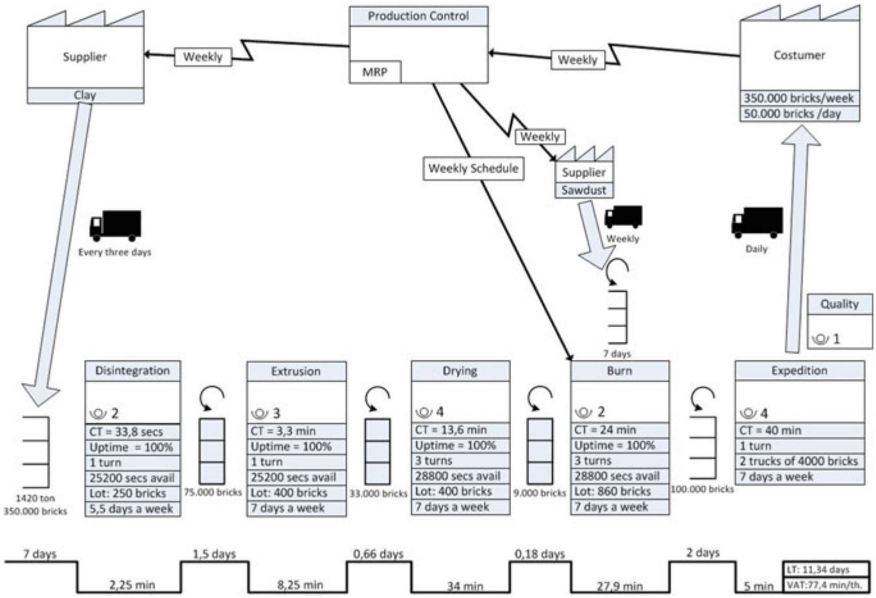


**Fig. 2** Future state map

**Table 1** Expected results after implementing the future map

| Points of improvement | Before | After | Improvement (%) |
|---|---|---|---|
| Finished product inventory | 900,000 bricks | 100,000 bricks | 89 |
| Work-in-process | 185,960 bricks | 117,000 bricks | 37 |
| Raw material inventory | 750,000 bricks | 350,000 bricks | 54 |
| Lead time | 36.7 days | 11.34 days | 69 |
| Value-added time | 83.5 min/thousand bricks | 77.4 min/thousand bricks | 7 |

## 7 Conclusion

Lean Production, regardless of the industry in which it was introduced, should be applied to generate productivity for the organization and, above all, generate customer value. This study sought to show the company the waste that inventory and practices related to customers may cause. The main change is that the company should think its manufacture according to the customer, producing according to what the customer asks, thereby reducing inventories.

The VSM tool allows the visualization of waste by both researchers and the company. The map also allows an appropriate choice of other methods of Lean

Production to be applied to the production process, and the consequences brought by the implementation.

The application of lean production is complex and time consuming, requiring changes in the company culture, persistence of managers, and employee awareness in favor of lean thinking. These factors caused difficulties in obtaining the necessary data for the construction of the value stream maps presented in this paper.

It is important that data collection is well structured, and such structure should result from knowledge of the production process. Frequent conversations with the administration during the processes of data collection and map construction are also important.

As can be seen in the expected gains shown in Table 1 (e.g., 89 % improvement in finished product inventory), the application of VSM in a ceramics company is of great value. Since few companies in the ceramic sector apply Lean Production, this is considered an important contribution of this paper. Thus, although the future state map has not been yet implemented in the company considered in this study, it is expected that after the implementation of the future state map, the improvements shown in Table 1 can lead the company to an even greater amount of sold products in a very competitive market.

After implementing the proposed future map in the company, a future work will be the construction of a new future map, seeking continuous improvement.

## References

1. FIESC (2012) Santa Catarina in data. Florianópolis, Brazil (in Portuguese)
2. Mafra AT (1999) Proposed performance indicators for the red ceramic industry. M.Sc. Dissertation (Production Engineering), Universidade Federal de Santa Catarina, Florianópolis, Brazil (in Portuguese)
3. Ohno TO (1988) Toyota production system: beyond large-scale production. Productivity Press, 1st edn
4. Salgado EG, Mello CHP, da Silva CES, Oliveira ES, de Almeida DA (2009) Analysis of the application of value stream mapping to identify waste in the product development process. Gestão Produção 16(3):344–356 (in Portuguese)
5. Rother M, Shook J (1999) Learning to see—value stream mapping to add value and eliminate MUDA. Lean Enterprise Institute, Brookline
6. Womack JP, Jones DT (2003) Lean thinking: banish waste and create wealth in your corporation. Free Press, New York
7. Salgado EG (2008) Investigation of waste in the process of product development through the lean manufacturing approach. M.Sc. Dissertation (Production Engineering), Universidade Federal de Itajubá, Itajubá, Brazil (in Portuguese)
8. Shingo S (1989) Study of the Toyota production system: from an industrial engineering viewpoint. Productivity Press
9. Ferro JR (2007) The essence of the value stream mapping tool. Lean Institute, Brasil (in Portuguese)
10. Rentes AF, da Silva AL, Silva VCO, de Castro SA (2003) Applying the concepts of lean production in a shoe company: a case study. In: SIMPEP, Bauru, Brazil (in Portuguese)

11. Moraes MN, Arpini BP, Scardua RF, Cha FUS (2011) Using value stream mapping to identify waste: a case study in a clothing company. In: Encontro Nacional de Engenharia de Produção, Belo Horizonte, Brazil (in Portuguese)
12. Fernandes JM, Pereira AL, Dionízio AC, Nereu MR, Marques MAR (2011) Analysis of the feasibility for the implementation of lean manufacturing in a tests pilot plant in refractories. In: Encontro Nacional de Engenharia de Produção, Belo Horizonte, Brazil (in Portuguese)
13. Lima MLSC, Zavislak PA (2003) Lean production as a differential factor in the supply capacity of SMEs. Revista Produção 3(2):57–69 (in Portuguese)

# Specific Strategies for Successful Lean Development Implementation

**Uwe Dombrowski, David Ebentreich and Kai Schmidtchen**

**Abstract** Due to globalization, enterprises face an increasing competition that influences their strategy. To achieve a sustainable market position, enterprises have to differ from their competitors through cost or performance advantages. Both competitive advantages are linked to decisions in product development. Therefore enterprises start to initiate optimization efforts in product development. In production, enterprises achieve positive results by implementing lean production systems (LPS) to optimize their production processes. The aim of LPS is the reduction of waste and the implementation of a continuous improvement process to assure sustainable success. Due to the positive results, enterprises intend to apply the lean approach also in product development (lean development). Enterprises that want to implement lean development (LD) are faced with many different concepts and strategies for the implementation. To analyze the different concepts, criteria for an implementation process need to be identified. For that reason, the article analyzes LD-concepts regarding these implementation criteria and describes the agreements between the different concepts. Thereby, enterprises can develop a strategy for LD implementation. Based on the implementation criteria, a study was carried out among enterprises that want to establish a lean development system. The study identified which specific strategies for implementation was preferred by the enterprises.

## 1 Introduction

Global competition and increasing customer requirements challenge manufacturing enterprises to increase both, productivity and flexibility at the same time. In production many enterprises have already reacted by implementing lean

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production systems similar to the Toyota production system [1]. Changes of the economic environment not only influence production but all divisions of an enterprise. Especially product development is focusing on optimization measures. Therefore, enterprises have increased their efforts to find and implement concepts to improve efficiency and effectiveness of product development [2]. Transferring the principles of lean thinking to the process of product development is a promising approach, following referred to as lean development (LD). Toyota, the leading enterprise in the automobile sector, is working with LD-principles in the development, summarized in the Toyota product development system (TPDS). Toyota is able to develop automobiles in less time and better quality than North American or European manufacturers [3]. Also the spending on research and development is on a lower level, in relation to the turnover. Enterprises, which want to follow the example of Toyota, are challenged to develop enterprise-specific LD-concepts and suitable ways for their implementation. Especially the implementation of holistic LD-concepts involves numerous obstacles and difficulties which many enterprises have already experienced during the implementation of lean systems [4].

Due to the differences between production and product development, it is to be noted that the methods and tools of lean production cannot be transferred directly to product development [5]. While the main focus in production lies on physical processes, in product development most processes are of cognitive nature. Furthermore, the process times of Product development (weeks, months) and production (seconds, minutes) differ significantly and while there are mostly repetitive operations in production most of the activities in product development are unique operations with no certain process result [4]. When implementing LD-concepts the different framework conditions have to be taken into consideration.

## 2 Methodology

On the one hand LD implementation holds great potential on the other hand it confronts enterprises with the challenge to develop an appropriate strategy to do so. The following article has the objective to analyze the LD-concepts described in literature and to identify the consensus regarding implementation specifics. Furthermore, this paper will highlight the aspects on which there is no consensus or which have not been explored enough yet. Thereby the current state of knowledge about LD implementation will be clarified by the systematic examination of consensus and dissent.

Hence, criteria need to be defined to evaluate existing LD implementation concepts. Subsequently, the LD-concepts will be evaluated towards the fulfillment of the criteria. In addition, experts were questioned to estimate the importance of the criteria for a successful LD implementation. Thirteen experts of different sized enterprises and industries, which have been dealing with the implementation of

Lean Development for several years, participated at the study. Therefore, the results are not limited for a specific enterprise size or industry. An analysis for each criterion summarizes the results in order to determine whether there is a primarily consensus or dissent.

## 3 Criteria for Implementation

For a successful LD implementation enterprises have to consider different aspects like the organization, change management, the sequence of LD-elements or the scope. These criteria have to be defined for a sustainable implementation [6], also described in VDI 2870 [1]. To analyze the LD concepts the criteria are described in detail in the following.

The **organization of the implementation** determines which level of the organizational structure manages the LD implementation and therefore demonstrates the priority within the enterprise. According to Wildemann and Baumgärtner [7] there are several alternatives as shown in Fig. 1. The first possibility is the implementation in direct responsibility so that the management has the responsibility for the implementation and for the everyday business at once. In a staff guided implementation a project leader has the responsibility for guiding the implementation. In a champion supported organization, selected employees are educated to support the lean implementation within the plant or department. In contrast, using a task force for the implementation is a possibility to share the responsibility of everyday business and LD implementation [7].

The LD implementation is more than a rationalization project. As the participation of the employees is a main factor for a sustainable implementation, it is important to involve and motivate the employees [8]. Moreover, the leadership has to set rules for the change and enables the employees to achieve the needed transformation (**change management**).

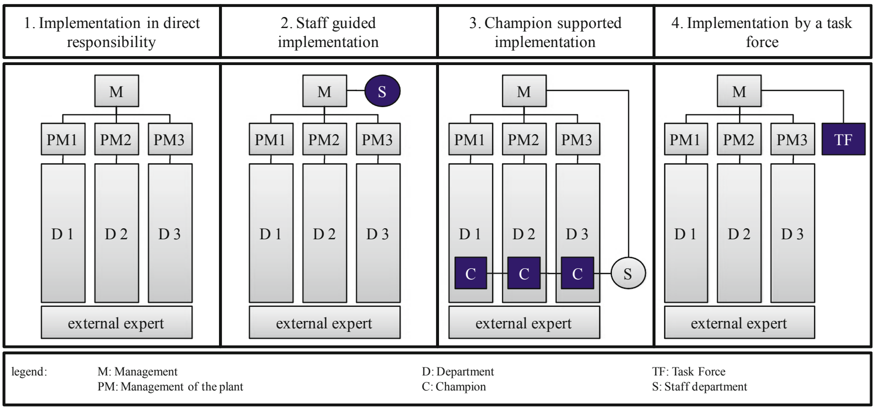


**Fig. 1** Organization of the implementation [7]

The **sequence of the implementation** describes which principles, methods and tools and in which order they will be implemented. To identify the convenient methods and tools, a problem-based approach could be used. In contrast, another possibility is a defined order for the implementation. This might be appropriate if the LD-methods and tools are based on each other [9].

The **scope for implementation** describes the organizational departments in which the LD concept will be implemented. So it is possible to implement the concept in all affected departments simultaneously or a successive implementation after a predetermined order, e.g., starting with a pilot project.

On the basis of the four defined criteria, which are significant for a sustainable implementation, the following LD concepts will be analyzed. Besides the presented criteria the VDI 2870 [1] describes that within the implementation of lean the change of the corporate culture, which is reflected by the basic convictions, values, and attitude of the employees, as well as the changes in management have to be considered. However, this paper is first of all addressed to enterprises which already possess experience with lean in production. The need for cultural change and management style should have been previously recognized throughout the enterprise so that the change has already started. Therefore, these aspects are neglected in this article.

## 4 Analysis of the Concepts

The analysis examines nine relevant LD implementation concepts, which were published in the past 10 years. The results of the analysis are summarized in Table 1.

**Table 1** Analysis of LD-concepts

| criteria / lean development concepts | organization of the implementation | | | | change management | | sequence of the implementation | | scope for implementation | |
|---|---|---|---|---|---|---|---|---|---|---|
| | implementation in direct responsibility | staff guided implementation | implementation by a task-force | Champion supported implementation | standards for employee participation | rules for leadership | defined order for the implementation | problem oriented approach | implementation with a pilot project | implementation in all affected units simultaneously |
| 1. Kennedy, 2003 [10] | | | ● | | ○ | ● | | ● | ● | |
| 2. Haque und James-Moore, 2004 [11] | | | | ● | | | ● | | ● | |
| 3. Cooper und Edgett, 2005 [12] | | | ● | | | | | ● | | |
| 4. Fiore, 2005 [13] | | | ● | | ● | ● | | ● | ○ | |
| 5. Morgan und Liker, 2006 [3] | | | | ● | ○ | ○ | ● | | ● | |
| 6. Mascitelli, 2007 [14] | | | | | | | | ● | ○ | |
| 7. Ward, 2007 [15] | ○ | | | | ○ | ● | | ● | ○ | |
| 8. Schuh et al., 2006-2011 [16], [17] | | | | ● | ○ | ○ | | ● | ● | |
| 9. Sehested und Sonnenberg, 2011 [8] | ○ | | | ○ | | ○ | ○ | ○ | ○ | ○ |

legend: ● recommended ○ suggested

*Legend* ● Recommended ○ Suggested

### 4.1 Product Development for the Lean Enterprise

In the first step the LD implementation should be organized by a core team which will be expanded by an integration team after the decision for the LD implementation. Afterwards the implementation team will train numerous employees. Information about the change management will be given to motivate the employees and to ensure a successful change. By doing so the urgency and the importance of the LD implementation shall be illustrated by the management. As an implementation side Kennedy [10] recommends to start the LD implementation in a pilot project followed by an enterprise-wide rollout. Regarding the implementation elements Kennedy does not suggest an order. Instead he advises to analyze the level of transformation and to convey customized measures.

### 4.2 Applying Lean Thinking to New Product Introduction

In their concept Haque and James-Moore [11] focus on applying the general lean principles in product development. Practical application for LD implementation can be found in the case studies. It is indicated that experts should be trained (organization) to carry out the implementation in the different departments (scope of implementation). Regarding the implementation elements it is advised to start with the 5S method followed by establishing the seven types of waste concept. Afterwards visual management and standardization as well as the implementation of the process of continual improvement are recommended. Change management is not further addressed by Haque and James-Moore.

### 4.3 Lean, Rapid, and Profitable New Product Development

Cooper and Edgett [12] advise that for LD implementation a task force should be created (organization). An order is not suggested for the implementation elements but a problem-based approach is proposed. That means that the level of implementation should be analyzed and customized measures should be conveyed. The scope of implementation and change management are not further mentioned.

### 4.4 Accelerated Product Development

As a preparation for the implementation Fiore [13] describes that a kick-off-event where a discovery team is formed (organization) should be arranged. The discovery team's assignment is to carry out the LD implementation. A problem-based approach is described for the implementation elements as well. As additional advice Fiore proposes that the derived measures should be implemented one after another and that it should start with the 5S method. Moreover, Fiore describes the change management within the implementation. In a detailed stage plan the operations and measures for the implementation are defined, e.g., the duties of the discovery team's management and employees should be fixed in a contract. It is also mentioned that the implementation can be done independent from the implementation departments.

### 4.5 The Toyota Product Development System

For the implementation process the authors Morgan and Liker [3] developed a five point stage plan, which measures the management behavior and the employee participation. Furthermore, it describes the measures for the implementation (change management). Advice is given on the preparation of the LD implementation as well as on the procedure of workshops. The stage plan also describes further implementation elements. Methods like value stream planning for product development and A3 should be used in the first phase. Methods which are more complex and extensive to implement, i.e., chief engineering or digital prototyping, should be introduced later in the process. Though, an exact classification of the methods is not carried out. As an implementation side the authors advice to start with pilot sites for a time span of approximately 1 year. Furthermore, it is advised to install a change agent together with a lean steering team. The change agent is responsible for the organization of the implementation and is supported by external champions.

### 4.6 The Lean Product Development Guidebook

Mascitelli [14] describes the approach of LD implementation rather briefly. The author recommends a problem-based approach for the implementation of the LD-elements and to start with a showcase focusing on selected LD-elements. As soon as success is confirmed the next element is implemented. The remaining criteria are not being discussed further.

### 4.7 Lean Product and Process Development

In his book Ward [15] concentrates on the general design of LD. The LD implementation is only mentioned shortly. Regarding the organization of the implementation Ward suggests integrating employees which are dissatisfied with the current situation. Further advice is given on the general design of the change process (change management): The support of the LD implementation by a strong commitment of the management is favored and opportunities for knowledge exchange should be established as well. The remaining criteria are not being discussed further.

### *4.8 Lean Innovation*

Schittny and Lenders [16] and Schuh [17] advise to start with an audit which analyzes the enterprise regarding the implementation of lean development. This should lead to an action plan for the implementation of the elements such as value stream analysis or the 5S method in a pilot unit (implementation scope). The alignment of the goals and the framework as well as their implementation measures should be developed in close cooperation with the employees (change management). The audit takes place in form of a workshop (organization).

### *4.9 Lean Innovation*

Depending on the implementation element and the implementation scope Sehested and Sonnenberg [8] provide four different implementation strategies (Big-bang, Domino, Cascade, and Small-steps). In Big-bang- and Cascade-implementation LD will be established in all divisions at the same time. In the Cascade-implementation only a few elements are applied while in the Big-bang-implementation all elements are applied at once. In the Domino-implementation all elements are applied simultaneously as well but not in all divisions at once. In the fourth strategy, the Small-steps-implementation only a few elements are applied in a few divisions. The strategy should be chosen depending on the organizational structure, purpose, goals, skills, and experience. Furthermore, the authors shortly describe the change management. They suggest considering the ideas of the employees regarding the LD implementation to reinforce their motivation. For the organization of the implementation it is advised to involve customers as well as the management.

### *4.10 Results of the Expert Survey*

Along the examination of the relevant literature regarding LD a survey among experts has been conducted. The participants of the survey were questioned about the identified criteria of LD implementation. Within the survey 13 enterprises participated, which have been dealing with the implementation of Lean Development for several years.

At first the survey focussed on the analysis of the optimal sequence of implementation. 77 % of the respondents stated that a problem-based approach should be used for implementation. On the other hand only 23 % of the respondents said that a fixed order is expedient. Accordingly, none of the respondents regards a decentralized fixed order, set by the respective department, as useful.

Three essential issues need to be considered when using a problem-based approach for implementation. At first an identification of problems needs to be executed. Based on those results measures which need to be performed must be deduced. If multiple measures have been identified, the measures need to be prioritized. In order to gain a more detailed analysis of the success factors those participants were interviewed further, who responded that they use a problem-based approach for implementation. All of the respondents stated that the identification of problems is conducted by the respective departments. Different approaches exist on how to identify problems. 80 % of the enterprises believe that analytical methods (e.g., value stream methods) are suitable. Auditing by means of a maturity model or stage model is rated as useful by 70 %. The problem identification through key figures is regarded to be expedient by 40 % of the enterprises and only 20 % think a subjective identification of problems in the departments is useful.

The enterprises stated that the derivation of measures, similar to the problem identification, is to 100 % task of the particular departments. 90 % of the enterprises declare that single LD-methods (e.g., value stream design) are being used to deduce measures and the desired state. Only 10 % of the enterprises use subjective estimations to derive measures. The derivation of measures through a maturity or stage model is exercised in 50 % of the enterprises and 30 % know approximately how their key figures and the respective measures correlate.

A decentralized prioritization with participation of employees is considered useful by 67 % of the respondents. In contrast 23 % of the respondents state this should be done centralized by the management. Furthermore, 80 % of the enterprises stressed that first those measures should be introduced, which possess the highest cost-benefit ratio. The sustainable implementation of single prioritized LD-methods ("core methods") and subsequently further methods is regarded as beneficial by 30 %. The theme-orientated implementation as well as a coherent level of all LD-methods during the implementation is being advised by 10 % of the enterprises.

The analysis of the optimal implementation is followed by the consideration of the proper organizational form. With 67 % the champion-supported implementation is the highest ranked form of organization. None of the questioned enterprises regards the implementation in form of project teams or task forces as expedient. The self-reliant implementation is assessed with 25 % and the staff guided implementation with 8 %.

Conclusively, an analysis was conducted about which department is best suited to begin with the LD implementation. Half of the questioned 13 enterprises (54 %) stated the implementation should start in a pilot department. A pilot project for the start of an implementation is recommended of 38 %. On the other hand only 8 %

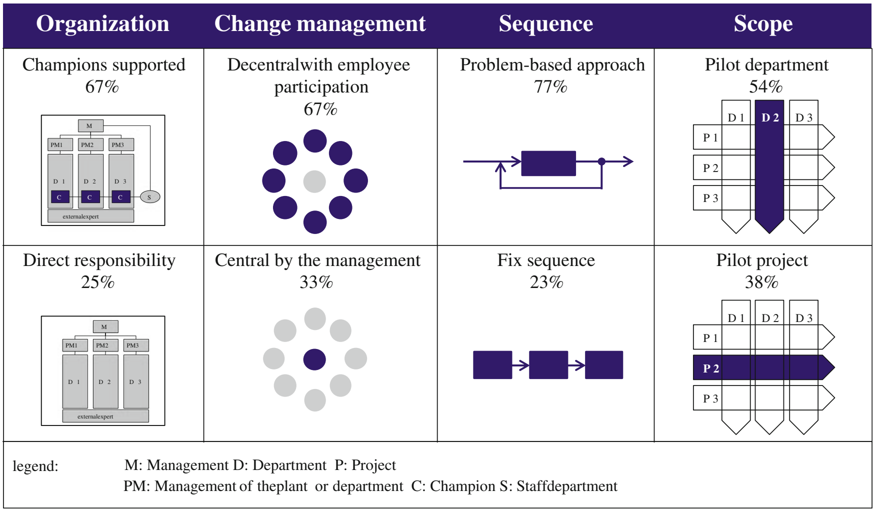


**Fig. 2** Results of the expert survey

agreed that the implementation should start in all departments and projects at the same time (Fig. 2).

## 5 Summary of the Results

In the following the most important consensus for each criterion will be summarized. Regarding the organization of the implementation several authors suggest to establish a task force [10, 12, 13]. The project team is supposed to lead the concept development in the early stages and is responsible for the implementation. The project team should report directly to the management and should be assisted by external experts if necessary. Within the organization the project team should be expanded after the LD-concept development and a kick-off-event. The expanded project team should organize workshops, process improvements, and trainings. The further the implementation progresses the more the expanded project team should be integrated into the original organizational structure, in order to prevent that the LD implementation is seen just as a limited project [8, 13]. Aside the task force option, champion supported implementation is mentioned several times [3, 11, 16, 17]. Equally, the results of the expert survey recommend the champion supported implementation (67 %). In this case champions are trained on the LD contents and installed in the different departments. Tasks like workshops, process improvements, and trainings are carried out by each division on their own. The coordination of the champions is organized by a staff department.

In terms of change management most authors only mention that it is important to involve and motivate the employees and managers. Further, there is an agreement that it is the responsibility of the management to involve and motivate the employees [10, 13, 15]. So it is essential to comply with agreements, to clarify the importance of the LD implementation and to strongly consider the employees ideas [13]. In the same way, the participants of the survey recommend employee participation by making decentralized decisions.

For the sequence of the LD-elements implementation a problem-based approach without a clarified order of the elements is advised by Kennedy [10], Cooper and Edgett [12], Fiore [13], Mascitelli [14], and Schittny and Lenders [16], and Schuh [17]. The level of implementation of the LD-elements should be identified by an audit [16]. Measures to improve the LD-elements implementation should be designed based on the results of the audit. Also the participants of the survey suggest the problem-based approach. An appropriate method for this approach is the value stream analysis, which is mentioned by the participants.

Other authors like Haque and James-Moore [11] as well as Morgan and Liker [3] indicate that it is wise to start with elements that are not complex and can be implemented with little effort (i.e., 5S, A3, and value stream analysis). Complex LD-elements such as sustained transcribed ongoing improvement process or a chief-engineer-system should be implemented afterwards. An evaluation regarding the complexity or implementation effort as well as an implementation order for the LD-elements is not given by any of the authors.

A special position is presented by the four implementation strategies by Sehested and Sonnenberg [8]. They describe different combinations of implementation elements and departments, but it is not clarified how to choose the right strategy depending on the organizational structure, purpose, goals, skills, and experience.

Regarding the implementation department nearly all authors suggest to start with a pilot project and roll out the LD to other divisions afterwards. A more detailed description of the suited implementation department is given by Sehested and Sonnenberg [8] for the different implementation strategies. Which implementation department in the product development process suits the most as a pilot side is not clarified by any of the authors.

## 6 Conclusion

As a reaction on global competition and the increasing customer requirements, enterprises increasingly try to improve efficiency and effectiveness in product development by developing new concepts. Through analysis and summarization of existing LD implementation strategies it has been derived systematically where there are consensus and disagreement and which aspects have not been taken into consideration yet. Regarding the organization of the implementation it can be seen that two alternatives (task force or champion supported implementation) emerge. An implementation in self-responsibility or a staff based implementation is not recommended explicitly. Only little concrete information is being given regarding change management. For the criteria implementation elements and implementation department there are clearer results. A problem-based approach is preferred over a fixed order by most of the authors and also nearly all authors recommend to start with a pilot department. None of the analyzed LD-concepts recommends a simultaneous implementation of all elements.

In further research activities, empirical analysis could be carried out within the industry to identify the ideal LD implementation strategy. Moreover, the LD implementation strategies have to be analyzed regarding different industries or different sizes of the enterprises. It is conceivable that small and medium sized enterprises have to choose other strategies than the recommended strategies.

## References

1. VDI 2870 (2012) Lean production systems, original citation. Ganzheitliche Produktionssysteme, Beuth Verlag
2. Dombrowski U, Zahn T (2011) Design of a lean development framework. IEEM Conference
3. Morgan JM, Liker JK (2006) The Toyota product development system, integrating people, process, and technology. Productivity Press, New York
4. Dombrowski U, Zahn T, Schulze S (2011) State of the art: lean development. CIRP Design Conference
5. Dombrowski U, Ebentreich D, Schmidtchen K (2011) Systematic approach to adopt LPS principles in product development. In: Proceedings of 22nd international conference on flexible automation and intelligent manufacturing, Helsinki, FI, pp 901–908
6. Daniel A (2001) Management of implementation—practical design options, original citation: Implementierungsmanagement: Ein anwendungsorientierter Gestaltungsansatz. Gabler Verlag, Wiesbaden
7. Wildemann H, Baumgärtner G (2006) Finding your own way: individual implementation concepts for a lean production system, original citation: Suche nach dem eigenen Weg: Individuelle Einführungskonzepte für schlanke Produktionssysteme. ZWF 101(10):546–552
8. Sehested C, Sonnenberg H (2011) Lean Innovation. Springer, Berlin
9. Hoppmann J (2012) The lean innovation roadmap. Diploma thesis, Online: http://lean.mit.edu/, 2009. (Accessed 14 Dec 2012)
10. Kennedy MN (2003) Product development for the lean enterprise. Oaklea Press, Richmond
11. Haque B, James-Moore M (2004) Applying lean thinking to new product introduction. J Eng Des 15(1):1–32
12. Cooper R, Edgett SJ (2005) Lean, rapid and profitable: new product development. Product Development Institute, Ancaster
13. Fiore C (2005) Accelerated product development. Productivity Press, New York
14. Mascitelli R (2007) The lean product development guidebook. Technology Perspectives, Northridge
15. Ward AC (2007) Lean product and process development. The Lean Enterprise Institute, Cambridge
16. Schittny SU, Lenders M (2010) Am I lean or do I still administrate?—Lean Innovation audit, original citation: Bin ich schon Lean oder verwalte ich noch?—lean innovation-audit. Complexity Manag J 2:10–13
17. Schuh G (2006) Success factor Lean Innovation: initiate a change process within producing companies, original citation: Erfolgsfaktor Lean Innovation—Initiierung eines Veränderungsprozesses bei produzierenden Unternehmen. In: Schuh G, Wiegand B (pub.): 3. Lean Management Summit—Aachener Management Tage, WZL, Aachen

# Adaptation of Lean in the Wood Industry

**Urs Buehlmann, Omar Espinoza and Christian Fricke**

**Abstract** The U.S. wood products (NAICS 321) and furniture manufacturing (NAICS 337) industries have been greatly affected by economic cycles, rising production, and transportation costs, changing buyer habits, and, arguably, most powerfully, increasing global competition. Tens of thousands of jobs were lost and a large number of companies in the industry experienced bankruptcy, closed operations, or relocated to other countries. However, theories exist stating that the use of management systems, such as Lean management, allows companies to become more competitive and enhance the likelihood of survival. To investigate Lean management practices in the wood products and furniture manufacturing industry, a census survey with all known members of these two industry sectors in the Commonwealth of Virginia was conducted. Findings indicate that a majority of Virginia's wood products and furniture manufacturing industries have heard about Lean, but few enterprises have implemented or have started to implement Lean principles in their operations.

## 1 Introduction

Manufacturing industries in the U.S. have been greatly affected by economic cycles [1, 2], rising transportation costs [3, 4], changing buyer habits [5], and increasing global competition over the last decades [6–8], Virginia's wood

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products (NAICS 321), and furniture manufacturing (NAICS 337) industries among them. For example, the non-upholstered wood household furniture sector (NAICS 337122) has seen the market share of imported products soar from 19 % in 1992 to 64 % in 2008 [6]. Mainly producers in Southeast Asia, thanks to favorable production economics, were able to displace one of the most historic U.S. industries [6, 8–10]. The decline of U.S. furniture manufacturing has impacted the entire wood products value chain, with suppliers loosing domestic customers [6, 11, 12] and as a result, employment in the U.S. wood products and furniture manufacturing industries decreasing by almost 108,000 between 2002 and 2007 [13, 14].

In response to these challenges, the U.S. wood products and furniture manufacturing industry has undertaken serious efforts to find remedies for the ongoing loss of competitiveness. One idea is to employ Lean management methods to improve the efficiency and effectiveness of the industry's operations [6, 8] as Lean management has proven effective in helping companies across different industries to improve their organizational performance [15–17].

Lean management, originally derived from Toyota's Production System (TPS) and first discussed in Womack et al.'s book "The Machine that Changed the World [18]," focuses on creating customer value without waste [17]. The book, stemming from research conducted by the International Motor Vehicle Program (IMVP) and funded by the U.S. Federal Government revealed that Japanese car manufacturers need less human effort and time, less space, and less average inventory to manufacture products of higher quality containing higher value for the customer [18]. Thus, based on Womack et al.'s [18] premise, Lean companies are more effective and efficient than companies that do not apply Lean principles and thus, Lean companies are more competitive and profitable.

Lean has gained a group of highly skilled and devoted followers in the wood products (NAICS 321) and furniture manufacturing (NAICS 337) industry. In fact, several industry participants successfully transformed their operations through the application of Lean. Some reaped the Shingo Price for Operational Excellence in Manufacturing (the highest such award handed out annually to world class manufacturing companies in the U.S. [19]), for their efforts [20–22]. However, case studies of actual Lean implementation efforts in the wood products and furniture manufacturing industry are rare, making it difficult to assess the level of Lean awareness and the status of Lean implementation efforts in the industry beyond the few published examples. Pirraglia et al. [9] indicated that the U.S. wood products and furniture manufacturing industries have been slow in adapting the Lean management approach compared with other industries. Interestingly, this is despite a belief that Lean management may help improve company competitiveness and reduce the loss of jobs to locations overseas [8, 9].

The objective of this research was to gain an overview of Lean management practices in the wood products (NAICS 321) and furniture manufacturing (NAICS 337) industry in the Commonwealth of Virginia. Particularly, the three areas of interest were: Lean awareness, Lean implementation status, and the need for support in Lean implementation. The following hypotheses were tested:

**Lean Awareness**

$H1_0$: "The majority of wood products (NAICS 321) and furniture manufacturing (NAICS 337) industries in the Commonwealth of Virginia are not aware of Lean."

**Lean Implementation**

$H2_0$: "The majority of wood products (NAICS 321) and furniture manufacturing (NAICS 337) industries in the Commonwealth of Virginia have not implemented Lean."

**Need for Support**

$H3_0$: "The majority of the wood products (NAICS 321) and furniture manufacturing (NAICS 337) industry in the Commonwealth of Virginia does not need support for their Lean implementation."

## 2 Methodology

A mail questionnaire was chosen as the method of choice for this study. Mail surveys are commonly used to obtain data to make inferences about a population's characteristics. For this purpose, measurements need to be taken from a randomly selected sample of the population [23, 24]. To be able to draw meaningful conclusions from the survey, proper survey design is of high importance [24, 25].

### *2.1 Survey Population*

The population of interest for this study consisted of all companies operating in the wood products (NAICS 321) and furniture manufacturing (NAICS 337) industry in the Commonwealth of Virginia. According to the U.S. Census [13], wood products manufacturing (NAICS 321) includes companies categorized in "sawmills and wood preservation (NAICS 32111)", "veneer, plywood, and engineered wood product manufacturing (NAICS 32121)" including trusses, "millwork (NAICS 32191)" including windows, doors, and flooring, "wood container and pallet manufacturing (NAICS 32192)", and "all other wood product manufacturing (NAICS 32199)" including manufactured and prefabricated homes [13]. Furniture manufacturing (NAICS 337) includes companies categorized in "wood kitchen cabinet and countertop manufacturing (NAICS 33711)", "household and institutional furniture manufacturing (NAICS 33712)", "office furniture (including fixtures) manufacturing (NAICS 33721)", and "blind and shade manufacturing (NAICS 33792)" [14]. According to the Quarterly Census of Employment and Wages [26] the total number of establishments in the Commonwealth of Virginia in these industries in 2009 was 1,033 (513 establishments in wood products manufacturing (NAICS 321) and 520 establishments in furniture manufacturing (NAICS 337).

Due to a lack of a state-wide address list of the companies of interest, addresses were collected from: Manta's online business listings [27], the 2009 Virginia industrial directory [28], the manufacturer index of the Wood Products Manufacturers Association [29], and the members list of the Architectural Woodwork Institute [30]. After correcting for surveys that could not be delivered, companies out of business, or companies that were not involved in wood products (NAICS 321) or furniture manufacturing (NAICS 337) the final sample size for this survey was 1,193, which was used for a Census survey [25, 30].

## 2.2 Questionnaire Design

A mail questionnaire directed at wood products manufacturing (NAICS 321) and furniture manufacturing (NAICS 337) companies in the Commonwealth of Virginia was developed. The first part consisted of nine questions to gather basic demographic company information regarding NAICS classification, company size, and the membership of employees in unions. The second part asked questions regarding the company's Lean practices. This included questions about Lean awareness, implementation status of Lean, and Lean improvement success. The third part asked questions assessing the respondents' need for support regarding Lean transformations, while the fourth part consisted of product and market-related questions. Two types of questions were used, namely (1) categorical and (2) open-ended [24, 31, 32].

In this study, to evaluate the level of Lean awareness and implementation, a set of common Lean elements listed in Table 1 were used as proxies [10, 33, 34]. Twenty-nine Lean elements categorized in four categories (4P's–philosophy, process, people, and problem solving) established by Liker [34] were used (Table 1).

Kirby and Greene [34] found a direct positive relationship between the number of Lean elements (Table 1) implemented and the level of an organization's Lean maturity. They defined five maturity levels from level one with companies starting Lean but not having fully implemented the entire set of Lean tools, to level five having extensively implemented and making full use of the entire set of tools. It was found that the number of implemented Lean tools increased between maturity levels one to four. By level four, however, the entire set of Lean tools was implemented so that between levels four and five the only distinction in Lean maturity could be made through the evaluation of the intensity the Lean tools were implemented. Based on the available publications [9, 10] and personal observations, the research team expected the level of Lean implementation to be low among Virginia's wood products and furniture manufacturing companies, and thus the survey only focused on the patterns of Lean maturity from level one to level four without considering the differences in usage intensity between levels four and five.

**Table 1** Twenty-nine Lean elements (Liker 2003) used as proxies to establish Lean awareness and Lean implementation status in companies surveyed

| 4P's | Lean elements |
|---|---|
| Philosophy | Vision statement |
| | Mission statement |
| Process | Value stream mapping |
| | Takt time |
| | Pull system |
| | Supermarket replenishment system |
| | Just-in-time |
| | One-piece-flow |
| | Kanban-system |
| | Standard work |
| | Standardized work sheet |
| | Leveling production and schedules (Heijunka) |
| | Single minute exchange of die (SMED) |
| | Error proofing (Poka Yoke) |
| | Visual Management |
| | Notification system for quality and process problems (Andon) |
| People | Training shop floor employees |
| | Training administrative employees |
| | Training operational management |
| | Training executives |
| | Shop floor employee cross-training |
| | Shop floor employee skills matrix |
| Problem solving | Continuous improvement (Kaizen) events |
| | Root cause analysis (Fish bone diagram) |
| | 5-why-analysis |
| | Plan-do-check-act (PDCA)-Cycle |
| | A3-report |
| | 5S method |
| | Go to where the problem is and see (Genchi genbutsu) |

A draft questionnaire was reviewed by faculty of Virginia Tech and feedback was obtained from industry specialists at the USDA Forest Service and the Lean Management Institute, Netherlands. After incorporating several useful suggestions, a pretest mailing was conducted. A sample group of 25 addresses was randomly selected from the address list to test the questionnaire for clarity, comprehensiveness, and acceptability [24]. The pretest mail questionnaire was addressed to corporate-level decision makers in the wood products manufacturing (NAICS 321) and furniture manufacturing (NAICS 337) industry in the Commonwealth of Virginia. Each mailing consisted of a personalized cover letter, a mail questionnaire including a unique tracking number, and a first-class postage pre-paid return envelope. Seven responses were received. The responses were analyzed and minor changes were made to the mail questionnaire to address issues and to increase clarity [24].

## 2.3 Data Collection

The first mail questionnaire to the entire address list was mailed in July 2010 and was addressed to corporate-level decision makers in the wood products manufacturing (NAICS 321) and furniture manufacturing (NAICS 337) industry. Each questionnaire, contained a personalized cover letter, a questionnaire including a unique tracking number for accurate response monitoring and a first-class, pre-paid return envelope [24, 35]. To increase the response rate, the cover letter, and the questionnaire, were printed on colored paper [24]. A reminder postcard, a second questionnaire including a unique tracking number for accurate response monitoring and a first-class, pre-paid return envelope, as well as a second reminder postcard were sent out to all non-respondents one, four, and seven weeks after the first mailing, respectively. Ten weeks after the original mailing of the first questionnaire, thirty non-respondents were contacted by telephone and fax and asked three demographic questions. Two demographic questions asked which industry segment the respondent's company belongs to and how many employees work currently in the respondent's company. Additionally, one question asked if the respondents have "…Heard of the following terms: Lean Management, Lean Production, Lean Manufacturing, Toyota Production System, and Lean Thinking." Responses from these thirty non-respondents were used in the determination of non-response bias [24, 25]. All data was entered into a coded MS Excel data analysis spreadsheet [36].

## 2.4 Data Analysis

The data obtained was coded according to tracking number, date received, categorical data, and open-ended responses. The coded spreadsheet was then uploaded to JMP 8.0 statistical software [37] for statistical analysis, such as frequency distributions, contingency tables, and descriptive statistics [24, 25]. Survey data from questions pertaining to industry demographics, market structure, and Lean practices were tested using non-parametric statistics. Non-response bias was tested using the responses from the 30 of the 1,005 non-respondents who were randomly selected and contacted via telephone and fax [24]. Results of the non-response data collection were analyzed using Fisher's exact test to account for potential small sample sizes [23]. No significant ($\alpha = 0.05$) differences between the respondents and non-respondents were found ($p$ values 0.90, 0.19, and 0.67, respectively, for Fisher's exact test).

## 2.5 Definitions

The following definitions for measuring Lean awareness, Lean implementation status, and the need for Lean implementation support were used in this study. Survey participants were considered "aware of Lean" if at least one of five Lean terms Lean Management, Lean Manufacturing, Lean Production, Lean Thinking, or Toyota Production System (TPS) listed in the survey questionnaire was answered affirmative to the question "Have you heard of the following terms (check all that apply)?"

The participants' Lean implementation status was also tested using the 29 Lean elements. If a respondent was indicating that his company is using at least one of the 29 Lean elements, the respondent's company was considered as working on or having "implemented Lean". Additional insights on respondents' Lean implementation status were gained from the analysis of type and number of Lean elements used.

To evaluate the need for Lean implementation support, the survey participants were asked to answer the question "Do you have a need for external support in order to improve your organization's performance." Affirmative answers were used to conclude a need for Lean implementation support.

## 2.6 Limitations

A major limitation occurring in mail survey research is that results are based on only one respondent from each company. Thus, the respondent's feedback may not reflect company policy or the view of other management level employees. Such personal bias may particularly affect answers made to questions regarding Lean awareness, Lean implementation, and the need for Lean implementation support as answers tend to be subjective.

This study used awareness of at least one of the five Lean terms and use of at least one of the 29 Lean elements [10, 33, 34] to determine Lean awareness and Lean implementation status. If a respondent simply chose to ignore questions regarding those five Lean terms and 29 Lean elements, bias occurred through a possibly wrongful classification of the respondent as "is not aware of Lean" and "has not implemented Lean." However, a respondent need only indicate one of the five Lean terms as "aware of" and one of the 29 elements as "used" to be classified correctly. Thus, the research team decided that misclassification could only occur in few cases and should not bias the overall results of this study.

A Fisher's exact test was conducted to test on reliability between the population and the responses to compare every industry sub-segment's representation. The test showed a significant difference ($p$ value $= 0.01016$) in representation from the original data (Fisher's exact test, $\alpha = 0.05$). Companies from "other wood product manufacturing (NAICS 3219)" including "millwork (NAICS 32191)", "wood container and pallet manufacturing (NAICS 32192)", and "manufactured home (mobile home) manufacturing (NAICS 32199)" were overrepresented, while companies from "office furniture (including fixtures) manufacturing (NAICS 3372)" were underrepresented.

Lastly, this survey asked questions about a specific topic (Lean). It can be argued that individuals knowledgeable about Lean tend to be more likely to respond to the survey. However, the results obtained seem consistent with previous research [9, 16, 38–40] regarding Lean awareness, Lean implementation, and the need for Lean implementation support. Thus, if bias is present, it should be low.

## 3 Results and Discussion

Roughly three-fourth of the responding wood products (NAICS 321) and furniture manufacturing (NAICS 337) companies in the Commonwealth of Virginia are aware of Lean as measured by the knowledge of at least one of the five Lean terms listed in the questionnaire (Lean Management, Lean Manufacturing, Lean Production, Lean Thinking, or Toyota Production System (TPS) by the responding company employee. However, relatively few companies who are aware of Lean have implemented or are implementing Lean. Despite the relatively low level of Lean implementation in these two industry sub-sectors, less than a quarter of respondents indicated an interest in obtaining external Lean implementation support.

### 3.1 $H1_0$ : Lean Awareness

As shown in Fig. 1, about 28 % of the survey respondents are not aware of Lean and have not heard about any of the five terms typically used to refer to Lean: Lean Management, Lean Manufacturing, Lean Production, Lean Thinking, or Toyota Production System (TPS). However, 72 % of survey respondents have heard of at least one of the terms (Fig. 1).

Of the five Lean terms listed in the survey [Lean Management, Lean Manufacturing, Lean Production, Lean Thinking, or Toyota Production System (TPS)], Lean Manufacturing was the most widely recognized name (56 %, Fig. 1, right graph) followed by Lean Management, Lean Production, Toyota Production System (TPS), and Lean Thinking (51, 44, 30, 25 % frequency, respectively, Fig. 2).

Thus, hypothesis 1, "The majority of wood products and furniture manufacturing industries in the Commonwealth of Virginia are not aware of Lean", has to be rejected as the majority (72 %) of respondents are aware of Lean as measured by knowing at least one commonly used term to refer to Lean. This conclusion was further supported when measuring Lean awareness by awareness of the 29 Lean elements: 76 % of the survey participants had heard of at least one Lean element.

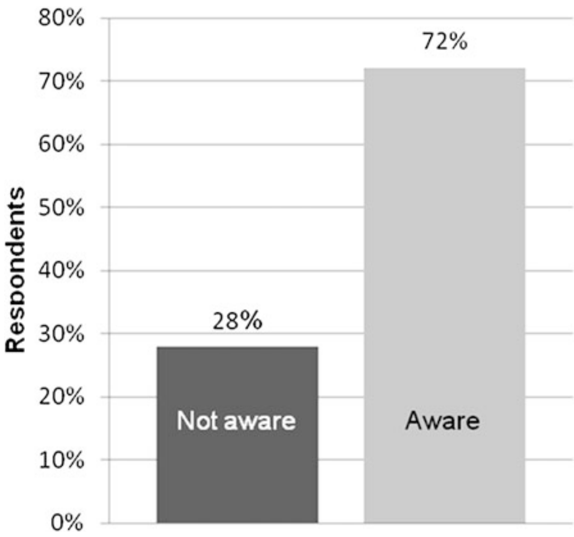


**Fig. 1** Lean awareness of survey respondents as measured by knowledge of at least one of five lean terms

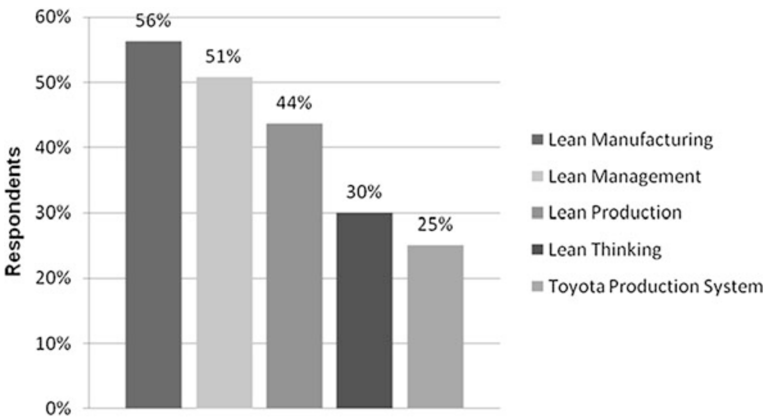


**Fig. 2** Frequency of recognition of lean terms by survey respondents who were aware of lean

### 3.2 $H2_0$ : Lean Implementation

While 72 % of responding companies are aware of at least one Lean term (Fig. 1), only 47 percent of the survey participants claim to have implemented one or more of the 29 Lean elements [10, 33, 34]. Thus, based on the results of this survey, Lean implementation in companies of the wood products and furniture manufacturing industries of the Commonwealth of Virginia is rather low, a result consistent with Pirraglia et al.'s findings [9]. In this survey, from 188 responding businesses, 100 reported that none of the 29 elements are used, 35 companies report that one to five elements are implemented, 29 companies report six to ten, six companies 11–15, seven companies 16–20, four companies 21–25, and seven companies report that 26–29 elements are implemented, respectively. Figure 3 provides an overview of these findings.

Given that 47 % of respondents indicated that Lean elements are implemented, hypothesis 2 stating that "The majority of wood products and furniture manufacturing industries in the Commonwealth of Virginia have not implemented Lean management," could not be rejected. Thus, based on this research, it can be concluded that the majority of the wood products and furniture manufacturing industries in the Commonwealth of Virginia have not implemented Lean or individual elements of Lean [10, 33, 34].

### 3.3 $H3_0$ : Need for Lean Implementation Support

Only 23 % of respondents answered the question "Do you have a need for external support in order to improve your organization's performance?" affirmative. Thus, hypothesis 3, "The majority of the wood products and furniture manufacturing industry in the Commonwealth of Virginia does not need support for their Lean implementation," could not be rejected. Interestingly, the "need for support" is influenced by the level of Lean awareness of respondents. Eighty-five percent of respondents indicating a "need for support" are aware of Lean, while only 15 % of respondents indicating a "need for support" were not aware of Lean. For respondents indicating "no need for support," 70 % were aware and 30 % were not aware of Lean. Figure 4 displays the need for support by companies aware and not aware of Lean.

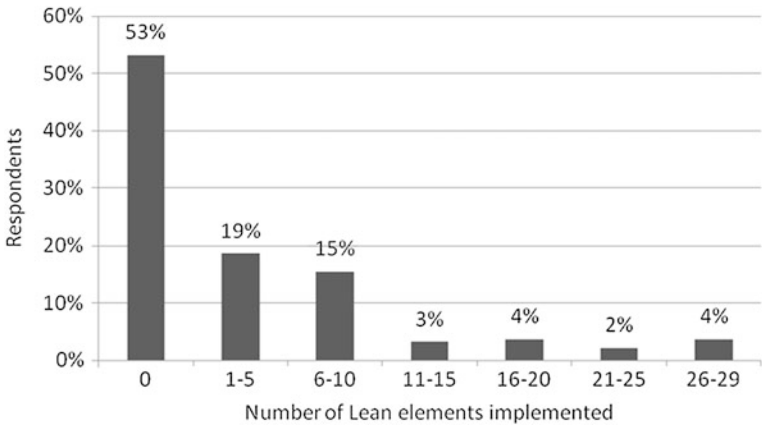


**Fig. 3** Respondents categorized by number of lean elements implemented

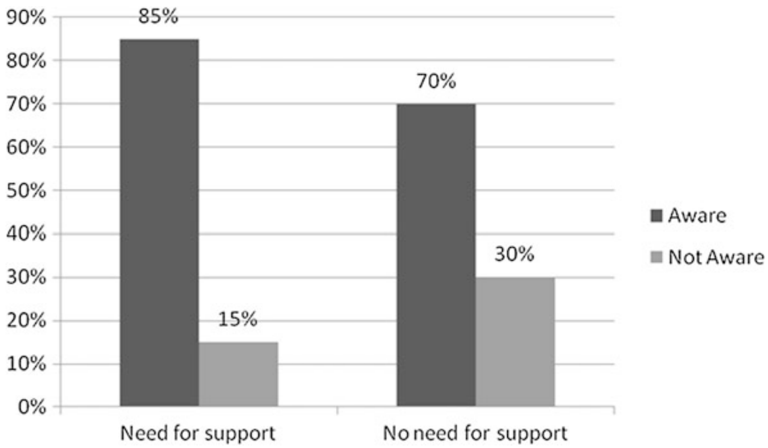


**Fig. 4** Comparison of Lean awareness and the need for support

# 4 Summary and Conclusions

While roughly three-fourths (72 %) of the wood products (NAICS 321) and furniture manufacturing (NAICS 337) industries in the Commonwealth of Virginia are aware of Lean, less than half (47 %) of all respondents of this survey indicated that they have implemented Lean elements in their business. Interestingly, despite the relatively low level of Lean implementation among companies in the wood products and furniture manufacturing industries in the Commonwealth of Virginia, only 23 % of the respondents claimed to have a need for Lean implementation support.

The outcome of this study shows that the wood products and furniture manufacturing industry in Virginia is slow in adopting and implementing Lean elements. Also, the low number of respondents indicating the need for Lean implementation support (23 %) suggests that companies may not be aware of the potential benefits that Lean might generate. Thus, future efforts should focus on the dissemination of potential benefits of Lean for the wood products and furniture manufacturing industries. Future research should also investigate Lean awareness and implementation status of other industries to establish the relative status of the wood products and furniture manufacturing industries in respect to other manufacturing industries. However, the ultimate measure of business success is survival and growth, two characteristics that have been sorely missing in the wood products and furniture manufacturing industries in Virginia for the last decade. Lean might be a way to improve the industry's success rate, should more Lean followers emerge in the future.

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## References


1. Bull A (2008) Home sales at 10-year low, jobless claims jump, Reuters. http://www.reuters.com/article/idUSN24503749200807247feedType=RSS&feedName=topNews
2. International Forest Industries (2009) Updated softwood lumber market outlook for the US, International Forest Industries. http://www.internationalforestindustries.com/2009/11/19/updated-softwood-lumber-market-outlook-for-the-us/
3. BBCWorldNewsAmerica (2008) Ikea in Danville Virginia, BBC World News America. http://www.youtube.com/watch?v=XJ7IIOye7H4&feature=youtube_gdata
4. Smith M, Fannin J, Vlosky R (2009) Forest industry supply chain mapping: an application in Louisiana. Forest Prod J 59(6):7
5. Huber T (2008) Timber trouble: hard times are hitting the timber industry of America, Associated Press. http://findarticles.com/p/articles/mi_qn4188/is_20080409/ai_n25145404/
6. Buehlmann U, Schuler A (2009) The US household furniture industry: status and opportunities. Forest Prod J 59(9):20–28
7. Buehlmann U, Schuler A (2002) Benchmarking the wood household furniture industry in a global market. Wood Dig 52–57
8. Schuler A, Buehlmann U (2003) Identifying future competitive business strategies for the U.S. residential wood furniture industry: benchmarking and paradigm shifts, USDA forest service. http://www.fs.fed.us/ne/newtown_square/-publications/technical_reports/pdfs/2003/gtrne304.pdf
9. Pirraglia A, Saloni D, van Dyk H (2009) Status of lean manufacturing implementation on secondary wood industries including residential, cabinet, millwork, and panel markets," BioResources 4(4):1341–1358 (http://www.bioresources.com)
10. Czabke J, Hansen E, Doolen T (2008) A multisite field study of lean thinking in U.S. and German secondary wood products manufacturers. Forest Prod J 58(9):77–85
11. Luppold W, Bumgardner M (2008) Forty years of hardwood lumber consumption: 1963 to 2002. Forest Prod J 58(5):7–12
12. Grushecky S, Buehlmann U, Schuler A, Luppold W, Cesa E (2006) Decline in the US furniture industry: a case study of the impacts to the hardwood lumber supply chain. Wood Fiber Sci 38(2):365–376
13. U.S. Census Bureau (2010a) Industry statistics sampler—NAICS 321, U.S. Census Bureau. http://www.census.gov/cgi-bin/naics/index.cgi
14. U.S. Census Bureau (2010b) Industry statistics sampler—NAICS 337, U.S. Census Bureau. http://www.census.gov/cgi-bin/naics/index.cgi
15. Mintz Testa B (2003) Lean manufacturing—processing buzzword or operational lifesaver? Eng Wood 6(1):12–15
16. Stuart I, Boyle T (2007) Advancing the adoption of 'Lean' in canadian SMEs, Ivey Bus J Online. http://proquest.umi.com.ezproxy.lib.vt.edu:8080/pqdlink?-index=39&did=1399135151&SrchMode=1&sid=1&Fmt=3&VInst=PROD&VType=PQD&RQT=309&VName=PQD&TS=1288063234&clientId=8956
17. Womack JP, Jones DT (2003) Lean thinking: banish waste and create wealth in your corporation, 1st edn. Free Press, New York
18. Womack JP, Jones DT, Roos D (1990) The machine that changed the world: based on the massachusetts institute of technology 5-million dollar 5-year study on the future of the automobile. Rawson Associates, New York
19. The Shingo Prize (2008) About us, The Shingo prize for operational excellence. http://www.shingoprize.org/htm/about-us/the-shingo-prize
20. Steelcase (2006) Steelcase receives shingo prize for manufacturing excellence, Steelcase. http://ir.steelcase.com/releasedetail.cfm?releaseid=371341
21. Hon (2010) News and media center, HON Company. http://www.hon.com/About-HON/Press—Media/Press-Releases/The-HON-Company-Backgrounder.aspx

22. Merillat-Masco Builder Cabinet Group (2009) About Merillat, Merillat. http://www.merillat.com/company/index.aspx
23. Ott L, Longnecker MT (2010) An introduction to statistical methods and data analysis, 6th edn. Brooks/Cole Cengage Learning, Belmont
24. Rea L, Parker RA (2005) Designing and conducting survey research: a comprehensive guide, 3rd edn. Jossey-Bass, San Francisco
25. Dillman D, Smyth JD, Christian LM (2009) Internet, mail, and mixed-mode surveys : the tailored design method, 3rd edn. Wiley, Hoboken
26. Virginia Workforce Connection (2010) Quarterly census of employment and wages (QCEW). http://www.vawc.virginia.gov/analyzer/searchAnalyzer.asp?cat=HST_EMP_WAGE_IND&session=IND202&subsession=99&time=&geo=&currsubsessavail=&incsource=&blnStart=True
27. Manta (2010) Company profiles and company information, manta. http://www.manta.com/
28. Dand B (2009) Virginia industrial directory. Dun and Bradstreet, Twinsburg
29. WPMA (2010) Manufacturer index of WPMA members, wood products manufacturers association. http://www.wpma.org/member_links.asp
30. AWI (2010) Find a member, architectural woodwork institute. http://www.awinet.org/FindaMember/tabid/167/Default.aspx
31. Alreck PL, Settle RB (1995) The survey research handbook, 2nd edn. Irwin, Chicago
32. Fink A (2003) How to ask survey questions, 2nd edn. Sage Publications, Thousand Oaks
33. Kirby KE, Greene BM (2003) How value stream type affects the adoption of lean production tools and techniques, Institute of Industrial Engineers. http://www.iienet2.org/Details.aspx?id=24634
34. Liker JK (2003) The toyota way, 1st edn. McGraw-Hill, New York
35. Biemer P, Lyberg LE (2003) Introduction to survey quality. Wiley, Hoboken
36. Microsoft (2007) MS Excel, Microsoft Corporation, Redmond, WA
37. SAS (2008) JMP 8.0, SAS Institute Inc., Cary, NC
38. Kumar M, Antony J, Singh RK, Tiwari MK, Perry D (2006) Implementing the Lean Sigma framework in an Indian SME: a case study. Prod Plann Control 17(4):407–423
39. Achanga P, Shebab E, Roy R, Nelder G (2006) Critical success factors for lean implementation within SMEs. J Manuf Technol Manage 17(4):460–472
40. Westhead P, Storey D (1996) Management training and small firm performance: why is the link so weak? Int Small Bus J 14(4):13–24

# Simulation Studies of Hybrid Pull Systems of Kanban and CONWIP in an Assembly Line

**Yue Huang, Hung-da Wan, Glenn Kuriger and F. Frank Chen**

**Abstract** Pull system is an important component of lean manufacturing that can effectively reduce typical wastes associated with push production systems, such as overproduction. Using Toyota's Kanban system, a production line can be configured as a pull system to avoid unnecessary accumulation of Work in Process (WIP). Another common method to carry out a pull concept is the CONWIP line, which maintains a constant WIP level within a segment of production line. Both methods have proven effective, but they may have different characteristics. The objective of this paper is to explore the potential to combine Kanban and CONWIP methods into a robust hybrid pull system that preserves the advantages of both methods while minimizing the disadvantages of each individual method. A simulation study has been carried out based on a real-world assembly line. Various pull system configurations of the assembly line have been evaluated and compared in terms of WIP level, number of Kanban cards in system, and throughput. The study shows that the productivity of CONWIP configuration outperforms Kanban configuration in majority of scenarios; and the performance of a well designed hybrid system can be more robust to various scenarios, compared to Kanban and CONWIP system.

## 1 Introduction

In the modern commerce, companies strive to be lean to stay competitive in the market. An effective production system should be able to produce the right parts with right quantities, at the right time, with a competitive price [1]. Pull systems, such as Toyota's famous Kanban system, avoids unnecessary accumulation of

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Work in Process (WIP) in order to realize the concept of Just in Time (JIT). In such systems, the Kanban cards are used for communication and inventory control. The strength and benefits of implementing a Kanban system have been well studied [1–6]. On the other hand, Kanban was found more suitable for repetitive manufacturing industries [7].

With a similar pull mechanism, Spearman et al. [1] proposed CONWIP, or Constant Work-In-Process. Kanban and CONWIP systems are both successful production systems that synchronize production, sales, and delivery [8]. The concept of Kanban and CONWIP systems are shown in Fig. 1, which emphasizes on the card flow. In a pure Kanban system, information is sent from a station to its immediate upstream proceeding station; while in a CONWIP system, production demand information flows directly from the final buffer to the first station [8]. Both as pull systems, Kanban and CONWIP have a lot in common, while they also differ from each other in some areas.

Between Kanban and CONWIP, Hopp and Spearman [6] noted that card count is an issue for Kanban system. In a single-card system, the user must establish a card for every station and the card is also part specific. On the other hand, CONWIP is line specific, i.e., cards do not identify any specific part number. Thus, it is relatively simpler than a Kanban system in that sense. In previous studies, CONWIP often outperforms Kanban when processing times vary in different stations, while Kanban is more flexible for the assembly system with respect to a given objective than CONWIP [9]. When there is high variation in demand, choosing CONWIP over Kanban can effectively lower the average WIP in the system [10]. As a result, combining Kanban and CONWIP systems into Hybrid Pull Systems may result in different performance characteristics.

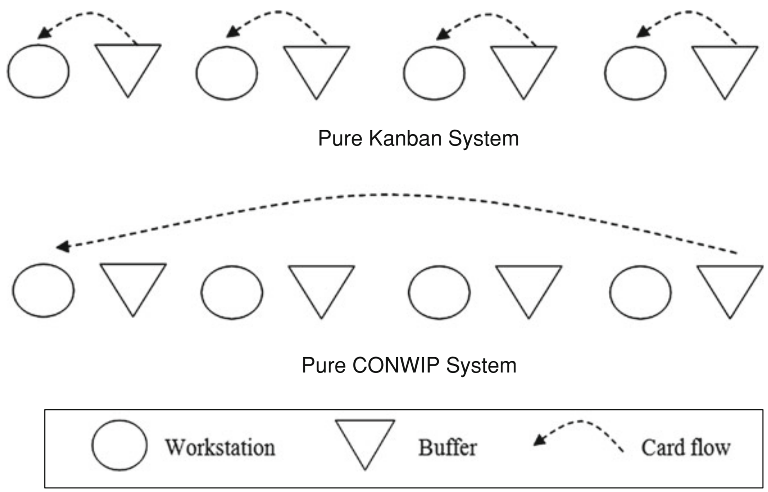


**Fig. 1** Card flows of pure Kanban and pure CONWIP systems

Hybrid system is a relatively new idea. Many previous researches combine push/pull system to form a hybrid system in order to take advantage of both the shorter delivery lead time (not production lead time) of push systems and low work-in-process (WIP) level of pull systems [11]. Many benefits of push–pull hybrid systems have been reported in literature [12–16]. However, Hybrid Pull Systems which integrates CONWIP and Kanban systems have not been discussed in major academic literature. Therefore, this paper aims to investigate the new type of hybrid manufacturing system.

The objective of this paper is to investigate the impact of using Kanban, CONWIP, and different Hybrid Pull system configurations on the performance of manufacturing systems. A simulation study was carried out based on a real assembly line of a manufacturing company, referred as "Company A" hereafter in this paper. Rockwell Arena was used to simulate the production line and evaluate the WIP level and throughput rate for comparison.

## 2 Studied Case: An Assembly Line of Beverage Dispenser

### *2.1 The Selected Assembly Line in Company A*

Company A is a leading manufacturer of beverage dispensing systems. The assembly line selected in this research is highly manual and labor intensive. As shown in Fig. 2, the assembly line comprises eight steps with two branches supplying subassemblies to the main line. The incoming inspection takes the largest amount of mean processing time and is considered the bottleneck of this line. This is due to the fact that parts made abroad would be inspected piece by piece before being used in assembly. Although it may not be a "lean" practice, this setting is used in this paper for studying the impact of various hybrid pull system configurations.

The process time of each station was carefully observed, and the time-based performance of each station has been collected from the real operations and summarized in Table 1.

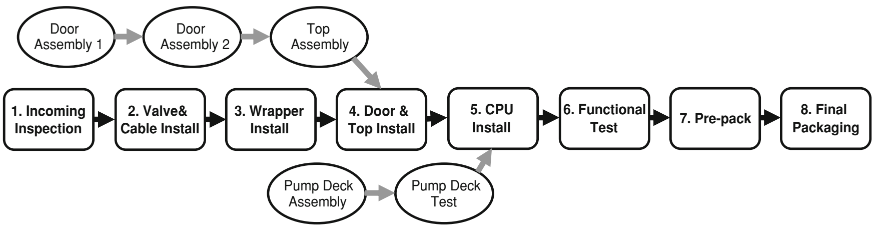


**Fig. 2** The eight-step assembly line with two branches

**Table 1** Process time of each station

| Process | Mode (s) | Lowest (s) | Highest (s) |
|---|---|---|---|
| Inspection | 1,056 | 1,003 | 1,108 |
| Valve and cable | 691 | 688 | 694 |
| Wrapper | 633 | 629 | 638 |
| Door Assy | 752 | 722 | 782 |
| Door Assy 2 | 467 | 437 | 497 |
| Top Assy | 204 | 174 | 234 |
| Door and top install | 182 | 151 | 213 |
| Pump deck Assy | 942 | 902 | 985 |
| Pump deck Test | 309 | 270 | 342 |
| CPU install | 562 | 560 | 566 |
| Functional test | 630 | 576 | 675 |
| Pre-packing | 490 | 425 | 543 |
| Packing | 322 | 450 | 517 |

In this paper, three performance measures were selected to be compared. They were collected as follows.

- Throughput Rate: The quantity of units produced in 100 h.
- WIP Level: The time average of work-in-process quantity in the system.
- Card Number: The number of Kanban cards or CONWIP cards in the main assembly line.

## 2.2 Settings of Simulation Studies

In this study, simulation software Arena v.13 by Rockwell Automation was used to perform the simulation analysis. The assembly process is simulated from components arrival (raw material arrival) to final assembly leaving the system after packaging. Each simulation run mimics 100 h of production with 10 replications. An additional 100 h warm-up period was given before the tally started. 85 % of system up time was assumed for the assembly operations.

Some assumptions and terminology of the simulation study are explained as follows.

- Each sub-assembly line (i.e., the branch) uses either one Kanban or two CONWIP cards.
- Each Kanban or CONWIP card contains only one piece of part.
- The WIP only accounts for those items in the main assembly line and does not include those in the sub-assembly lines.
- "Kanban card number" refers to the number of Kanban cards per station in the main assembly line.
- "CONWIP card number" refers to the number of CONWIP cards for the main assembly line.

The number of Kanban or CONWIP cards was considered in the following way. A pure Kanban System uses one Kanban card for each process (i.e., 8 cards in the main line), and each card represents one piece of part. Multiplications of cards (i.e., 16, 24, and 32) are tested as extra buffers in the system. On the other hand, the numbers of cards used in the CONWIP system can be lower than 8 cards. In this paper, the numbers 8, 16, 24, and 32 of CONWIP cards were used in the simulations for direct comparison with the Kanban system. The numbers 4 and 5, which were not possible in the Kanban system, were evaluated to study the scenario with fewer cards than the number of stations.

# 3 Simulation of Kanban, CONWIP and Hybrid Pull Systems

## *3.1 Design of Experiments*

The objective of this research is to investigate if there is a way to integrate the Kanban and CONWIP pull systems to keep the advantages and avoid the weaknesses. Since real experiments would be too expensive to conduct, several simulation models were created for the research objective.

In the real case, the dominant bottleneck is the first station in the system. However, in order to study the general impact of implementing Kanban and CONWIP systems, different locations of the dominant bottleneck were simulated, including the front, middle, and end of the main assembly line. Using different configurations to combine Kanban and CONWIP, three hybrid designs are proposed. Figure 3 shows how Hybrid systems I, II, III work when the bottleneck is at the middle of the line.

- Hybrid I: The bottleneck ("B" in the figure) is managed by Kanban and other stations by CONWIP.
- Hybrid II: The first station through the bottleneck is managed by CONWIP and the stations after the bottleneck are managed by a separate CONWIP.
- Hybrid III: The first station through the bottleneck is managed by Kanban and the stations after the bottleneck are managed by CONWIP.

Using the three Hybrid Pull systems as well as the pure Kanban and pure CONWIP systems, totally five designs are studied. With three configurations of different locations of bottlenecks, there should be 15 scenarios in total. However, when the bottleneck is at the beginning, Hybrid II and III results in the same configuration as the pure CONWIP system. Similarly, when the bottleneck is at the end of the system, the two hybrid systems become either pure CONWIP or pure Kanban. All the tested scenarios are shown in Table 2.

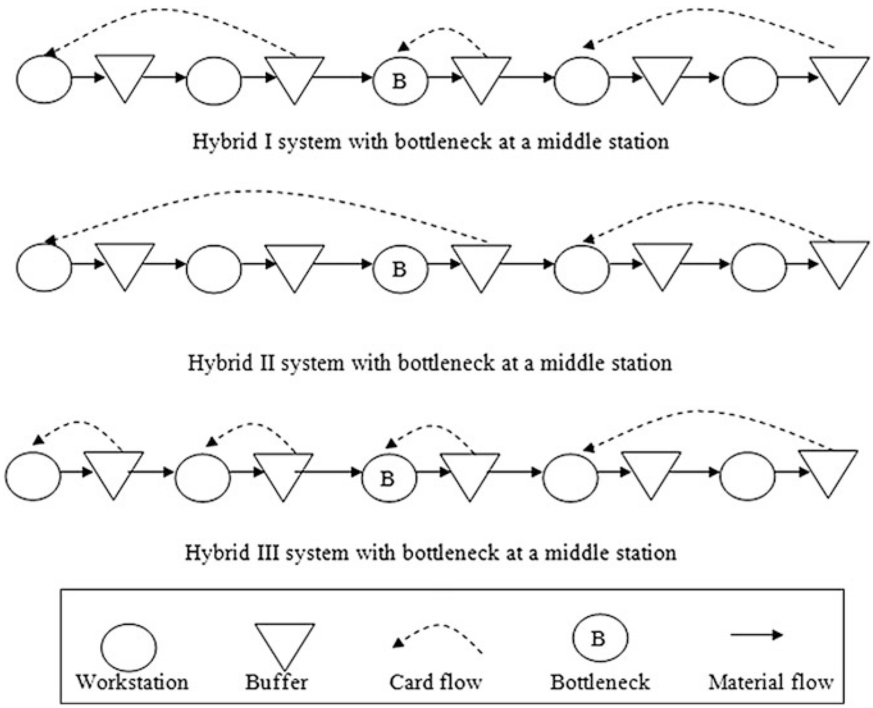


**Fig. 3** Hybrid I, II, III systems with bottleneck at a middle station

**Table 2** Various designs of pull system investigated in this research

| System design | Bottleneck at the beginning | Bottleneck in the middle | Bottleneck at the end |
|---|---|---|---|
| Pure Kanban | X | X | X |
| Pure CONWIP | X | X | X |
| Hybrid Type I | X | X | X |
| Hybrid Type II | (Equivalent to pure CONWIP) | X | (Equivalent to pure CONWIP) |
| Hybrid Type III | (Equivalent to pure CONWIP) | X | (Equivalent to pure Kanban) |

## *3.2 Simulation Logic of Pure Kanban and Pure CONWIP Systems*

Kanban system is a production information and control system. The Kanban card and the operator are both considered as resources in the simulation and the station or process needs to have both of those resources available to start. Figure 4 shows the entire logic for Kanban system simulation.

CONWIP, as the name suggests, is a production system with a constantly capped WIP level. Instead of making a Kanban card for each part number, a CONWIP card works for the whole product line, which could consist of several stations or processes. The Arena model for the CONWIP system is shown in Fig. 5.

The logics of hybrid pull systems combines the models in Figs. 4 and 5 in several different ways. Due to the page limitation, the simulation logics of the hybrid systems are omitted in this paper.

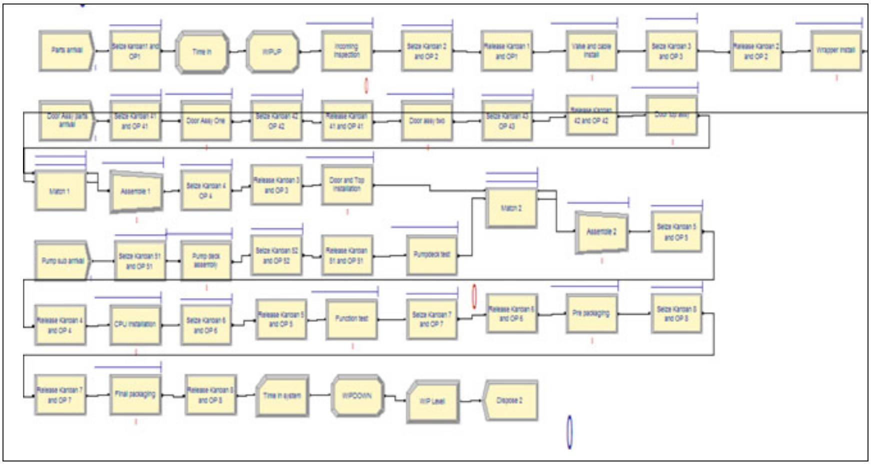


**Fig. 4** Kanban system simulation logic

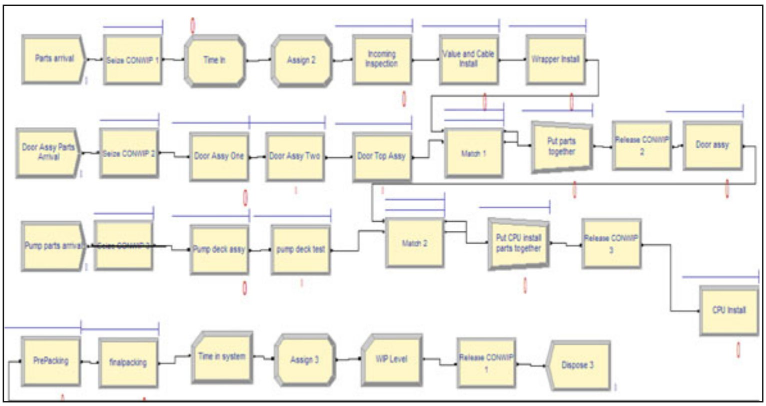


**Fig. 5** CONWIP system simulation logic

## 4 Simulation Results

The results of the simulation studies have been plotted in the Figs. 6, 7, and 8. Note that the upper lines in figures are the throughput rates, which use the y-axis on the left. The lines at the bottom of the figures represent WIP levels, which use the y-axis on the right. According to Table 2, there are five scenarios (i.e., five lines for throughput and five lines for WIP) when the bottleneck is assumed to be at the middle of the assembly line, while only three scenarios were tested for the other two configurations.

As shown in Fig. 6, when the bottleneck is at the beginning station, the throughput for the Hybrid I system is the best, slightly better than CONWIP system. It has lower WIP than the CONWIP system and slightly higher WIP compared to the Kanban system. This characteristic combines the strength of both CONWIP and Kanban with fewer cards in system and lower WIP while maintaining output.

Figure 7 summarizes the performance when the bottleneck is at the middle of the assembly line. The throughput of CONWIP, Hybrid I and II ramp up quicker than the other two systems. Once the throughput saturates, Hybrid III, and Kanban systems have the lowest WIP, followed by Hybrid II. Although Kanban system has the lowest WIP level, it also has lowest throughput.

Figure 8 shows the scenarios with the bottleneck at the last station. The differences between systems are small in both throughput rates and WIP levels. If WIP level is the focus, Kanban system is slightly better, although the throughput is also lower than others. Hybrid I and CONWIP seem to have comparable performance.

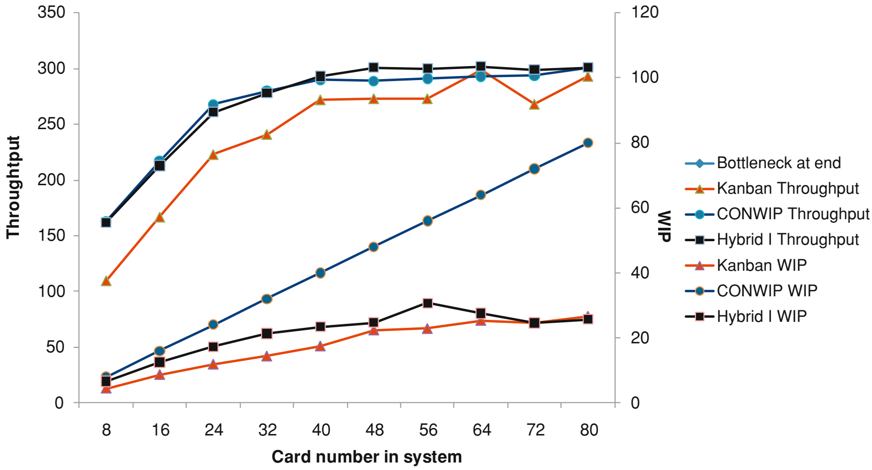


**Fig. 6** Throughput, WIP, and number of cards with bottleneck at the beginning of line

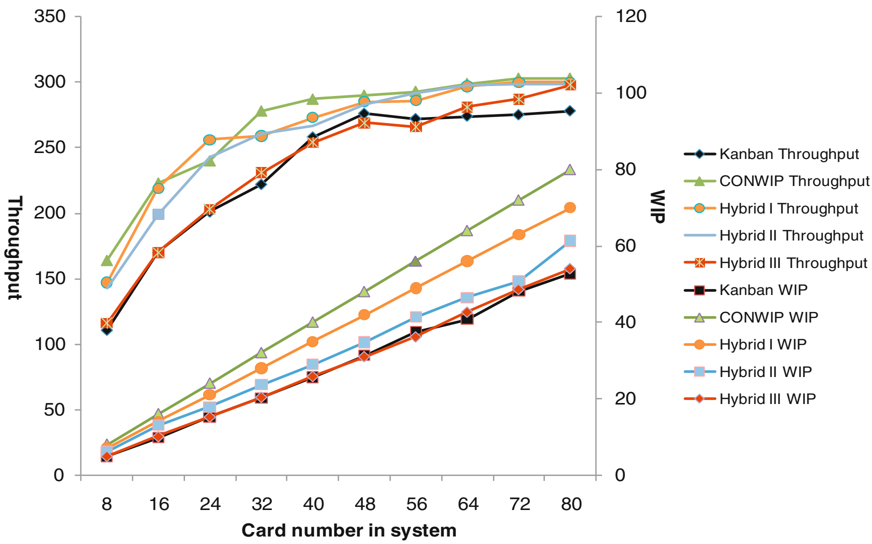


**Fig. 7** Throughput, WIP, and number of cards with bottleneck at the middle of line

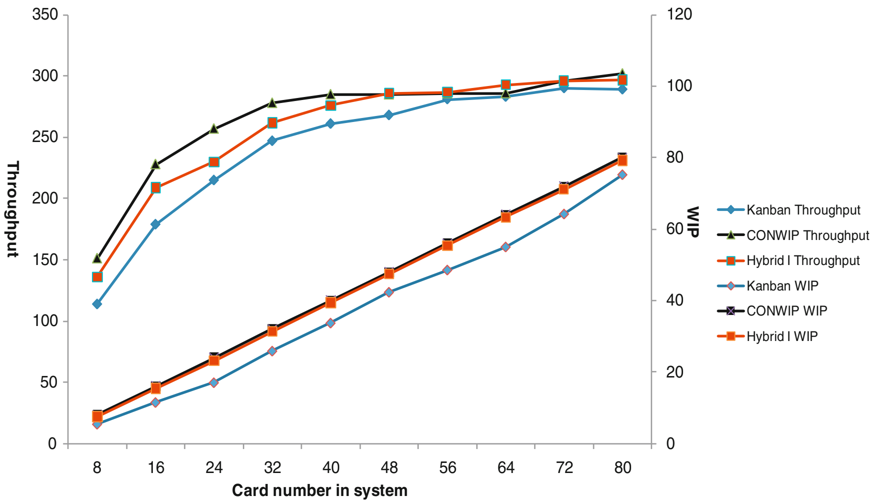


**Fig. 8** Throughput, WIP, and number of cards with bottleneck at the end of line

In summary, if the bottleneck is at the first station, Hybrid I system (with Kanban managing the bottleneck and CONWIP managing other stations) performs better than pure CONWIP or Kanban system. If the bottleneck is at the end, Hybrid I and CONWIP have comparable output while Hybrid I has slightly lower WIP. If the bottleneck is at the middle, Hybrid II system is a good compromise, since with different card numbers in system, it has consistent high-yield output compared to other systems and significant lower WIP as compared to other high-yield systems, such as CONWIP and Hybrid I.

Although none of the systems is dominant in all performance measures, Hybrid II seems to achieve a good balance in most cases. The results show that, in most cases, a hybrid pull system can be constructed, which can perform better than or equal to pure Kanban and CONWIP systems, although further investigation should be carried out to verify.

## 5 Conclusions

The benefits of pull production systems have been studied extensively in previous research. However, the performance of possible configurations of pull production systems has not been reviewed in detail. Part of the reason is that there were many case studies which replaced a push system with a pull system while implementing lean concepts, but it was not common to experiment different pull settings. Trying out various configurations of pull system can be expensive, time consuming, and sometimes even risky. Therefore, with the help of simulation, this paper was able to investigate various configurations of pull production systems, including Kanban, CONWIP, and three different hybrid configurations that integrate the former two.

The results of the five system configurations have been compared in terms of throughput and WIP level versus the number of cards. Most of the time, CONWIP outperforms Kanban system by being able to reach desired (or maximum) throughput with fewer cards in the system than using Kanban system and thus is easier to manage. A hybrid pull system with a CONWIP model to manage the first station through the bottleneck and a separate CONWIP model to manage the rest of the stations performs better than or equal to pure Kanban or CONWIP systems. Overall, a well designed hybrid system can perform similarly as or better than a pure Kanban or CONWIP system in various scenarios.

Although the simulation results show that hybrid pull systems can perform well in general, more detailed investigations are needed to determine how a hybrid pull system should be designed. The use of suitable analytical models or heuristics to optimize total number of cards in the hybrid pull systems as well as distribution of cards in the systems should be investigated. Further, the system studied in this paper was a simple assembly line. More hybrid pull systems should be investigated to understand the impact of complex routing and high variability in processing time. Finally, testing the hybrid systems in real cases will provide invaluable insight. It will be beneficial to further investigate relevant real-world cases and carry out the hybrid concepts in industry when applicable.

## References


1. Spearman LM, Woodruff LD, Hopp JW (1990) CONWIP: a pull alternative to Kanban. Int J Prod Res 28(5):879–894
2. Sugimori Y, Kusunoki K, Cho F, Uchikawa K (1977) Toyota production system and Kanban system materialization of just-in-time and respect-for-human system. Int J Prod Res 15(6):553–564
3. Schonberger RJ (1986) World class manufacturing: the lessons of simplicity applied. The Free Press, New York
4. Ohno T (1988) Toyota production system: beyond large-scale production. Productivity Press, University Park, IL
5. Pascal D (2007) Lean production simplified. Productivity Press, University Park, IL
6. Hopp JW, Spearman LM (2008) Factory physics, 3rd edn. Waveland Press, Long Grove, IL
7. Hall WR (1981) Driving the productivity machine: production planning and control in Japan. American Production and Inventory Control Society, Chicago
8. Sato R, Khojasteh-Ghamari Y (2012) An integrated framework for card-based production control systems. J Intell Manuf 23(3):717–731
9. Khojasteh-Ghamari Y (2009) A performance comparison between Kanban and CONWIP controlled assembly systems. J Intell Manuf 20(6):750–760
10. Sakhardande RA (2011) Performance comparison between Kanban and CONWIP through simulation. In: Proceedings of the 2011 industrial engineering research conference, Reno, NV
11. Ghrayeb O, Phojanamongkolkij N, Tan BA (2009) A hybrid push/pull system in assemble-to-order manufacturing environment. Intell Manuf 20(4):379–387
12. Olhager J, Oestlund B (1990) An integrated push/pull manufacturing strategy. Eur J Oper Res 45(2):135–142
13. Lee CY (1993) A recent development of the integrated manufacturing system: a hybrid of MRP and JIT. Int J Oper Prod Manage 13(4):3–17
14. Beamon BM, Bermudo JM (2000) A hybrid push/pull control algorithm for multi-stage, multi-line production systems. Prod Plan Control 11(4):349–356
15. Takahashi K, Nakamura N (2004) Push pull, or hybrid control in supply chain management. Int J Comput Integr Manuf 17(2):126–140
16. Cochran JK, Kaylani HA (2008) Optimal design of a hybrid push/pull serial manufacturing system with multiple part types. Int J Prod Res 46(4):949–965

# Value Stream Mapping Application on Mould Making Industry: Results and Discussion

A. Costa, E. Henriques, M. Domingues and P. Peças

**Abstract** This paper presents the results of a project aiming to understand the viability of value stream mapping techniques on the "one of a kind production" context typical of mould making industry. More than having a representation of a standard process, the idea is to use the mapping techniques to support the analysis and the discussion of the time-oriented performance of the whole manufacturing process. The project involved the creation of a VSM application tool which improves the analysis of the mould making critical processes, the automatic calculation of the main process indicators, and the generation of the value stream map of each process under analysis. Several mould makers were involved to support the design of the tool and to evaluate its potential in guiding purposeful improvement actions. The results presented are quite satisfactory. Even if the process is not a repetitive one, its time-oriented performance analysis reproduces repetitive time waste patterns in each company. Moreover, the visual nature of VSM techniques facilitates the process understanding and leads the improvement teams in focusing towards the global improvement.

## 1 Introduction

Mould industry has faced innumerous challenges at a global completion scale [1]. Moulds are getting technologically more complex and clients' demands on mould-makers are getting tougher as regards the payments schemes, life cycle guarantees

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and manufacturing lead time [2]. Especially regarding the mould manufacturing lead time a 30–50 % reduction was already accommodated, but the pressure is still alive [3].

In a one-of-a-kind production context, low production cost asks for a production system working close to its full capacity. But shorter lead times are easier to achieve if a certain level of resources idle time is available to manage the work in progress and to facilitate the operations scheduling for a fast throughput. Also the on-going lead time reduction is more difficult as far as moulds requirements, as regards functionalities, target performance and guarantee conditions, are harder to achieve. For the mould-maker this means that more complex moulds have to be designed, engineered, built and tested in a shorter time [4].

The one-of-a-kind nature of the mould manufacturing process should not inhibit the ability to represent the process and take advantage of value stream mapping (VSM) techniques, typical of repetitive industry. Even if it is necessary to make adjustments to the typical VSM approaches, such representation can contribute to structure and get the most out of continuous improvement practices focused on lead time reduction.

This paper is about the application of VSM techniques to the mould industry. The objective is to make possible the comprehensive understanding of the mould process chain, creating a common basis to drive the improvement team in its continuous effort to reduce the mould manufacturing lead time. Instead of relying on the local analysis and insular improvement, a VSM representation allows the global and simple view of the all process. Moreover, it facilitates the identification and quantification of potential waste (lead time waste) and creates the conditions to make sound decisions on improvement actions, based on their impacts on the overall process.

## 2 Mould Industry

The design and manufacturing of moulds are demanding engineering processes involving modern and capital intensive production technology. In its origins the competitiveness of national engineering and tooling industry was essentially supported by the low cost of manpower. However, it progressively evolved during the 90 s for a competitive industry based in advanced hard and soft technologies and high qualified human resources. The typical mould design and manufacturing cycle starts with a preliminary engineering design solution, which is validated and approved by the client, and ends up with the mould delivery after the demonstration of its ability to produce conformed moulded parts. In between, and just after the first outcomes of the detailed design, the mould construction process is carried out using basically a combination of numerically controlled machining processes, essentially milling, drilling, grinding and electro-discharge machining. A significant amount of time is spent to obtain the suitable moulding surfaces (frequently surface engineering technology is required), before arriving to the final adjustment and assembly of all components and to the trial-out of the mould functionality and performance in shaping the required parts.

A mould is composed by different sub-systems and hundreds of different components, each with a specific flow of manufacturing steps. Therefore, at the shop-floor each mould "explodes" in several manufacturing processes that concurrently converge to the final assembly. The need to reduce the total lead time has indeed push for parallel work, which made the companies often to start the rough machining after the approval of the preliminary design and before the detailed design is over. The approach of simultaneously carry out the design and the manufacturing operations can save to a couple of weeks in the total lead time, but sometimes it only pushes the waiting time forward if the detail design can't provide in time the job-floor with the necessary information.

In fact, in a tough competitive context, the sustainability of any mould making company depends not only on a strong technological basis, but also on the ability to efficiently take advantage of the available production resources and, based on technological knowledge, of the continuous improvement of this efficiency of exploitation [5]. Since the mould making companies can have between 10 and 30 simultaneous moulds in production, each with thousands of components with their own process sequence, one can understand that the inherent process of generating value is indeed complex and deeply dynamic. The bottlenecks of the production vary in time, inducing different planning issues. Moreover, due to the high variability of the manufacturing processes, the inefficiencies and waste in the value stream are difficult to evaluate and their causes difficult to root.

## 3 Lean Manufacturing and Value Stream Mapping

Lean manufacturing relies on lean thinking five basic principles consisting on defining the value, defining the value stream, assuring the flow, let the client pull and chasing the perfection [6, 7]. These basic principles can provide important guidelines to improve the capability to create more value with the existent technological basis. In accordance to lean manufacturing definition, the approach seems to provide a framework to more efficiently fulfill the client's expectations. Through the systematic elimination of waste all along the manufacturing process, lean manufacturing supports the reduction of lead time, increases the overall quality and efficiency and sustains a more competitive and market-responsive company. However, the omission of specific methods and guide-lines towards lean implementation in mould making companies has difficult its adoption. In fact, the opinion of general mould-makers about lean manufacturing points to a dominant skepticism. The skepticism is reinforced as far as they note that the proposed operational methodologies (Kanban control systems, cellular manufacturing flow, statistical process control, etc.) are designed for repetitive production systems and do not seem to have correspondence with the mould-making environment. More than that, the sporadic introduction of those operational methodologies in mould making has resulted in a limited success [8].

In spite of that, lean manufacturing basic principles rely strongly on the total manufacturing time reduction (and cost reduction) through waste elimination (waiting time, non-quality, rework, over-processing, resources under-utilization …). So, as far as time and cost are important competitive factors in mould making sector, one can believe that lean manufacturing dissemination within mould makers is essentially a question of adapting the lean support methodologies and tools to the particular one-of-a-kind engineering order context.

Lean manufacturing is supported by a set of techniques materialized as the antidote to waste all along the value stream [7]. One of these tools is value stream mapping (VSM). It allows a simple and intuitive visual representation of processes, from the client request till the final delivery of products. The objectives of any VSM can be listed:

- Make the current process visible (visibility improves understanding and promotes communication).
- Facilitate the identification of problems and opportunities for improvement in the current process.
- Establish a reference for evaluating impacts of improvement actions.
- Establish a working basis for an improved state of the process (the vision of the future process as it should be).

In fact, the VSM will not solve process problems, but facilitates their identification and evaluation, and creates a more robust basis to support informed decision making on what improvement actions will provide a greater impact on the overall process. In particular, it avoids the local views of the process, where each stakeholder strives in the optimization of their individual activity, forgetting the potential impacts on the global value stream [9].

Still it should be mentioned that a major novelty of VSM in relation to other more conventional mapping techniques is that the VSM considers and treats all activities: the ones that are necessary and add value to the process, and the ones, either necessary or not, that do not strictly contribute to generate value in the perspective of the final client. In reality both consume resources and induce costs and so both need to be controlled. When representing the process, any omission of non-added value activities just results into unknown hidden wastes, inhibiting action for their elimination/reduction [10].

Traditionally, the lead time improvement in mould making sector has been focused on the reduction of time needed for each manufacture step (rough milling, electro discharge machining, drilling, finish milling, etc.). Whenever one talks about improvement or "optimization" of the mould production process what is usually meant is the improvement or "optimization" of a step of the whole process, normally associated to a single technology. The underlying principle relies in the idea that if it is possible to perform a step quicker, then the total lead time for mould manufacturing will be shorter. However, this conjecture might be somehow tricky. To perform quicker one step in the process might not result in an effective improvement of the overall process, especially if that step is not a bottleneck or if the work in progress will then be waiting to go through the following step.

It is often considered that the mapping of the value stream is geared to large organizations, following a well-defined methodology (Fig. 1), and only applies to repetitive manufacturing. However, even if it is necessary to make adjustments and simplifications of typical techniques, such representation will allow the global visualization of the process and the identification and quantification of potential waste, creating the conditions to generate a common basis for the improvement team to discuss, design and plan their future actions. The global visualization will drive the team, shifting their traditional focus on local improvement, often with damaging effects, for an approach engaged in intelligent improvement measures judged based on their impact on the global process performance. More than that, the mapping can begin by evaluating the material and information flow as regards their time oriented performance, but can evolve to consider also the generation of materials waste and energy consumption, in an eco-efficiency perspective.

One should note that it is not intended to create a standard map of the manufacturing process of moulds, even because, due to the uniqueness of each mould, this standard map does not exist. It is rather intended to provide a tailored and simple technique to map punctually (periodically and systematically) the flow of

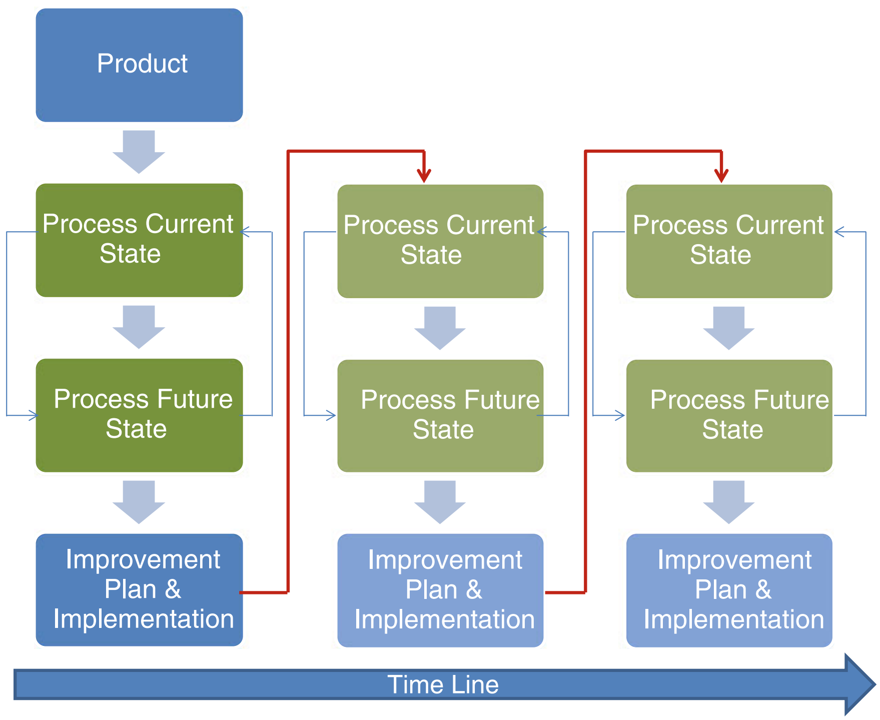


**Fig. 1** Methodology of VSM [10]

the main processes of a mould, in a visual format with both qualitative and quantitative information. This representation can then be used as a working and common visual basis by a multidisciplinary improvement team to facilitate the identification of drawbacks in the current process and the discussion of how the process should/could be. Moreover, it provides a supporting framework for the team to derive purpose oriented measures guided towards the process global improvement.

## 4 Methodology

The VSM was applied to a set of mould making companies along 4 different phases. The first one was a preparatory phase, concentrated in the companies' familiarization with the mapping and VSM technique, its scope, objectives, and procedures. It was decided not to address the process of a whole mould, but to deal with the mould components responsible for the critical path of the process, usually the mould core components. However, insofar as the choice and the process of a single mould might result in a map not representative of the typical performance, it was suggested to analyze 3 different moulds recently produced. If only one mould is studied, the analysis and discussion of value stream map will induce the stakeholders to justify inefficiencies and wastes with every kind of untypical and uncontrollable problems. If the same waste patterns is present in the processes of the 3 moulds this easy and tricky way of hide waste is overcome. In the second phase the data was collected and treated and the VSMs were created. Afterwards, the VSMs and the associated process indicators were discussed with the process stakeholders in half a day workshops leaded by the authors. The objective was to test the suitability of the approach and discuss and identify ensuing adjustments needs. The major result achieved with the second phase was the validation of the interest of the analysis and the fully motivation of the teams in all companies. The third phase of the project was then launched, intending to follow the process in real time. There, each company took the leading role following in real time the process of 3 moulds. To simplify the data collection and its analysis, a guide with a set of data collecting forms was provided, included in a VSM tool to support the automatic calculation of relevant indicators and the automatic generation of the value stream map of the process under analysis, ready for print in A2 format (or larger). On this "VSM application tool" the inputs are organized based on hierarchical layers, from more general information to the sequence of the process and the detail of each step in the process. Figure 2 gives an overview of this organization. The tool was developed in Excel, allowing the manual interaction if special instances are necessary to accommodate.

Besides collecting quantitative data (Fig. 2), the significant events along the process were also recorded as notes in the VSM tool. Considering the long duration of the typical mould-making processes (10–20 weeks), these registers are needed to help the companies in preparing the final internal workshops with all the

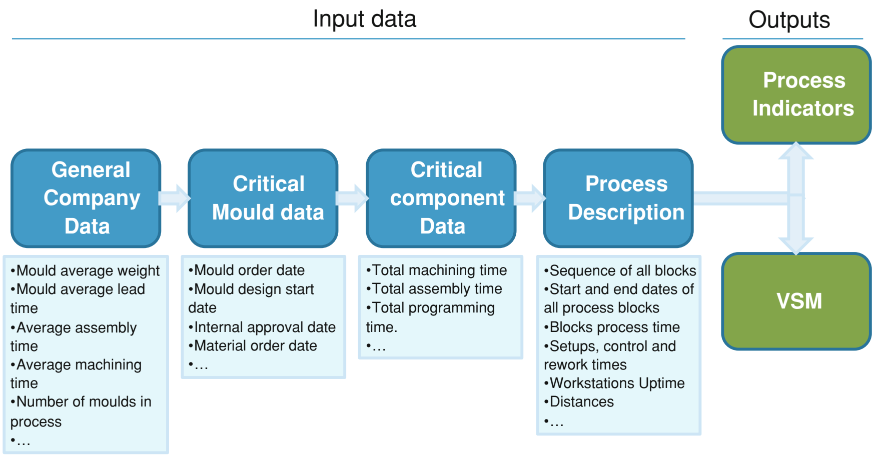


**Fig. 2** Inputs/outputs schema of the VSM application tool

stakeholders to discuss the performance, inefficiencies causes and, above all, to create the vision of the future process and identify the set of actions to turn this vision into reality.

In the following paragraphs we make use of the data collected in one company to represent the potential of the tool. Then we present some results of all companies as a benchmarking study. Because of confidentially issues, the companies are not revealed.

## 5 Results of the VSM Application

Figure 3 represents some relevant data collected in one company. After feeding the inputs, the VSM tool is able to provide the process indicators (Table 1) with the quantitative information about the whole process, and the VSM representation (Fig. 4) ready for printing and further analysis.

The analyzed mould was completed in more time than the average lead time of past recent moulds. As the mould complexity/size seems to be smaller than the average (mould machining and assembly hours are lesser than the average), this is something that justifies an analysis. One should note that the sum of the preliminary design lead time and the production lead time does not represent the total lead time of the mould. This happens because after the preliminary design is accepted by the client, the materials procurement is launched and, in parallel, the detailed design is started. The detailed design and CNC programming steps of the process develop in parallel with the mould material flow in the shop-floor. So the mould total lead time is indeed directly conditioned by the preliminary design, material procurement, and production lead time. However, if not synchronized,

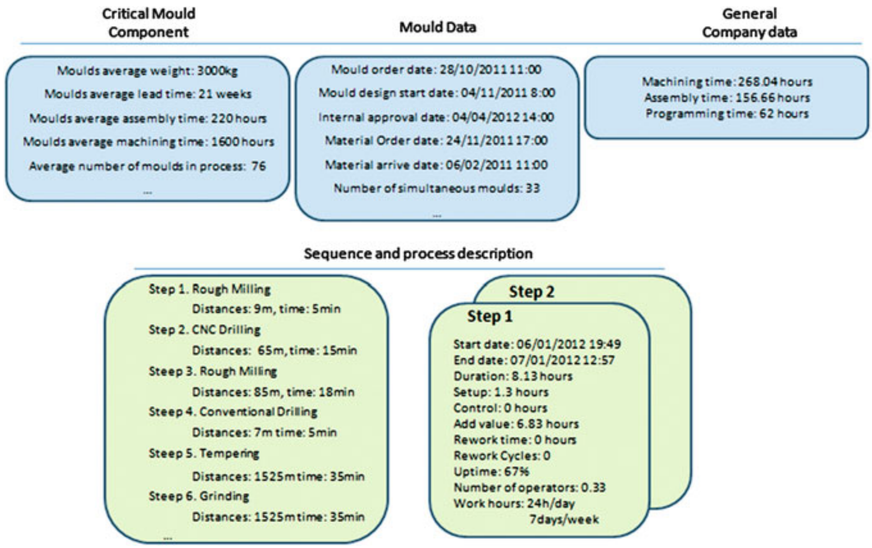


**Fig. 3** Some input data of the example case

delays in providing outputs from the mould design embodiment and CNC programming process might be responsible for the increase of the production lead time.

In the present process, the material acquisition took 1 day, but the material order only happened 5 days after the client preliminary design approval (ball 1 in Fig. 4). After that, materials arrived in 1.7 weeks (Table 1). This is an aspect that clearly points to an improvement. In in fact, the material procurement can start during the preliminary design, so that it can be launched as soon as the client approves the preliminary design. A significant reduction in the total lead time (1 week) would be achieved in this case. Another important aspect to highlight is the waiting time for the production process to start. Once the materials arrived to the shop floor, they stayed there for 1 month before starting the first production step (ball 2 in Fig. 4). It was noted that the average uptime of workstation involved in this first step was valued as 67 %, meaning that a shortage of workstation availability does not seem to be responsible for the delay. The elimination of this waiting time would result either in the reduction of the lead time, if production could start earlier, or in an economic benefit, if materials are ordered later just to make them available as soon as they are needed in the shop-floor. The causes for other significant waiting times between processes (ball 3 in Fig. 5), should also be particularly addressed.

Apart from the waiting times between processes, the utilization ratio of the whole process is a major waste indicator. Its value is 68.3 % (Table 1). It seems like the mould core component is waiting for something to happen in some steps of the process (inside some workstations). Some causes for that were pointed out: operators not available or few operators running a set of equipment, CNC

**Table 1** - Output indicators by the VSM application tool

| | | | |
|---|---|---|---|
| *Lead time* | | *Specific process steps* | |
| Recent past moulds average lead time (w) | 21.0 | Process time of all process steps (h) | 979.4 |
| Total lead time (mould in analysis) (w) (LT) | 22.7 | Add value time of all process steps (h) | 913.5 |
| Preliminary design lead time(mould in analysis) (w) | 2.9 | Utilization time in production process steps (h) (UT) | 693.1 |
| Production lead time (w) (LTprod) | 17.2 | Process time in production process steps (h) (TP) | 521.4 |
| Lead time for material deliver (w) | 1.7 | Add value time in production process steps (h) (Tva) | 484.3 |
| *Waiting times* | | *Time ratios* | |
| Waiting time inside all process steps (d) | 23.1 | Production lead time ratio (LTprod/LT) | 77.3 % |
| Waiting time inside production process steps (d) | 7.2 | Utilization ratio in production process steps (TP/UT) | 68.3 % |
| Waiting time inside critical process steps (d) | 7.2 | Add value time ratio (Tva/TP) | 93.3 % |
| Waiting time between all process steps (d) | 190.0 | Setup time ratio (Tsetup/TP) | 3.6 % |
| Waiting time between production process steps (d) | 70.9 | Control time ratio (Tcontrol/TP) | 0.3 % |
| Waiting time between critical process steps (d) | 83.4 | Rework ratio (Trework/TP) | 0.4 % |
| Total inefficiency time (d) | 106.5 | Waiting time between critical processes ratio (Twbp/LT) | 52.4 % |
| Total waiting time (d) | 203.1 | Waiting time inside critical processes ratio (Twip/LT) | 4.5 % |
| Total critical waiting time (d) | 90.6 | % Quality at first time | 27.2 % |

programmes not ready, missing tools, equipment failure, machines loaded with a batch of components meaning that one is waiting for the others,…

The total waiting times between and within process steps are important indicators to make the stakeholders perceive the process performance. In the example case, from the 159 days of lead time, 90.6 days were waiting time in the process critical path (preliminary design, materials procurement and shop-floor production steps). Globally, the core component spent 52.4 % (Twbp/LT ratio in Table 1) and 4.5 % (Twip/LT ratio in Table 1) of the production lead time waiting for "something to happen" between and inside the process steps, respectively, meaning that just in 43.1 % of the total time machines were effectively working on it. However, this includes yet the setups, reworks and controls, being the value added time 93.3 % of the process time (Tva/TP ratio in Table 1). So, only in 40.2 % of the production lead time value is effectively added to the mould core component. As far as this is the mould critical component, one can imagine how lower this time can be for the non-critical ones.

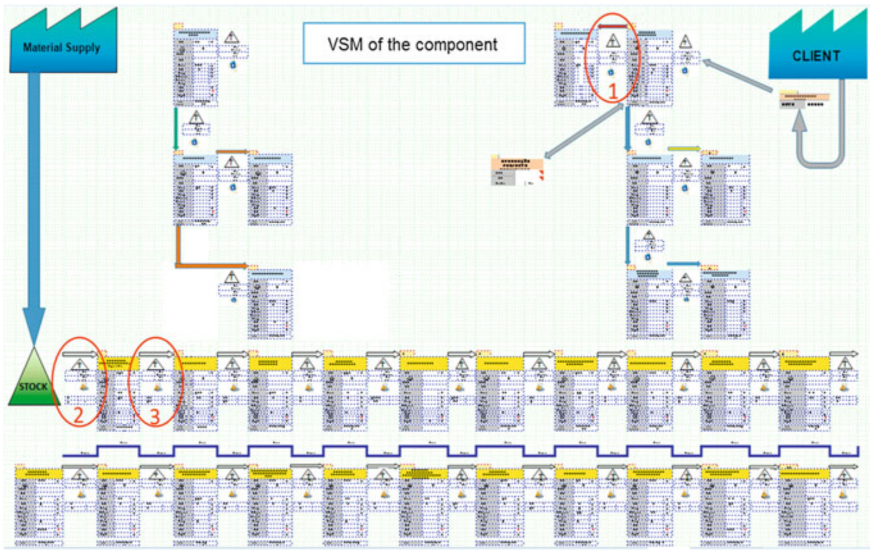


**Fig. 4** Overview of the VSM automatically generated with pictorial and quantitative information (to print in A1 paper format)

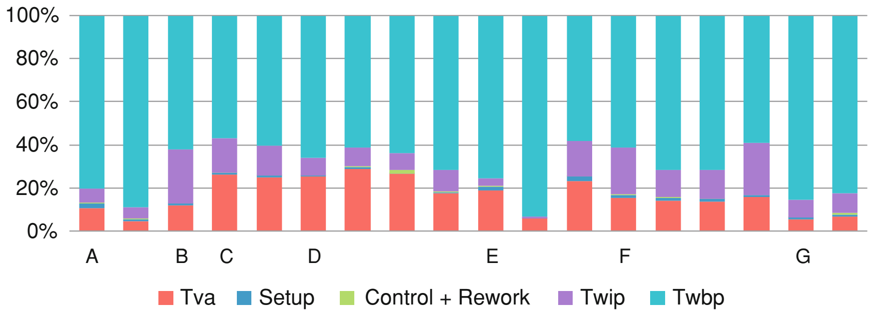


**Fig. 5** Lead time distribution of the moulds core components. Study developed in 7 mould making companies (A–G)

# 6 Study of Benchmarking

The waiting time between process steps of the mould critical component emerged as a critical issue that significantly increases the total lead time. As shown in Fig. 5, depending on the company, the waiting time between (Twbp) and within (Twip) process steps can go from near 70 % to more than 90 % of the total lead time. Reasons for that rely on lacks of synchronism between the mould core components and the remaining (not so critical) mould components; a high workload in the whole system and uncontrolled bottlenecks; and poor look ahead

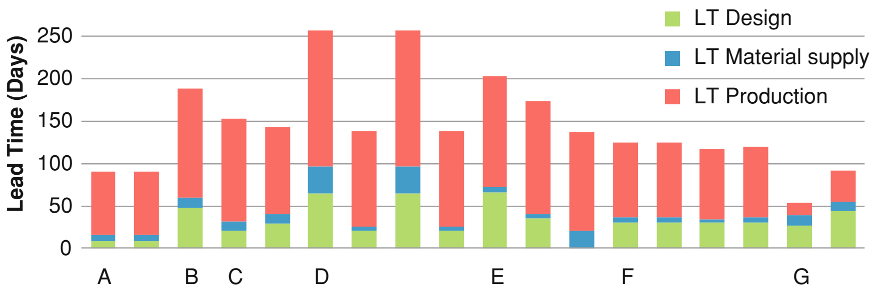


**Fig. 6** Lead times of design versus production

planning capabilities. In fact from the workshops in the companies, missing information, the work queues, urgent last minute jobs, and even long delays in initially not critical components of the same mould appeared as the most frequent reasons for the inefficient stop and go process of the mould most critical component.

One should note that the shop-floor production steps take most part of the total lead time (Fig. 6). However, in some cases the design is also very long, going together, in an intermittent way, with the production. The material supply lead time is quite similar in the studied cases, and quite constant among the different moulds in the same companies.

It's clear that the shop-floor production time is the most important part of all the mould process. Because of that, production starts just after the materials arrival, even if the design is not finished yet. However, all companies keep spending a lot of time waiting inside and between the production steps. That time can go from 30 to 90 % of the production lead time (Fig. 7). Reasons for this high percentage of waiting rely on lack of planning, machine waiting for available operators, equipment failure, the need to process rush jobs (frequently from rework needs in other almost ended moulds). Frequently, the waiting time is concentrated in initial steps, meaning that low control is provided when the mould is still far from its delivery date. So different causes deserve a deeper analysis but the understanding

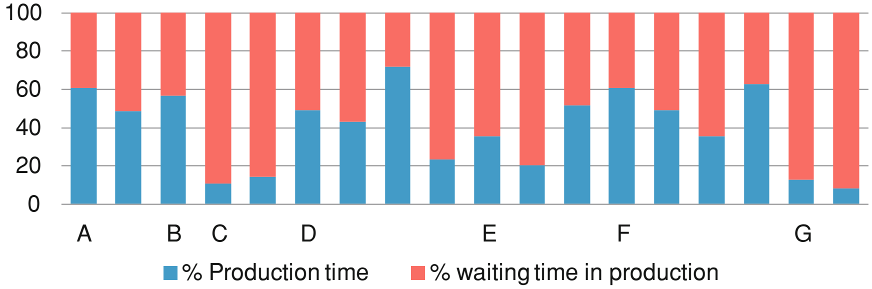


**Fig. 7** Production lead time distribution

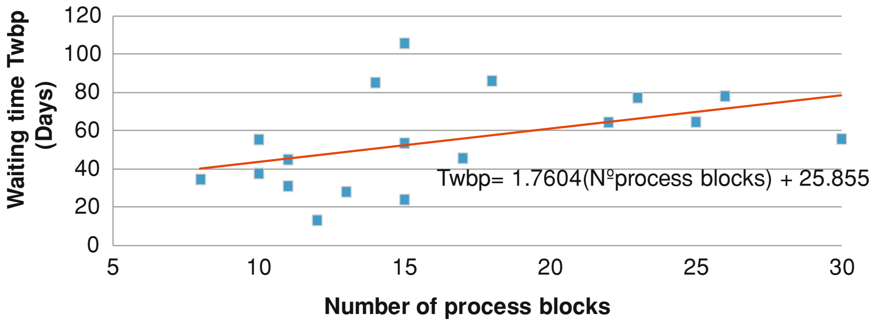


**Fig. 8** Number of process steps versus waiting time analysis

of the whole process pushes the involved stakeholders to design the appropriated actions to improve the global performance.

Another relevant result is that the waiting time tends to grow with the number of process steps (Fig. 8). Apart from some exceptions the tendency is very perceptible, process with a small number of steps use to wait less than "more broken" processes with twenty or thirty steps.

## 7 Conclusions

Mould makers keep relying must more on the technology performance than on the global improvement of the manufacturing management organization and procedures. Aiming to contribute to change this attitude, this paper intended to understand the potential of VSM techniques to facilitate, organize and take a better advantage of improvement practices in the one-of-a-kind processes of mould making industry. With the use of the VSM, it's possible to punctually and periodically represent in a simple but effective way the manufacturing process of critical components of a set of few moulds. The representation does not intend to define a standard process, even because that standard process does not exist. In industrial terms its benefits were recognized as regards to making the process visible, recognize the problems and opportunities, establish relative references to evaluate the effects of potential improvement actions. However, due to the high variety nature of mould making processes, one cannot assume that the performance of one process can be stated as an absolute baseline to really evaluate the effect of any implemented improvement actions. This is indeed a major drawback when compared to VSM application in repetitive industry.

Finally, one should say that to create a value stream map of the process does not by itself solve or point out solutions to the process improvement, but it is an efficient and effective way to identify inefficiencies and diagnose important problems of the process. Real time collected quantitative and qualitative data and the visual representation of the process that a critical component went through provides a solid ground to establish a sound analysis of what needs to be improved, aligning operators, designers, and supervisors in the vision for a better future process.

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## References

1. ISTMA World (2007) ISTMA statistical year book: on tools, dies and moulds industry international trade and manufacturing. International Special Tooling and Machining Association. ISTM: Portugal
2. Christman A, Naysmith J, Molmakers (2001) Catch 22, moldmaking technology magazine, Mar, 2001, Communication Technologies Inc
3. Henriques E, Peças P (2011) New business models for the tooling industry. In: Nelson WD (ed) Advances in business and management, vol 4. Nova Science Publishers, USA. ISBN 978-1-61324-822-5
4. Neto H (2000) Production difficulties in portuguese moulds industry, O Molde, n 43, Cefamol, p 9
5. Pereira D (2007) A Lean production na indústria dos moldes, O Molde, n 76, Cefamol, pp 32–36
6. Womack JP, Jones DT (2003) Lean thinking: banish waste and create wealth in your corporation. Free Press Business, New York
7. Hines P, Rich N (1997) The seven value stream mapping tools. Int J Oper Prod Manage 17(1):46–64
8. Hines P, Silvi R, e Bartolini M (2002) Lean profit potential. Text matters, Cardiff
9. Costa A, Henriques E, Peças P, Domingues M (2012) Mapping the mould production process: a work tool for improvement. PMI
10. Rother M, Shook J (1998) Learning to see: value stream mapping to add value and eliminate Muda. MA The Lean Enterprise Institute, Brookline

# Implementation of Lean Principles in a Food Manufacturing Company

**Ian Kennedy, Andrew Plunkett and Julfikar Haider**

**Abstract** Lean is a powerful tool, which can bring significant benefit to manufacturing industries by creating value through reduction of waste. Although the lean concept has become very popular in mass production industries such as the automotive industry, more recently the concept has been adopted in different batch processing industries and service sectors. The application of lean tools into the food processing industry has not received the same level of attention compared to the traditional manufacturing industries. The paper focuses on implementation of lean tools in a food manufacturing company in UK. The company produces diverse ranges of meat-free and dairy-free food products such as vegetable burgers, sausages, cutlets etc., and supply to the major supermarket chains in UK. In general, the typical manufacturing cycle includes raw material preparation, cooking, mixing, forming into a desired shape, coating with a crumb mixture, and frying. Finally, the products are frozen and then packaged. First, lean tools and lean practices in food manufacturing industries have been briefly presented. The implementation of lean into the company started with reviewing the products, manufacturing processes, technical facilities, and process flow charts. Key areas have been identified to achieve tangible benefits by implementing lean tools such as waste elimination, 5S, single minute exchanges of dies (SMED), Andon system, visual management, work standardisation etc. The results have been presented in the form of a case study. The paper concludes that lean tools can be successfully implemented in a food manufacturing company to improve production efficiency, to improve product quality, and to reduce production cost by reducing waste and adding value. The information presented will be of interest to general food manufacturers and in particular to frozen food manufacturers.

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# 1 Introduction

In the constantly changing environment, businesses whether large or small are facing tougher competition than ever. Food and drink industries are no exception. Rising operational costs, highly variable material costs, increased regulation on carbon emissions and waste reduction, food safety and improved quality requirements are some of the major challenges the food manufacturers have to deal with [1–3]. Furthermore, customer demand of high quality and tasty food at a lower price, organic food, balanced nutritional content in the food, and efficient food supply increases pressure on the manufacturers. In an attempt to achieve these multidimensional objectives while maintaining profitability, the industry has to develop an integrated approach of improved food processing efficiency, better quality management, effective use of energy and resources, and efficient recycling of manufacturing by-products and waste. Application of lean principles in food manufacturing could be considered as a viable solution to these challenges [4, 5]. The concepts of customer driven manufacturing and following the best practices in other industries were also suggested [6, 7]. Lean is defined as a concept of manufacturing high quality products at the lowest cost with the shortest time by systematically identifying and eliminating non-value adding activities. Although the concept was originated in automotive industry [8], it has been applied extensively in other manufacturing and service industries.

It is generally perceived that lean manufacturing principles cannot be easily applicable in industries where the production operation is carried out in large batches such as in food and drink industry. Typically, they are not considered as make to order business [7]. Although the food industry is similar to other traditional manufacturing industries in many respects, lean has not yet been widely adopted within it. However, evidence found in the literature suggests that lean manufacturing can be successfully applied in some food manufacturing areas such as red meat processing, seafood processing, production of canned food, bakery, meal production in kitchen, pizza, ketchups, sauces and jam production etc., [9–15]. The following lean tools have been generally applied in the food industries: Value Stream Mapping, 5S, quick changeover, Total Productive Maintenance (TPM), cellular flow, Kaizen, work standardization, and visual management. Typical improvements such as production efficiency, product quality, employee involvement, team spirit, co-ordination between production and maintenance, and reduction in waste, production cost, batch size, changeover time, and lead time were reported as the key achievements from the implementation of lean. However, no study on the application of lean or continuous improvement program in frozen ready-meal manufacturing was found in the literature. This paper illustrates the implementation of lean principles in a ready-made vegetable-based frozen food manufacturing. The aims of this work program are to reduce waste, increase production efficiency, improve overall business performance, and to reduce the impact on environment.

## 2 Food Manufacturing in UK

The food and drink industry in the UK is characterized by efficient and high quality manufacturing processes. This is the largest manufacturing sector in terms of both value (representing over 15 % of manufacturing turnover) and employment (almost 380,000) [3, 16, 17]. In a recent report, the impact of food and drink manufacturers on the UK economy has been analyzed [18]. The statistical figures show that the food and drink industry has remained a resilient element among the manufacturing sectors despite the recent economic downturn and has returned to the pre-recession output level at the fastest rate.

Product and process innovation through significant investment in research and development (4 % of the total R&D spend) is a core strength of the sector. The food and drink manufacturing in the UK has shown strong and positive response to environmental and health concerns by reducing $CO_2$ emissions (by at least 11 % since 1990) and lunching new health products. Although exports for food and drink in the UK have increased significantly over the past decade (by approx. 15 %), the growing trade deficit is a major concern due to faster rise in imports. UK government is planning to invest in research and development to encourage an increase in efficiency, sustainability and competitiveness in the food processing, and manufacturing sector [3].

## 3 Case Company and Manufacturing Processes

The case company manufactures a range of vegetarian and vegan (meat-free) ready meal products in the form of burgers, sausages, cutlets etc. The company produces its own brand as a key supplier in vegan products and also produces for major supermarket chains in UK. Although the company's main business is focused on manufacturing supermarket brands (90 %), the launching of own branded products has opened up opportunities to increase the customer base, to promote brand image and to strengthen the company's competitive offering. The company employs approximately 100 people and manufactures over 100 products of different recipes. The product development team continuously introduces new products every year.

The manufacturing cycle starts with collection of required raw materials, preparing, cooking and mixing them according to the specified recipe. The raw material is subsequently formed into the desired shape. Frying is carried out after coating with powdery crumb materials. Finally, the products are frozen and packaged ready for delivery or storing. The overall manufacturing steps of the food products are presented in Fig. 1. The manufacturing process is deemed as semiautomatic with two lines operating for fried and non-fried products.

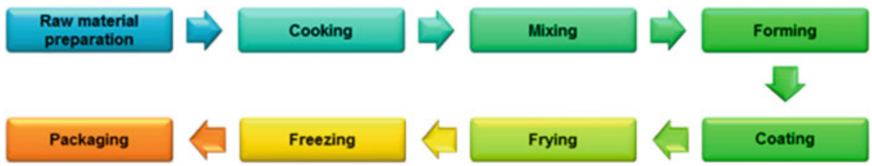


**Fig. 1** General food products manufacturing cycle

## 4 Methodology

First, a lean team was formed with the people from different departments in the company, who were knowledgeable and experienced about the products, processes, equipment, and planning. Lean team leader collected the production data and generated the process map by studying each stage of the manufacturing processes with the help from the team members. Strategic areas for implementing lean tools were identified based on the data and observation. Among many issues related to manufacturing, high waste in raw materials and motion, high consumption of water, electricity and liquid nitrogen, lack of 5S and Total Productive Maintenance (TPM) in practice, high machine downtime during changeover and lack of communications between departments were considered for investigation.

Five Key Performance Indicators (KPIs) were identified: Safety, Quality, Volume and delivery, Cost, People and Morale, and Environment. The lean projects strongly relevant to the KPI of the company were carefully and systematically selected and implemented in order to achieve immediate tangible benefits with minimum investment. A data collection procedure and structured problem solving technique were established. Boards were displayed in the shop floor to communicate action lists and control charts. The progress of lean implementation was regularly reviewed in senior management meetings as well.

## 5 Results of Lean Implementation

Although a number of lean techniques were applied in the production, packaging and warehouse areas, in this paper the results were presented based on mainly four lean principles: Waste reduction, 5S, Single Minute Exchange of Dies (SMED), and Overall Equipment Effectiveness (OEE).

### *5.1 Waste Reduction*

Data collection on food waste over a three-month period indicated that forming, frying, mixing, X-ray, and crumbing represent the high waste areas (Fig. 2). Waste

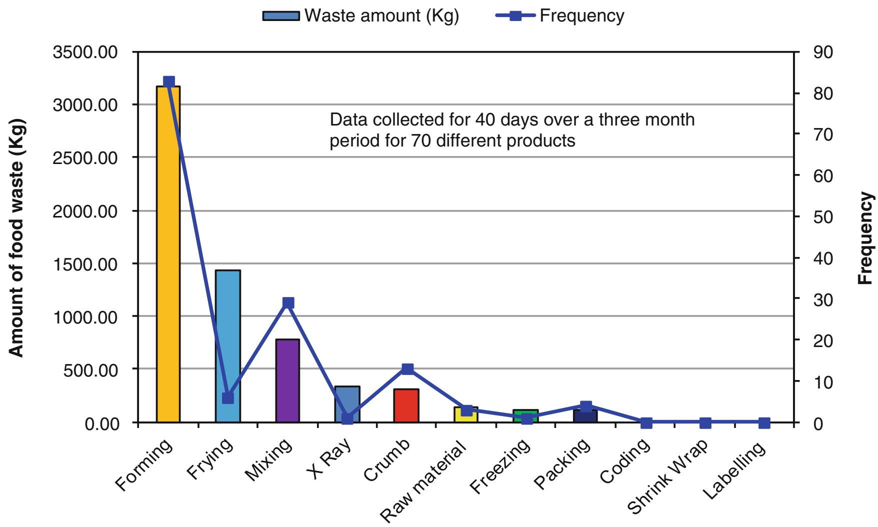


**Fig. 2** Total amount of product waste in different areas of production and the corresponding frequency of waste occurrences

was generated in the forming process more frequently than the other areas in production. With the application of good practices, the daily waste produced in mixing, raw materials during weighing, packing, and freezing areas were drastically reduced.

Significant waste was detected due to oil dripping from both ends of the fryer. On average approximately 30 kg waste of oil per day was measured as shown in Fig. 3. An oil re-routing mechanism was designed and installed to return the dripping oil back into the fryer leading to substantial reduction in oil waste.

It was also noticed that a lot of crumb covering was pulled off from the product to fall on a tray under the belt due to belt transfer problems. The measurement showed that the daily crumb waste was approximately 40 kg as shown in Fig. 4. The best way to resolve this issue was to reduce the amount of belt transfer after the crumbing operation wherever possible. To achieve this, a new belt was installed in the production line and the crumb waste was significantly reduced. The new belt also provided a sustainable solution to this waste reduction as seen in the review after almost a year.

In an attempt to reduce the cost associated with the utilities (electricity and water), monitoring system was installed to measure and review utility usage. Changes in production procedures such as placing lids on the top of pans resulted in a reduction in water usage by 80 L per cook (30 % less). LED lighting was installed with the help of interest free loan from Carbon Trust in some of the storage areas (freezer and spice room) to reduce electricity consumption. This also enabled further reduction in electricity consumption by installing light switch and motion sensors saving 53 tons of $CO_2$ per annum. The combination of high belt

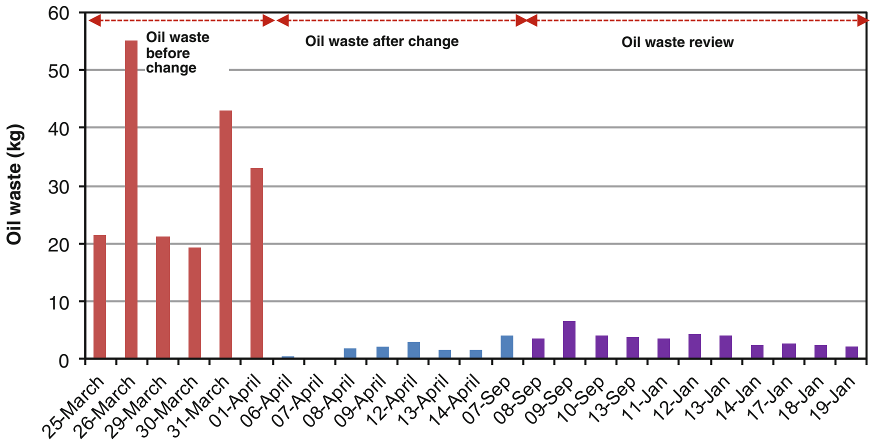


**Fig. 3** Cooking oil waste before and after the change

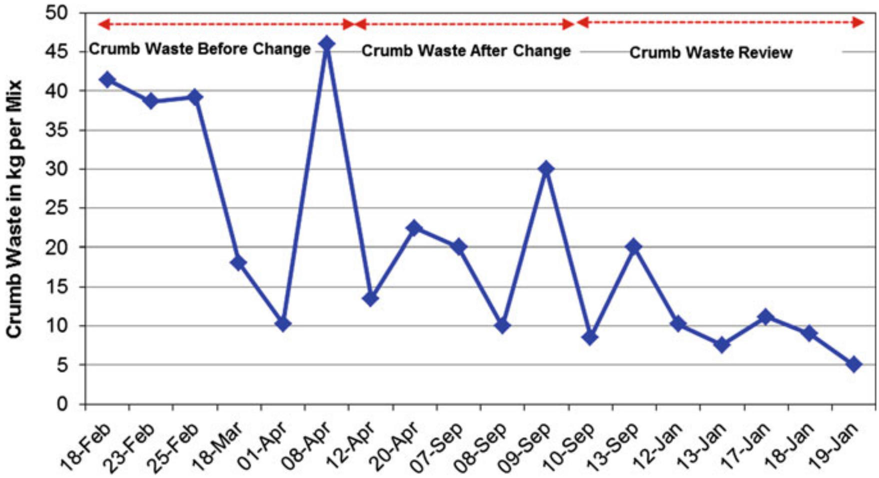


**Fig. 4** Food crumb waste before and after the change

speed (27 % higher) and low temperature (−120 °C) in the freezing tunnel resulted lower production efficiency (transfer belt was not fully loaded with products) and high consumption of liquid nitrogen. Optimizing the belt speed (medium) and temperature (−100 °C), it was possible to reduce the liquid nitrogen consumption and to improve the production efficiency.

As a part of lean implementation, the team concentrated further efforts on reducing the amount of time travelled by production staff. The staff needed to leave the production area to collect raw materials for cooking. However, they cannot re-enter production without rewashing their boots in order to ensure no contaminants enter the production. This means that staff have to take a long walk

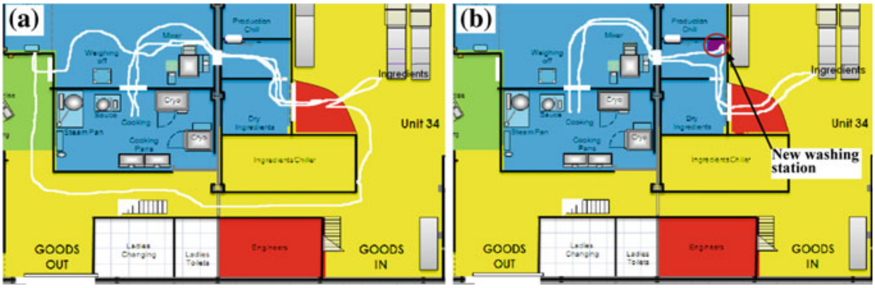


**Fig. 5** Movement path of production operator **a** before and **b** after installing a new washing station

around to enter into the production area again as the washing station is close to the production entrance (Fig. 5a). As a solution to eliminate this waste in motion, a new washing station was installed close to the production exit (Fig. 5b) so that staff do not waste time (45 % saving) in walking around leading to a higher production efficiency.

### *5.2 5S*

The housekeeping tool 5S has been implemented in the daily routines across the entire site from production to office space to improve the organization of production. 5S areas of responsibilities were distributed among the employees to own the process. Single point lessons were learnt from each activity and 5S audits were carried out regularly to generate 5S score point. New 5S audit boards for production, packing, warehouse, and office were put in the shop floor to communicate the activities and scores. Although, the initial score was low (between 30 and 40), gradually the score was improved as shown in the data collected for three months (Fig. 6). Dramatic improvements were achieved in housekeeping and cleanliness, which was absolutely essential in food manufacturing [5]. Furthermore, 5S activities generated standard operating procedure, reduced the time searching for tools, improved 5S awareness, and increased employee motivation through ownership.

### *5.3 Single Minute Exchange of Die*

European food manufacturing industries are characterized by wide range of product mix, frequent changeover in the production line and shorter production runs. In some food processing operations such as in this case company, one product does not run through a particular production line everyday rather multiple

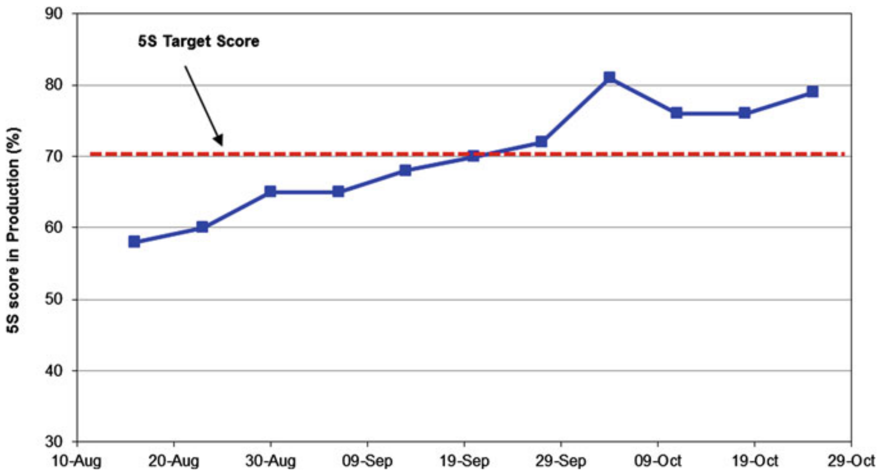


**Fig. 6** 5S scores in production over a certain period showing a steady rise

products are manufactured even in a single day. This shorter production run means frequent changeover, which leads to increased machine down-time and labor hours. Single Minute Exchange of Die (SMED) is a lean tool, which can dramatically reduce the changeover or set-up time. Set-up time is defined as the time between the last good piece off the current run and the first good piece off the next run. Several SMED activities were carried out at the packing and forming areas. Using Video analysis and reviewing the process, the changeover time in the forming machine was significantly reduced. By working as a team in a Formula 1 pit stop style, the operations of cleaning with hot water, standardizing equipment position in the line and standardizing changeover procedure reduced the changeover time resulting in better production capability, flexibility, and production efficiency.

### *5.4 Overall Equipment Effectiveness*

Overall Equipment Effectiveness (OEE) is a powerful lean manufacturing tool to measures the effectiveness of a machine or a process line by integrating factors related to availability, quality, and performance [15]. An Andon system allows monitoring of production and measuring, and analyzing of OEE. An Andon system was installed on production to collect data on equipment downtime for scheduled and unscheduled activities. To identify the equipment creating the most downtime and to drive forward priorities for the planned maintenance schedule, a scanner was fitted to the Andon system and a barcoding structure was set up to enable effective capturing of the data. Figure 7 presents an example of machine breakdown causes in different equipment and measurement of stoppage time. Significant improvement in performance and quality was also realized through the reduction of machine idling, minor stoppage and set-up times.

The OEE measured in the lines were between 55 and 60 %, which was quite a distance away from the target (85 %). However, with this system in place, the company is in a much better position to measure the OEE to progress towards the world class operation and to prepare for an organized preventative maintenance plan [15].

## 6 Discussions

In this study, the lean tools have not only been implemented but also the tangible benefits to the company have been measured in each case. Figure 8 presents the estimated cost saving through the waste reduction in six major areas totaling over £45,000. Although a significant waste of expensive raw materials was eliminated in the mixing area, it was difficult to estimate in terms cost saving. However, the activity surely contributed to the improvement in process yield. The elimination of waste not only helped the company financially, but also brought considerable environmental benefit, reducing the company's carbon footprint. Whist the exact changes in environmental impact are yet to be fully determined, it is clear that these changes are very much in the spirit of the company's long-term mission.

It should be emphasized here that financial benefits were achieved with a minimum amount of investment, which could be paid back in a short time in most cases within a year. It has been demonstrated earlier that simple changes to the machines (frying and belt) saved a lot of waste in oil and food crumb. Therefore, working closely with the equipment manufacturers could be a way forward in

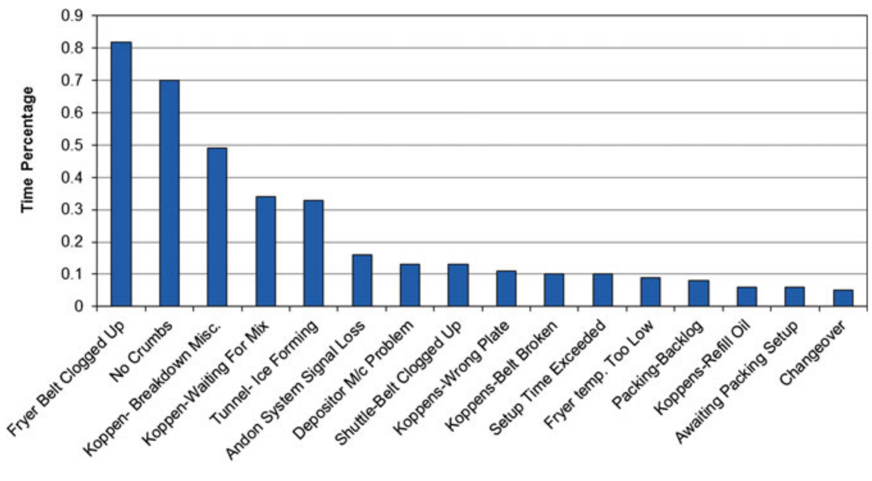


**Fig. 7** Pareto chart of machine breakdown estimation for the most common reasons

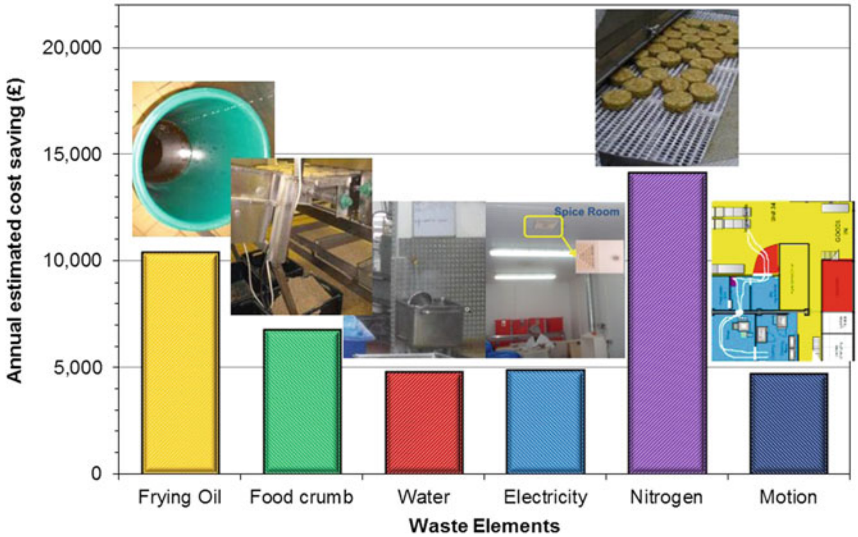


**Fig. 8** Estimation of annual cost savings due to the reduction of different waste elements

order to improve the machine design for reducing waste, easy maintenance and quick changeover. Although the general shop floor workers were not familiar with the concept of lean manufacturing, they quickly learned it through a structured training program and hands on practical work in the team. This created a learning environment through team working and a continuous improvement culture in the company by involving everybody from operator to senior management. This also generated friendly competition between shifts resulting in improved production efficiency. Finally, the establishment of continuous improvement team in the company ensured that a long-term improvement plan was in place for sustaining the lean program and the quest for continuous improvement was carried on [2]. The biggest challenges in implementing the lean were the resistance to change from the operators and personnel changes in production management. The implementation of lean manufacturing does not happen overnight; it needs time, stamina, better communication and support from the top management to make the changes a reality. As the competition is rising continuously, it is absolutely vital to accomplish and sustain the incremental changes towards achieving the long term stability and competitiveness in the business.

## 7 Conclusions

This case study clearly demonstrates that it is feasible to apply lean principles in a ready meal frozen food manufacturing company. The systematic application of lean tools has started with the waste elimination in different process steps of the manufacturing cycle across different product range. Waste reduction in cooking oil, food crumb, water, electricity, liquid nitrogen and operator movement has resulted significant cost savings for the company and created more value for the customers. The introduction of 5S across the whole factory including office areas has led to a more organized, clean and safer production area and also increased efficiency due to motivated operators and shorter time for searching tools. The SMED activities have increased the opportunities for set-up time reduction leading to quick changeover and shorter lead times. The implementation of Andon system in production has provided the opportunity to measure OEE, thus leading to more efficient manufacturing operations. In summary, the lean activities can facilitate the food company to be competitive in the market by reducing cost, improving productivity, teamwork, and consistency of product quality.

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## References

1. Dudbridge M (2011) Handbook of lean manufacturing in the food industry. Wiley-Blackwell, Hoboken
2. Higgins KT (2006) State of food manufacturing: the quest for continuous improvement. Food Eng 78(9):61–70
3. Anon (2013) Food processing and manufacturing efficiency-competition for collaborative R&D Funding, 2012 http://www/innovateuk.org/_assets/comp_agrifood_crd_final.pdf. Accessed 1 Feb 2013
4. Schmidt CJ (2013) Getting the fat out of food manufacturing-a practical approach to lean manufacturing in the food industry, 2010 EnteGreat, Inc. http://www.entegreat.com/. Accessed 1 Feb 2013
5. Beal D (2009) The ABCs of good food manufacturing. Food Safety Magazine, August/September
6. Mann R, Adebanjo O, Kehoe D (1999) Best practices in the food and drinks industry. British Food J 101(3):238–254
7. van Donk DP (2000) Customer-driven manufacturing in the food processing industry. British Food J 102(10):739–747
8. Womack JP, Jones DT, Roos D (2007) The machine that changed the world. Simon & Schuster, New York
9. Simons D, Zokaei K (2005) Application of lean paradigm in red meat processing. British Food J 107(4):192–211
10. Engelund EH, Breum G, Friis A (2009) Optimisation of large-scale food production using lean manufacturing principles. J Foodservice 20(1):4–14
11. Đekić I (2012) Lean manufacturing in two Serbian food companies-case studies. Int J Qual Res 6(2):131–136
12. Lehtinen U, Torkko M (2005) The lean concept in the food industry: a case study of contract a manufacturer. J Food Distrib Res 36(3):57–67
13. Anon (2013) Lean food processing at Gorton's Seafood, http://www./leanadvisors.com/lean-success-stories/manufacturing/lean-food-processing-at-gortons-seafood. Accessed 1 Feb 2013

14. Heymans B (2013) Lean manufacturing and the food industry,http://www./flowmakers.com/articles/Articlefoodindustryand-kaizen.pdf. Accessed 1 Feb 2013
15. Tsarouhas P (2007) Implementation of total productive maintenance in food industry: a case study. J Qual Maint Eng 13(1):5–18
16. Huxley R, Land J, Lobley M (2011) A Review of the UK food market. Cornwall Food & Drink Ltd, UK
17. Anon (2011) Food statistics pocketbook 2011. Department for Environment, Food and Rural Affairs (DEFRA), UK
18. Anon (2010) Value of food and drink manufacturing to the UK. Institute for Manufacturing, University of Cambridge, UK

# The Use of Lean Pull Strategy and Simulation in Solving Total Laboratory Automation Problem

**T. Yang and T. K. Wang**

**Abstract** The results of laboratory test play an essential role for physicians to diagnose medical conditions and lead time is the major indicator of the performance. Due to the critical role of medical laboratory, increasing number of hospitals adopt total laboratory automation (TLA) to improve the performance. Although the average lead time has a significant improvement, lots of work in process (WIP) cause by specimens piled up with 40-count at the centrifuge module and batch mode at the DXC module in some peak hours. Therefore, the use of lean value stream mapping (VSM), constant work-in-process (CONWIP), and simulation were adopted. The decision variables of the upper limit WIP level, two break points for scheduling rules, and the batching time will be decided by simulation optimization. The methodology is compared with the original system in a real practical case. The results show that 74.36 % improvement in the service level was achieved.

## 1 Introduction

A laboratory test is a medical procedure that requires a sample of blood, urine, tissue or substance in the body to check for certain features. The results of laboratory tests plays an essential role in the process of medical services, as it is helpful for doctors to diagnose medical conditions, evaluate treatments, and monitor diseases over a period of time. Its efficiency and effectiveness is the vital factor of a medical treatment. If the laboratory work takes too much time, it will affect a physician to determine the impact of the diseases and the rights of patient [1]. Lead

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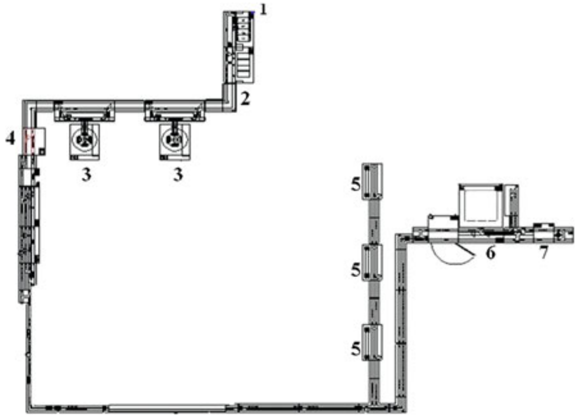
time measured from the sample registration to the result reporting is often the key indicator of the laboratory performance.

Due to the critical role of medical laboratory and its associated demanding requirements for its both efficiency and effectiveness, there are an increasing number of hospitals that adopt total laboratory automation (TLA) to improve their laboratory cycle time and accuracy, particularly, in a large medical center [2, 3]. For example, a medical center from Taiwan has improved its average laboratory system lead time from 41.48 to 1.74 h by the adoption of TLA [4]. Although the benefits of TLA are obvious, the system congestion is observed from time to time, particularly, in some peak hours. The peak-hour problem can be a very serious concern since it will cause a delayed report. The completion time of <60 min as the goal for acceptable lead time [5]. It becomes the motivation of the present study to alleviate the TLA congestion problem.

## 2 The Problem of the Case

The case is from an anonymous medical center located in southern Taiwan. There are 1,600 in-patient beds. In 2010, the annual number of in-patients and out-patients are 45,250 and 1,634,000 respectively. It purchased one TLA in 2008. There are seven processing modules that perform seven different operations toward the completion of a laboratory specimen. They are: inlet, barcode verification, centrifuge, de-capped, DXC, re-capper, and outlet as shown in Figs. 1 and 2. The study data are collected from the case hospital in April 2010. The sample size of the 1 month data area is 30,000 and is considered to be informative enough for the study. Each observation includes the information for the arrival time of entering the TLA, the cycle time in DXC, and the completed time. When observing the flow of specimens through the TLA, we are likely to see more batching and more delays in the centrifuge and DXC module. The current system performances and the

**Fig. 1** TLA system layout



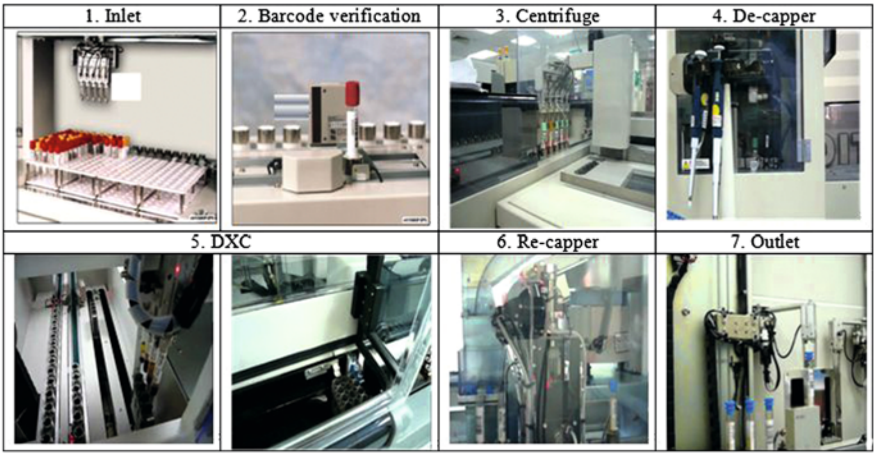



**Fig. 2** The snapshot for each TLA module

improvement opportunities lead the present study of using CONWIP, batching for centrifuge operation, parallel machine scheduling for DXC. Our major concerns to measure the service level which is defined as the percentage of specimens which lead times are less than sixty minutes.

## 3 The Methodology

### *3.1 The Current-State Value Stream Mapping*

The current-state value stream mapping (VSM) is a visual representation of the material, information flow, as well as the queues between processes as shown in Fig. 3 [6]. It serves as a visual aid to eliminate waste from current-state map to future-state map by pulling resources [7, 8]. Specimens will wait to be centrifuged until a full batch of 40 and will enter the DXC module by cyclically scheduling. There are three machines in the DXC module. Each specimen has various cycle times depending on the number and types of test order by physician. Considering the specimens is delivered in batches and the cycle time of a batch is equal to the completion time of the longest cycle time in the batch. The variation cycle time of each specimen is from 600 to 6,600 s. The uneven cycle time of specimens within the same batch group will cause the number of tardy specimens. From the current VSM of the case study, the process time is 2,091 s and the lead time is 7,320 s respectively. The non-value-added time represents 71 %. The current VSM shows the status needed to be improved and let the lean pull strategy to reduce non-value-added time.

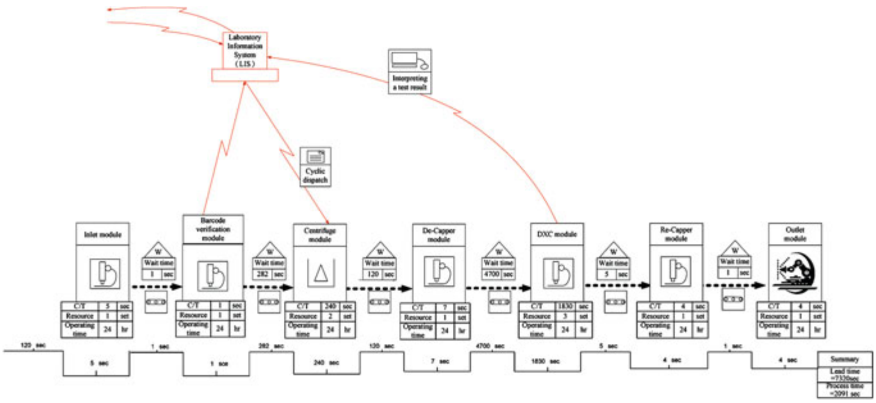


**Fig. 3** The Current-state VSM

## 3.2 The Pull Mechanism

After the material and information flow described from the current VSM, we find the batching of specimens in the centrifuge and DXC modules causes lots of WIP and idle time. By multi-CONWIP design of the pull mechanism eliminates more reductions in WIP inventory and lead time. There will be no WIP release into the CONWIP production line. The appropriate upper limit WIP level will be decided by simulation optimization.

## 3.3 Parallel Machine Scheduling

The parallel machine scheduling replaces the cyclically scheduling in DXC module. According to the accumulative percentage of total cycle time in DXC, they are evenly divided into three groups to the three machines. The three groups are from range 600 to 1,259, 1,260 to 1,499, and 1,500 to 1,799 s respectively. Schedule the specimens on each machine according to the break point order. The appropriate two break points for scheduling rule will be decided by simulation optimization.

## 3.4 Batch Processing Control

Specimens piled up at the centrifuge module and the batching time with 40-count is 120 s. In order to avoid lots of WIP, the appropriate batching time will be decided by simulation optimization.

## *3.5 Simulation Modeling and Optimization*

In order to evaluate the potential improvements based on the implementation of the Lean system, Rockwell Arena® 13.51 is used as the tool for building the simulation model that presents the overall laboratory automation systems as shown in Fig. 4 [9]. This study only deals with the improvement for the peak demand. Since there is no clear start and end times for the peak demand, steady-state simulation is used. In order to deal with the bias of empty entities and resources are idle, we have to determine the warm-up and run length. We observe the WIP of curve appears to have stabilized in order to get a reasonable warm-up period. The run length of 1.40 days (2,000 min) as the warm-up period is enough to settle out. From the perspective of coefficient of variation (CV), which is defined as the ratio of the sample standard deviation to the sample mean, is used as an indicator of the magnitude of variance. We find CV stabilizes when the number of replication reaches 30 times as shown in Fig. 5. The verification and validation are both taken, the gap between the throughput from the simulation and the system is only 3.74 %.

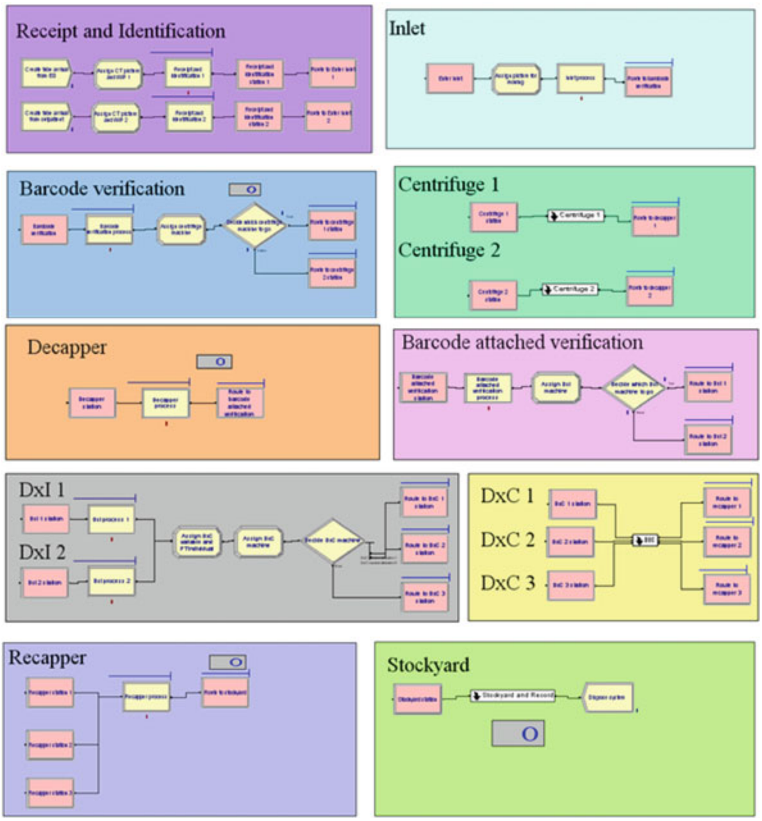



**Fig. 4** The screenshot of simulation model

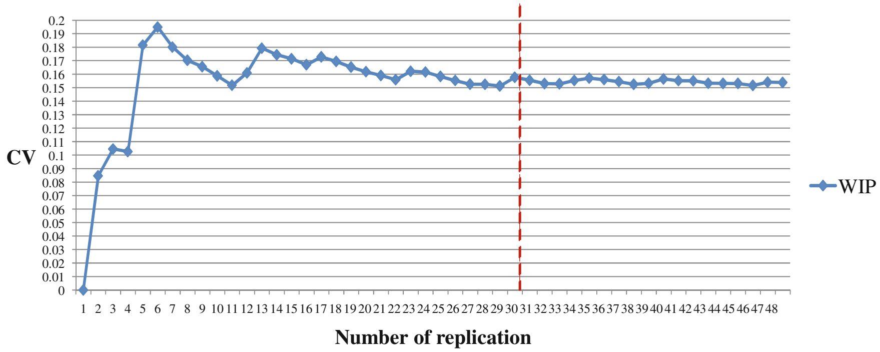



**Fig. 5** The CV chart

OptQuset is utilized in conjunction with Arena to solve the optimization of the CONWIP upper bound, the batch time in the centrifuge, and the DXC dispatching rules in order to eliminate the lots of WIP and lead time. The required notations for the formulation are defined as follow

Parameters

- $i$ The index of each specimen, $i = 1, 2, 3,\ldots,N$
- $j$ The index of CONWIP, $j = 1, 2$
- $TH_0$ Throughput of current simulation model
- $BT_0$ Batching time in the centrifuge module
- $C_j$ The upper bound of $\text{CONWIP}_j$
- $R_L$ The range of L based on data of scheduling rule in DXC module
- $R_U$ The range of U based on data of scheduling rule in DXC module

Intermediate variables

- $T_i$ The lead time of specimen $i$
- $NT_i$ A Boolean variable that indicates whether the lead time is within 60 min (the variable equals 1) or not (the variable equals 0)

Decision variables

- $CO_j$ The upper bound of the $\text{j}_{th}$ CONWIP
- $BT$ Batching time in the centrifuge module
- $L$ The break point of scheduling rule in the DXC module
- $U$ The break point of scheduling rule in the DXC module

The maximum average service level can then be defined as Eq. (1) for the larger-the-better response. Equation (2) shows throughput of applying new strategy has to be better than the one in the current system. Equation (3) set the limitation of upper bound in the CONWIP. The batching time in the centrifuge module must be set between 0 and 120 s in Eq. (4). Equations (5) and (6), searching the break points from the range 600–1,259 s, and the range 1,500–1,799 s for scheduling in the DXC module.

$$\text{Maximum Average Service Level} = \frac{\sum_{i=1}^{n} NTi}{N} \quad (1)$$

Subject to

$$\text{Throughput} \geq TH_o \quad (2)$$

$$1 \leq CO_i \leq C_i i = 1, 2 \quad (3)$$

$$0 < BT \leq BT_o BT_o = 120 \quad (4)$$

$$600 < L \leq 1,259 \quad (5)$$

$$1,500 < U \leq 1,799 \quad (6)$$

$$CO_i \in \mathit{Positive\ Integer}$$
$$BT \in \text{Real number}$$

## 4 Results

The result reveals that changing the batching time in the centrifuge and setting the DXC scheduling rules perform better than solo of a strategy; at the same time service level obtain the greatest improvement from 20.00 to 74.36 % among all the scenarios as shown in Table 1.

## 5 Discussion

As an observation the scenario in changing the batch waiting time in the centrifuge and setting the DXC scheduling rules not only provide the most significant improvement in service level from 20.00 to 74.36 %, an improvement of

**Table 1** The scenarios analysis

| Runs | Scenarios | Service level (%) | Throughput (unit) | Lead time (s) |
|---|---|---|---|---|
| 1 | Current status | 20.00 | 15,354 | 7,964 |
| 2 | Setting CONWIP | 17.68 | 15,516 | 8,443 |
| 3 | Setting the DXC scheduling rules | 57.48 | 15,349 | 4,222 |
| 4 | Setting CONWIP + DXC scheduling rules | 70.43 | 13,586 | 3,457 |
| 5 | Setting the batching time | 19.49 | 15,352 | 7,739 |
| 6 | Setting CONWIP + batching time | 17.08 | 15,350 | 9,003 |
| 7 | Setting the DXC scheduling rules + batching time | 74.36 | 15,367 | 3,330 |
| 8 | All | 73.00 | 15,551 | 3,337 |

217.80 %. Moreover, reducing lead time from 132.74 to 55.5 min, an improvement of 58.10 %.

However, the proposed methodology requires the amount of time to build a simulation model of the case problem of variable demand and arrival time in different months and seasons. This study only bases the data of April of 2010, which can extend the model for future research.

With increasing advances in technology of medical industry, patients care about not only the quality of service, but also efficient treatment. The demand of laboratory work has grown rapidly in recent years. A report laboratory test result promptly is often the key to successful treatment. It enables physicians to determine the patient's condition before further diagnosis and reduces the patient's waiting time. Therefore, how to shorten the waiting time for patients and improve their satisfaction becomes a very important issue for hospitals.

This study defines a lean implementation procedure, leading to a push-control system, and then to a lean pull-control system. The proposed analysis procedure can be simply extended to problems that have complex production variability and demand uncertainty, i.e., laboratory industry. By setting batch time to wait for the adjustment, improvement of dispatching rules, and combined with CONWIP strategy, our proposed method significantly improves the efficiency of laboratory work and reduces the patient's waiting time. This study also demonstrates the potential of lean to the laboratory system and could provide a vision of health care for the future.

**Acknowledgments** The authors thank the anonymous medical center for providing the case study. This work was partially supported by the National Science Council of Taiwan, Republic of China, under grant NSC-101-2221-E-006 -137 -MY3.

## References

1. Graban M (2009) Lean hospitals: improving quality, patient safety, and employee satisfaction. CRC Press, New York
2. Seaberg RS, Stallone RO, Statland BE (2000) The role of total laboratory automation in a consolidated laboratory network. Clin Chem 46(5):751–756
3. Sarkozi L, Simson E, Ramanathan L (2003) The effects of total laboratory automation on the management of a clinical chemistry laboratory. retrospective analysis of 36 years. Clin Chim Acta 329(1–2):89–94
4. Chien SW, Hsu YN, Kou CY, Hunag KH, Chen YF (2006) Implementation of a central laboratory with consolidated laboratory network for central Taiwan national hospital union. In: Proceedings of the 5th WSEAS international conference on circuits, systems, electronics, control \& signal processing, World Scientific and Engineering Academy and Society (WSEAS), Dallas, Texas, pp 181–185
5. Hawkins RC (2007) Laboratory turnaround time. Clin Biochemist Rev 28(4):179–194
6. McKenzie P, Jayanthi S (2007) Ball aerospace explores operational and financial trade-offs in batch sizing in implementing JIT. Interfaces 37(2):108–119

7. Womack JP, Jones DT (2005) Lean solutions: how companies and customers can create value and wealth together. Free Press, New York
8. Yang T, Lu J-C (2011) The use of a multiple attribute decision-making method and value stream mapping in solving the pacemaker location problem. Int J Prod Res 49(10):2793–2817
9. Yang T, Shen YA, Cho C, Lin YR (2012) The use of a simulation, a hybrid Taguchi, and dual response surface methods in the automated material handling system tool-to-tool strategy for a 300-mm fab. Eur J Ind Eng 6(3):281–3002012

# Part VI
# Energy Efficiency in Factory Life Cycle

# Dual Energy Signatures Enable Energy Value-Stream Mapping

**Egon Müller, Timo Stock and Rainer Schillig**

**Abstract** Minimizing waste is one of the essences of modern Lean Production Systems. The activities for waste reduction are usually focused on lead time and inventory. Therefore the method of Value-Stream Mapping (VSM) has proven itself as a very powerful tool. Nowadays the unnecessary consumption of energy is more and more regarded as a kind of waste, too. There is a need to extend the proven method of Value-Stream Mapping to an Energy Value-Stream Mapping (EVSM). Therefore criteria must be defined that allow us to divide the energy consumption into value-adding and non value-adding. This is shown by using the example of a chip removal process, where the energy requirement for an air-cutting process is compared to that for an operation with a workpiece. The dual view of value-adding and non value-adding energy consumption provides the opportunity of extending the Value-Stream Mapping systematic to an Energy Value-Stream Mapping.

## 1 Introduction

During the second half of the last century the energy demand of machine tools has increased approximately a hundredfold [1]. While, in the fifties of the last century, the powers of turning centers were still to be found in the single digit kilowatt range, they nowadays are frequently situated in the three-digit range. The increased energy consumption was primarily used to speed up the machines for achieving shorter cycle times and shorter tool change-over times.

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Nowadays, production processes not only have to be very fast they have to be energy efficient as well.

Lean Production Systems, which is based on the principles of the Toyota Production System, are currently regarded as the most efficient ones. The methodical core of Lean Productions Systems is to regard non value-adding processes as waste, and its objective is to remove such waste from the processes. Unnecessary inventories or waiting, for example, are typical forms of waste. In most cases creating waste is not only time-consuming but also energy-consuming [2].

## 2 Value-Stream Mapping and Energy Value-Stream Mapping

The value-stream mapping according to Rother/Shook [3] shown in Fig. 1 is the basic instrument for implementing the Lean Production Method. The optimizing of the value-streams is mainly achieved by reducing the production lead times and the inventories. In doing so the lead time of the entire batch is contrasted with the accumulated cycle times in the form of processing time. This shows clearly the lead time-extending effect of a batch-oriented production (see Fig. 1).

Rother/Shook doesn't predicate that there is no waste within the processes itself and thus within the process time. They do make a distinction between value-adding time and cycle time, their VSM graphics consistently represent the processing time as the sum of the cycle times. However the room for improvement between the processes is usually greater than the one inside the processes. Due to that their focus was to reduce the lead time.

Nevertheless this may convey the impression that the process sequences within the cycle times are, as a matter of principle, free from waste.

However, this is not so. As a consequence it is necessary to identify, within the cycle times, the value-adding and the non value-adding amounts of time. It is only then that the energy input in the cycle times can also be differentiated into value-adding and non value-adding inputs. If the view on the energy input is to be

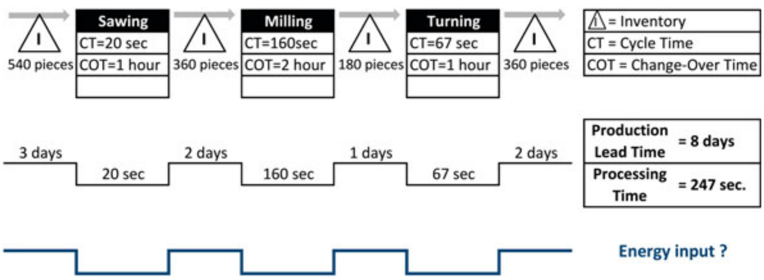


**Fig. 1** Value-stream mapping [3]

integrated into the VSM, then by analogy with the rectangular function of the time line an appropriate energy line must first be drafted.

There are different approaches for extending the classical VSM by a mapping of the energy value-stream [4–6]. Up to now, however, no energy value-stream view exists which provides an exclusively dual assessment of the energy input, based on the criteria value-adding and non value-adding. This perspective is, however, necessary when the view on the entire energy balance of a complex process chain is at the centre of interest.

# 3 Recording of Dual Energy Signatures Using the Example of a Chip Removal Process

## *3.1 Recording of Dual Energy Signatures: Test Set-Up*

Using a 3-axis vertical machining centre Hermle (Type C 30 V, see Fig. 2a), three grooves were milled in succession into a component made from heat-treated steel C45. Chip removal was done in full cut, with an indeed of 7.5 mm over a distance of 60 mm, using three HSS end mill cutters with diameters 8, 12, and 16 mm (see Fig. 2b).

The energy was measured using a portable wattmeter Yokogawa (Type CW240). This meter was connected during operation by means of a current transformer and clamp-type test probes (see Fig. 2a). Apart from the electric energy the machining centre also requires additional energy in the form of compressed air. The flow rate was measured in parallel with the energy measurement, using a flow sensor ifm (Type SD6000).

The first pass took place using the air cutting method, in other words without a workpiece. This enabled us to see what the energy signature of the process looked like without a workpiece contact (see Fig. 3a). The second pass took place with a workpiece, that is, using a workpiece contact. The energy signature achieved with

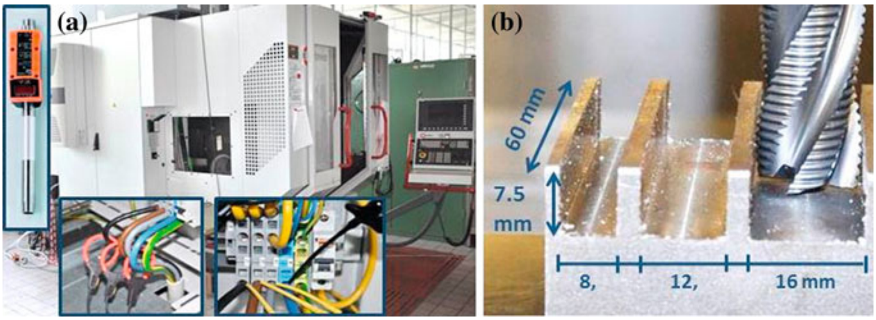


**Fig. 2** **a** Machining centre and measurement system. **b** Workpiece

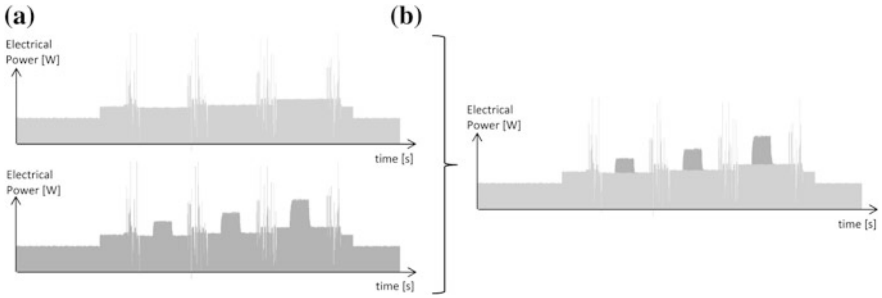


**Fig. 3** **a** Energy signature without and with workpiece. **b** Dual energy signature

a workpiece contact is represented in Fig. 3a. When both signatures are laid one on top of the other you get the dual energy signature shown in Fig. 3b.

## *3.2 Analysis of Dual Energy Signatures*

Figure 4 gives a detailed representation of the respective operating states of the machine and of the dual energy signature of the chip removal process. The signature in light grey shows the required electrical power during air cutting, while

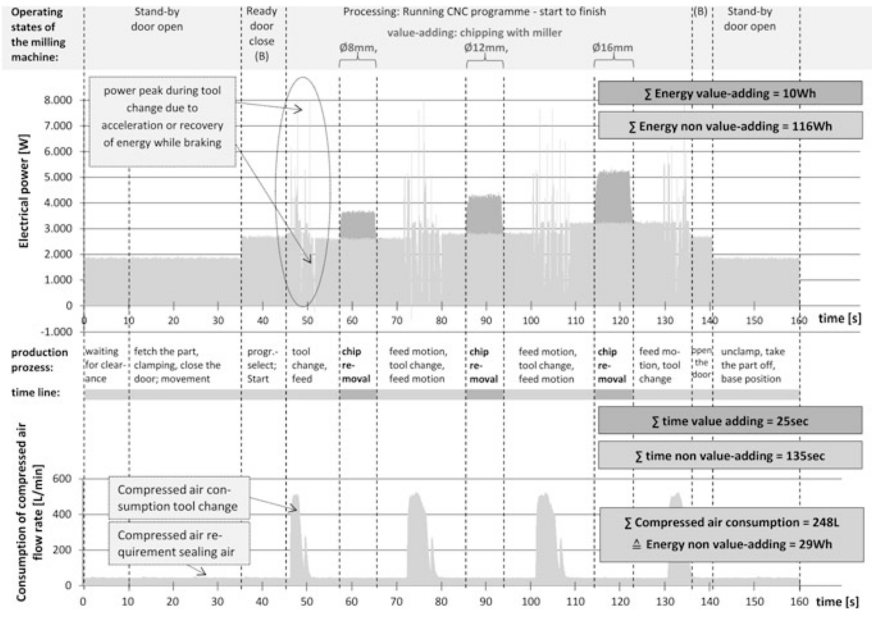


**Fig. 4** Dual energy signature of a milling process

the signature in dark grey shows the additional power consumption during chip removal. Only the chip removal process is value-adding.

The value-adding times are marked by means of dark grey bars in the time line shown beneath the signatures. The signature in light grey at the bottom end of the representation shows the consumption of compressed air. This consumption is exclusively non value-adding because it takes place outside the value-adding time.

The energy directly required for chip removal is 10 Wh, the value-adding time is 25 s. The non value-adding energy input on the contrary is 145 Wh (116 Wh electrical +29 Wh compressed air), while the non value-adding time used is 135 s.

In the signature of the electrical power requirement the power peaks appearing after the rise in power consumption in the ready to operate state of the machine are catching the eye as compared with the stand-by condition. These are caused by the tool change in the machine tool and the acceleration processes associated to them. At the same time also negative peaks can be perceived, which arise when the drives are decelerated and which feed energy back into the electric network.

The dark grey "energy bars" show the energy used for chip removal as opposed to air cutting. The energy required during chip removal rises as the milling diameters increase. This is due to the fact that all three chip removal operations took place at the same feed rate ($v_f = 450$ mm/min.), thus resulting in different material removal rates. In comparison with the end mill cutters with diameters 12 and 16 mm, the cutter with dia. 8 mm removes less material in the same period of time and, in consequence, requires less energy. The power requirement prior to and following the respective processing step varies because of the different power consumptions of the milling spindle at different speeds.

The signature of the compressed air measurement shows the flow rate [L/min] as a function of time [s]. In addition to the constant compressed air requirement for the sealing air, four areas of sharp compressed air rise can be seen. These rises are due to automatic tool changes. In total the compressed air consumption is 248 L for this cycle. There is no difference in consumption between air cutting and cutting using a frictional connection.

To allow for an appraisal of the total energy consumption the compressed air flow rate measured is converted into an equivalent electrical power. According to Ref. [9], for efficient compressed air systems values between 6.5 and 7.5 kW per $m^3$/min may be used as a basis. This investigation assumes that per $m^3$/min of flow rate and at a pressure of 6 bar, the power requirement will be 7 kW [10]. For the compressed air consumption of 248 L referred to above, the energy demand is, thus, 29 Wh (see Eq. 1). As the compressed air does not contribute to the chip removal or in other words to the value-added, it is considered non value-adding.

Energy consumption compressed air:

$$\text{Energy consumption compressed air} = \frac{7\,\text{kW}}{\text{m}^3/\text{min}} \times 248\,\text{L} = \frac{116\,\text{Wh}}{1{,}000\,\text{L}} \times 248\,\text{L} = 29\,\text{Wh} \tag{1}$$

It is now very easy to define the energy efficiency $\eta_{Eva}$ of the process as the quotient of the energy $E_{va}$ (value- adding) used to add value and of the total energy demand $E_{va} + E_{nva}$ (non value-adding) (Eq. 2). The same applies to the consideration of the $t_{va}$ (time value-adding) used within the cycle time. This approach in the first instance offers the opportunity of examining the process in a comprehensive way with regard to its energy input and, if need be, of subjecting it to critical analysis.

Efficiency and calculation example:

$$\eta_{Eva} = \frac{E_{va}}{(E_{va} + E_{nva})} \quad \eta_{Eva} = \frac{10\,Wh}{(10\,Wh + 145\,Wh)} = 6.5\,\%$$
$$\eta_{tva} = \frac{t_{va}}{(t_{va} + t_{nva})} \quad \eta_{tva} = \frac{25\,s}{(25\,s + 135\,s)} = 15.6\,\% \tag{2}$$

## 3.3 Process Analysis by Means of Energy Signatures

The use of the dual signatures makes it possible to shine a light on the production process itself as regards the time used and the energy input. The cycle time as well as the energy input within the cycle time are thereby consequently subdivided into value-adding and non value-adding portions [11].

Figure 5a shows how dual signatures contribute to increased transparency as regards value-added considerations. In Data Box Milling (see Fig. 5b) the results of the investigation are shown nominally in the form of concrete numerical values as well as proportionally in the bars beneath. The efficiency of the process in terms of time and energy can, thus, be seen immediately.

Based on such an overall view it may well be that one or another production process as such gives reason for questioning. In some situations it may be more advantageous to replace an inefficient process by a more suitable one instead of improving it at great expense [7].

According to Ohno [8] 'waste of processing itself' is a form of waste. That is to say, if the process being looked at is not the most efficient way of creating a

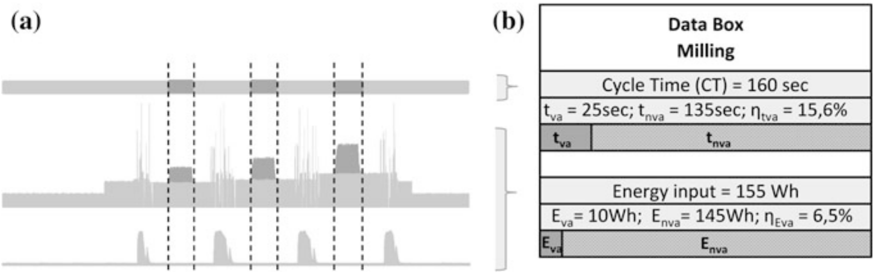


**Fig. 5** **a** Dual signatures. **b** Modified data box

desired functionality, then obviously there must be a more suitable process. In this sense the process looked at first is less efficient and, in consequence, abundant with waste. If now for example the relationship between a non value-adding energy input and a value-adding energy input is particularly unfavorable in a manufacturing process, then this might point to the necessity of questioning the process itself. This is why it is reasonable in Energy Value-Stream Mapping (EVSM) to pointedly look at the energy input and use the dual approach only.

## 4 Extended Value-Stream Mapping and Energy Value-Stream Mapping

The extended value-stream mapping in Fig. 6 systematically shows value-adding and non value-adding time and energy in the production process and along the value-stream. At the end of the analysis their sums are in addition contrasted with the lead time and the processing time. The internal logic of the VSM is maintained.

According to Rother and Shook [3], the cycle time is considered a value-adding time in VSM. This idea has, however, to be abandoned when looking at the energy because within the cycle time only a relatively small portion of the energy used contributes to the value-added. The same applies to time: the energy signatures make this quite clear. In consequence the representation of the energy value-streams makes it possible to develop the existing VSM further by revealing waste in form of energy and time also within the cycle times.

The VSM is thus consequently advanced to become an EVSM and in addition offers the user the opportunity of revealing and visualising any kind of waste in the production process itself.

When optimising energy value-streams it is important to look at the value-stream as a whole, for this helps to avoid sub optimizations. If the energy balance

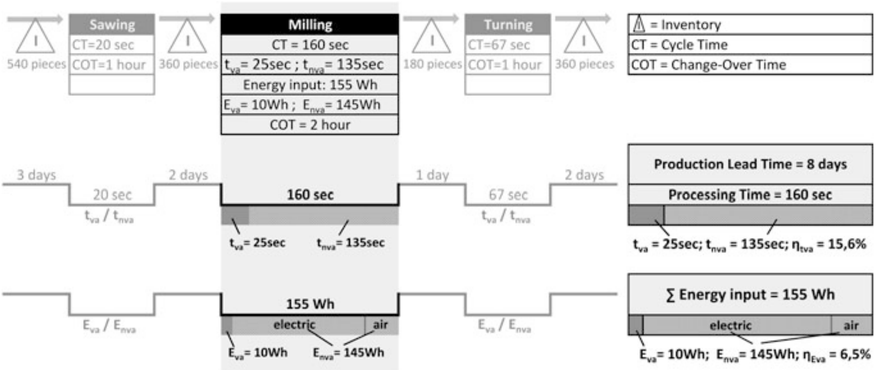


**Fig. 6** Extended value-stream mapping and energy value-stream mapping

is poor and if it is impossible to find a more efficient manufacturing technology and a more suitable process, then as a second step the energy input which does not contribute to adding value can be reduced systematically.

## 5 Summary

In the chip removal process the energy requirement for air cutting as opposed to that for an operation using a frictional connection can be determined by means of the energy signatures. The value-adding and non value-adding energy inputs can thus be determined relatively easily. This differentiation provides the opportunity of extending the value-stream mapping systematics to energy-related considerations.

In the same way as the comparison of cycle time and lead time, the energy signature helps to make up the balance of the production process itself with regard to value-adding and non value-adding time and energy. This makes any kind of waste clearly evident. While its internal logic is maintained, the value-stream mapping generally accepted in the production environment is extended by a representation of the energy input to energy value-stream mapping. The reduction to a dual approach makes it possible to subject the technology used to critical analysis in respect of its energy balance. This methodical procedure provides a practical tool to process designers for a comprehensive analysis and the improvement of value-streams.

## References


1. Zein A, Herrmann C, Sauermann D (2012) Wie viel verbraucht eine Werkzeugmaschine? Studie zu Einsparpotenzialen bei Werkzeugmaschinen im Automobilbau. Elektro Automation No. 2, p 22
2. Schillig R (2010) Lean und Green: Zwei Seiten einer Medaille. Presentation on the Aalener Gießerei Kolloquium, May 2010
3. Rother M, Shook J (2009) Learning to see value-stream mapping to create value and eliminate muda. Lean Enterprise Institute, Cambridge
4. Erlach K, Westkämper E (2009) Energiewertstrom. Der Weg zur Energie Effizienz Fabrik. Fraunhofer Verlag
5. Reinhart G et al (2011) Energiewertstromdesign. Ein wichtiger Bestandteil zum Erhöhen der Energieproduktivität. Wt Werkstattstechnik online, No. 4, hunt 101
6. Brüggemann H, Müller H (2009) Nachhaltiges Wertstromdesign. Integration der Energie- und Materialeffizienz in das Wertstromdesign. Wt Werkstattstechnik online, No. 11/12, hunt 99
7. Müller E, Schillig R, Stock T (2012) Darstellung von Energiewertströmen erlaubt umfassende Wertstromanalyse. VDI-Z, No. 7/8
8. Ohno T (1988) Toyota production system. Beyond large-scale production. Productivity Press, Portland, p 19
9. Bayrisches Landesamt für Umweltschutz (2004) Effiziente Druckluftsysteme Energie sparen-Klimaschützen-Kosten senken! Senser Druck Augsburg

10. Rief M, Kalhöfer E, Karpuschewski B (2010) Energiebetrag verschiedener Kühlschmiersysteme. Werkstatt und Betrieb. No. 09/10, pp 142–145
11. Müller E, Schillig R, Stock T (2012) Duale Energiesignaturen ermöglichen modifizierte Wertstromanalyse. In: Müller, Egon; Bullinger, Angelika C. (Hrsg.): Intelligent vernetzte Arbeits- und Fabriksysteme. Tagungsband zur 9. Fachtagung Vernetzt Planen und Produzieren: VPP2012 and 6. Symposium Wissenschaft und Praxis, Wissenschaftliche Schriftenreihe des IBF, Sonderheft 18, TU Chemnitz, pp 167–178, 08–09 Nov 2012

# Practical Approach to Analyze and Optimize Energy Efficiency Within a Press Hardening Process

**Horst Meier, Dennis Bakir and Björn Krückhans**

**Abstract** The experiences of 31 collaborative research projects, financed by the Federal Ministry of Education and Research, were connected through the "Efficiency Factory". The focal point of support was "resource efficiency in production". One of the selected projects "reBOP"(efficient production by resource-based evaluation and optimization of process chains) was investigated at the Chair of Production Systems, Ruhr-University Bochum from 2009 to 2012. A concept to identify weak points in terms of energy efficiency was developed within the project. The concept was adopted to analyze the process chain and machinery of an associate partner. Therefore the energy efficiency of the organizational and technical level was improved. Companies, involved in this project, achieved specific results to strengthen their competitive ability: enabling them—as a system provider—to create energy efficient process chains and to assist customers in efficient use of their machinery and equipment. Objective of mentioned cluster-project was to develop and implement a holistic concept to evaluate and optimize process chains and assets energetically. Energy efficiency in this context means a reduction of electric energy input at a constant output quantity. Inevitable need to evaluate and compare specific processes is their uniform, normed character. For this purpose a set of unique key performance indicators was created. This set enabled the companies to transform even dissimilar processes and, in the consequence, to benchmark and enhance them. Additionally, employing the novel simulation software, present processes were configured, under organizational and technical aspects, up to 30 % more energy efficient. The successor project "rebas" (resource efficient development and optimized operations of filling-facilities within the food industry through development of a novel simulation software) will be set up on "reBOP"-generated insights, focusing brewery-facilities. Systematic consideration of all kinds of process related resources and a steadily evolving plant layout planning tool, supported by novel simulations will extend previous generated solutions.

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# 1 Introduction

Former export champion Germany, highly productive but scare of essential resources at the same time, generated in 2011 total revenue of 658 billion euro, just regarding production output (25.6 % of GDP). At the same time more than 59 % of total energy consumption has to be covered by energy imports. Energy is still regarded as the most limiting factor, whose access has to be ensured. But the nexus of effects is quite more complex: In 2011 Germany was forced to import resources (including carriers of energy) for more than 137.2 billion euro. But high production rates are not only related to one single limiting factor but to a conglomerate of resources. Physical availability and the demanded price of these types of resources will be two of the most critical changes regarding the motivation of using fewer resources for means of the same level of production. In other words: it is inevitable to increase resource-productivity to stay competitive.

Between the years 1960 and 2000 Europe's specific energy usage (energy usage per output) was reduced by 64 % [1]. Coincident with this progress the total energy usage rose extraordinary, induced by a higher overall production output. Following this evolution resource-productivity rose, but total demand for resources escalated intensified. Both, economy and customer structure will increase steadily, so the demand of resources will increase. Another driving force is the clearly articulated customer need for greener products. This need goes hand in hand with the desire for more transparency in a more complex world [2]. Resource-productivity seem to be one answer to multiple questions; to produce more with less material, to save the environment, to create additional stakeholder transparency, and to sensitize deciders. Taken together, regarding material intensity in production, direct substantial potential exists, which has to be achieved [3] (Fig. 1).

For majority of companies intensification of productivity, in means of measures for ensuring and optimizing competitiveness, is a prioritized field of action. This evaluation means that this seems to be more crucial than product or process

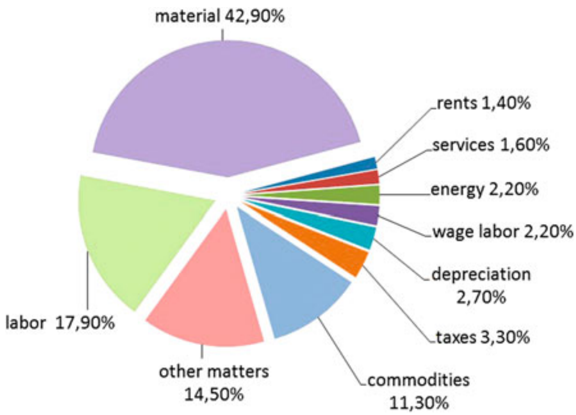


**Fig. 1** Average cost structure within German production sector [12]

innovations [4]. A detailed consideration of prevalent cost structures within the producing sector is also confirming this estimation. Stake of energy costs are about 2.2 %. Even, frequent discussed labor costs just mean 17.9 % of all costs. Overwhelming cost factor are costs of resources, which mean 42.9 %. To put it in a nutshell, enforced commitment regarding resource-productivity contains an unequal higher potential than further marginal optimization in the 2.2 %-area, which energy-efficiency can assess.

Offering a profound framework to analyze specific processes and components regarding limited resource considerations within producing industry was focal point of cluster project "reBOP". Generated holistic solution is able to identify and visualize inherent weak spots to optimize specific process chains. In the course of reBOP the whole press hardening process, executed at voestalpine Polynorm GmbH and involved components were analyzed and were designed at the organizational and technical level more resource-efficient. Main drivers were electric energy, heat energy, and compressed air.

Successor project "rebas", started in September 2012, will broaden the range of this approach. Resource is understood as all types of crude, operating, and auxiliary material affected by interlinked production processes. All resources will be assessed from an organizational and technological but also from an economic perspective. Another tier consists of a continual transformation of prevailing processes into a realistic material flow simulation tool. Material flow simulation will provide further immense contribution to efficient production. This type of simulation studies allows sustainable conclusions of several "what if"-scenarios without eventually disturbing already existing production systems. As a consequence, the studies do not cause additional costs. Using this tool a digital representation of modern industrial production system can be created. An optimization with regard to the factors time, cost, quality, and especially energy can be conducted based on the digital model [5].

## 2 Description of the Production Process

The indirect method of hot stamping is used to produce body parts for the automotive industry. It offers the possibility to produce high-strength and lightweight end products by combining pressing and hardening processes. This kind of production line for indirect press hardening was introduced at voestalpine Polynorm GmbH for the first time, which uses already preformed blanks. The production line is characterized by the linkage of resource-intensive processes, which are implemented from different manufacturers using different components.

At the beginning of considered process chain (Fig. 2) is the furnace of the manufacturer BSN Thermprozesstechnik GmbH to heat up the material to the required temperature for the press hardening process. After the first process step the actual pressing and curing process starts with a holding press from Dieffenbacher GmbH & Co. KG, within which high-performance drive components of Bosch Rexroth AG are

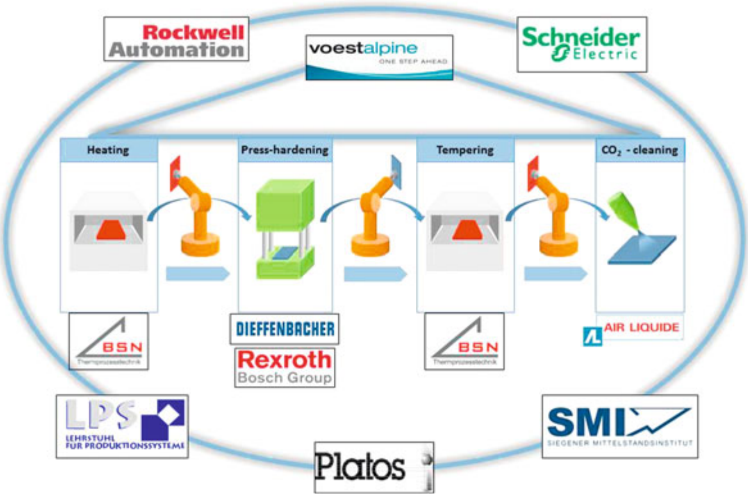


**Fig. 2** Press hardening process with members of the reBOP consortium

embedded. An additional furnace for optional tempering processes at a lower temperature level is available. The usage depends on the used material and the intended application of the components. An integrated $CO_2$ cleaning chamber is required, due to unavoidable scaling at high temperature in the first furnace. The component is implemented by Air Liquide Deutschland GmbH. It is state of the art, that these and similar process sequences are highly automated and adapted to direct coupling of the individual components. The design of the feedback level of each step varies and is mostly determined by the conflict of the information to be transmitted, the information quality and the necessary speed of the system response [5].

## 3 Practical Approach Within the Research Projet reBOP

The requirements of the project resulted in a division of four cross-sectional tasks (CST) [6], which together form a comprehensive, almost universal solution:

**CST 1: operating figures, analysis, and optimization methodology**

The goal of the first cross-sectional task was to develop a methodology to rate processes under resource considerations and subsequent optimization at the organizational level. This included the development of a methodology for the standardization of process data in order to adapt existing performance measurement systems, e.g., the Overall Equipment Effectiveness figure (OEE), to create a consistent, comparable data base. These figures had to be present in a sufficient detailed way, in order to be a control criterion in subsequent process optimizations. Necessary was the retention of an universal character; the universal applicability to different production processes, equipment, and process chains.

Another goal was to define specific reference values and limits to make a reasonable statement about the resource efficiency of processes, process chain, or a whole plant after recording all relevant data. On this basis, newly acquired process data and figures are valued consistently. Another goal of the first cross-sectional task was the detailed inspection of resource efficiency of process chains, equipment, and machines on economic aspects.

During the project period the gained experiences are actively used for marketing of resource-efficient systems. Especially an optimization methodology at the organizational level was part of this cross-sectional task to improve the resource efficiency of process chains. Developed methods were applied in the application phase to the process chain “press hardening”. Above mentioned aspects were supplemented by the development of a business model that focuses an active marketing of the external monitoring of resource efficiency as a service.

**CST 2: data collection**

Aim of the second cross-sectional task was the development of the required infrastructure and the IT-system used to record all relevant data for the resource efficiency. This included, based on the findings of the first cross-sectional task, the targeted selection of required sensors, the configuration of a database system, and the necessary communication components. New developed concepts were exemplary implemented in the participating manufacturing companies, validated and updated continually. The particular challenge was to receive the correct data at the right time, the right format, and to make it accessible.

**CST 3: development of analysis and visualization software**

At the center of the cross-sectional task 3 was the implementation of the developed methods. The software had been developed with modular components. Module 1 recorded online the defined figures and visualizes them. Module 2 captures more data and merges them with the calculated figures in Module 1. It enables also an offline-based rating of process chains. The figure visualization module works as a stand-alone solution. The offline module of the process assessment is also independent of the figure visualization module, but directly depends on the data collection.

**CST 4: Plant Optimization**

The fourth cross-sectional task focused the technical optimization of energy inefficient equipment and equipment components. Finally, the developed identification-approaches of energy-wasting components in cross-sectional tasks 1, 2, and 3 were applied in CST 4. Therefore the whole process chain of the plant operator was optimized.

By following the identified weaknesses within the process chain, alternatives, and technical solutions were compared to the expected resource efficiency. The developed solutions were finally implemented in the considered process chain.

Khalaf developed in dependence on VDI 3633 a methodology for producing energy efficient manufacturing strategies, validated at the press hardening process in the mentioned research project reBOP [7]. The process model is divided into the following steps:

1. define system boundary
2. collect relevant data
3. setting up a data base
4. construction of a simulation model
5. review of the simulation runs and derivation of optimization potential.

A parallel simulation model is, according to Khalaf, an important basis in order to obtain information about the energy efficiency. In the following, the simulation model used by Krueckhans and Khalaf [8] will be presented in extracts.

## 4 Optimization and Validation

### *4.1 Development of the Basis Simulation Model*

VDI 3633, part 4 was used with criteria of the automotive industry to select the correct simulation tool. The simulation software "Plant Simulation" from Siemens allows the modeling of highly complex production systems, control strategies, logistics systems and supply chain networks and is therefore suitable for solving the problem. As a basis for the execution of simulation studies the technical, organizational, and system load data are collected, validated, and analyzed.

The subsequent implementation with all feedback is implemented according to the VDI 3,633 guideline. To ensure the required simulation accuracy, a specific measurement concept was developed that determines the optimal data specifications for the simulation model. The hierarchical control concept of the plant constitutes the basis for the data acquisition. Because of the central role of the line computer, the main control signals of the system can be logged and analyzed at this single station. The subsequent analysis can be performed with an accuracy of 100 ms, and then imported into the simulation model.

The simulation study is modeled to make a statement about the different operating modes off, standby, setup, startup, and production disruption. These modes are used in the companies considered for the analysis of the press-hardening process.

### *4.2 Expansion of the Simulation Model to Consider Energy Usage*

The simulation model is extended so that the results of the measurement of energy consumption can be imported per operating condition. These are the necessary data for the acquisition of the actual state of the real system (see Fig. 3) expanded by the factor "energy". The evaluation is carried out using the recorded values at the reBOP server. In the evaluation the data of system conditions and energy

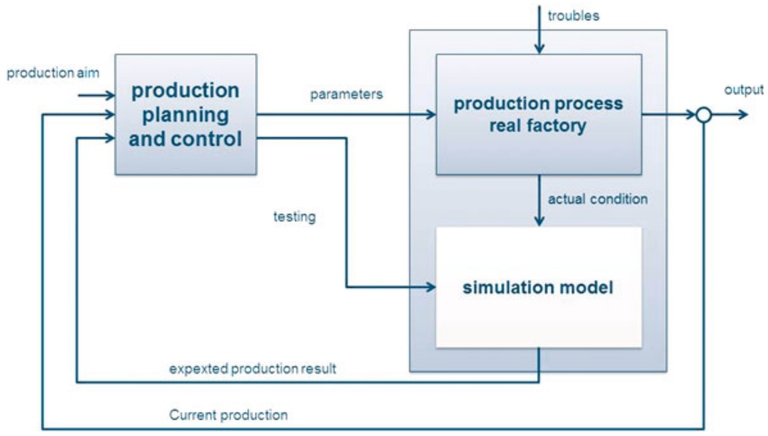


**Fig. 3** Expansion of simulation database [7]

consumption are superimposed and evaluated. The resulting values are imported via Excel interfaces into preconfigured tables of Plant Simulation. Appropriate methods allocate the appropriate energy per mode to the individual components of the production line, so subsequent analysis based on the energy consumption is possible. An integrated modeling and mapping of the production process is only possible because the entire production system was equipped with appropriate sensors (see Fig. 4).

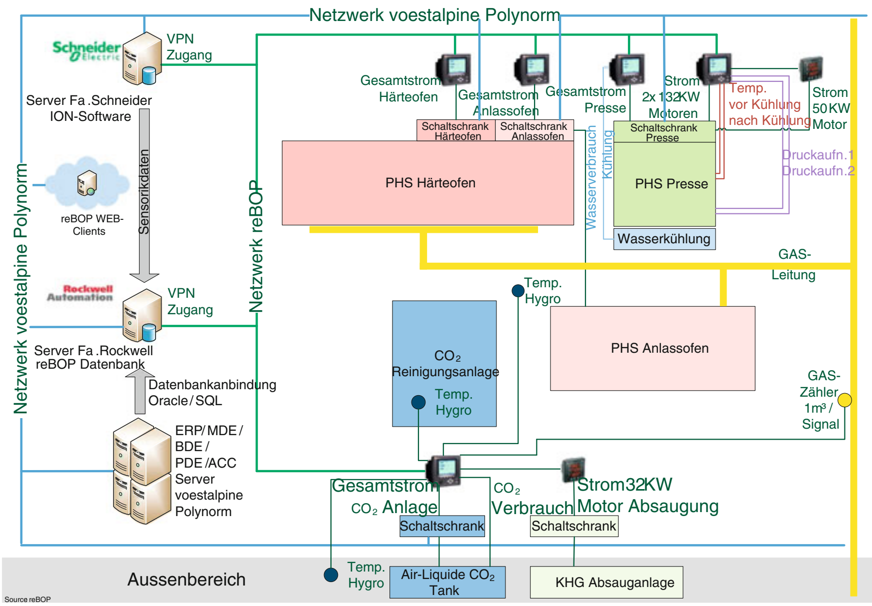


**Fig. 4** Measure concept of the press hardening process [6]

### 4.3 Implementation of Simulation Studies

During the first simulation studies, several scenarios were analyzed. These take into account the cycle of the hardening furnace, cycle times of the individual components and distribution of the operating conditions. A structured performance measurement system helps to interpret and to evaluate different variants. Different scenarios can be ideally performed by this process. They can be compared to examine the ideal operating point in the target system of production.

In the extended simulation model, energy data was added as an additional data base. Thus, a statement in the extended target system of production is possible, which additionally considers the factor of energy. Different production scenarios at the press hardening plant were compared with each other technically and organizationally.

## 5 Results

### 5.1 Results Based on Target System of Production

Especially in highly integrated production processes, a simulation study reveals enormous potential for optimizations to determine optimal operating point. Classically, production processes are characterized by three conflicting areas: time, cost, and quality. Every company tries to be positioned optimally in accordance to the requirements of the market. The organization of production is pursuing different goals that are the result of different interests [9]:

- resulting aim of initial investments
- aim of customer and market interest
- objectives of employee interest
- objectives of public interest.

From these consideration types—with their derived targets—quality, time, and costs are defined as the main aspects of the performance goals of production. These factors affect all measurable aims and thus have an essential importance. Conflicts between these three factors in practice cannot be avoided completely, because not all goals can be defined consistently. Therefore, determined operating points and solutions cannot be unique [7]. Optimization measures of the presented press hardening process are examined and evaluated by various factors.

**Factor "Cost":** *The higher the efficiency, the more optimal runs the process. The efficiency is defined as the utilization time divided by the total cycle time and is weighted by cost aspects.*

Components within the plant can improve their efficiency by increasing the value-added activities. The distribution of the cycle times is used from simulation results to calculate the efficiency. Hourly rates are used to weight the efficiency. In this simulation step energy costs of the components are embedded in this factor. As a result, the process could be operated 6 % more efficient from the cost perspective. Due to the optimization, the operating point of the whole concatenated system is more cost efficient (a more detailed description can be found in [8]).

**Factor "Process Quality":** *The smaller the non-value added components, the more efficient runs the production process.*

The process quality considers the timing of the different operating modes. Although the process has been improved in terms of costs the average load of the components declined. The average load rises from 69.29 to 70.37 % in the first optimization step. However, it decreases in the second optimization step to 65.36 % although the plant is more cost efficient. Although the capacity utilization is not directly relevant for the costs factor, it contributes significantly to the deterioration of the process quality. The operating point shifts towards factor cost, creating disadvantages in process quality.

**Factor "Time":** *The smaller the cycle time of the production line, the more parts can be produced per shift.*

By the first optimization, the clock cycle of the machine was reduced by 5 %. The better performance has a direct impact on the output quantity. This result confirms that the cycle time must be decreased as a relevant variable in order to increase the output quantity. Using the second optimization step, the cycle time again was reduced. The second optimization additionally reduces the cycle time about 6 %. Finally, the total cycle time was reduced about 11 % and the output of the plant was increased by 11 % per unit of time.

**Interim conclusion**

Altogether, different simulation scenarios were created in order to make a comprehensive statement concerning cycle times and operating conditions. The simulation allows the insight into "what-if" scenarios of altered production scenarios to evaluate scheduled optimizations. Using these scenarios, optimization potentials have been derived, identified, and assessed. The evaluation shows that the operating point in the target system of production changes by various optimization steps. However, each step affects not only one single factor but a nexus. An improvement regarding costs results in a deterioration of quality and optimization of time. The cycle time of the system could be reduced up to 11 %. At the same time, the cost weighted efficiency increases by 6 %. A specific statement regarding energy consumption could not be made because energy costs are still embedded within the cost factor. In the next chapter, this factor is considered and assessed separately.

## 5.2 *Results Based on Extended Target System of Production*

The previously described optimization potentials consider the factor energy as part of the total cost. Due to the increasing demand and price of energy [6] a separate

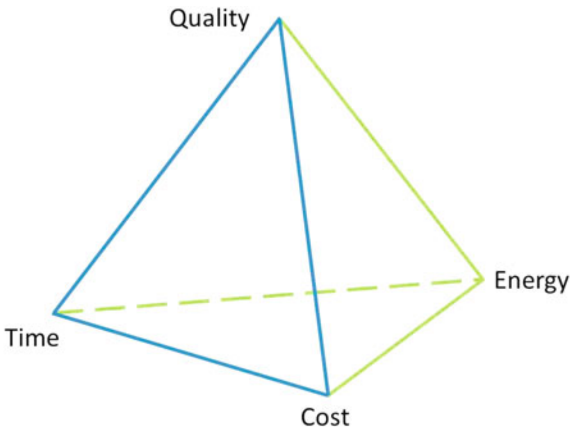


**Fig. 5** Expanded target system of production [11]

consideration of this factor in planning and assessment of production processes is essential (see Fig. 5).

This approach is supported by a study of the Fraunhofer Gesellschaft covering energy efficiency in production processes: Global aims must change from maximum profit by minimum capital to maximum profit by minimum resource input [10].

In the extended analysis model production strategies are developed, making it possible to derive information about possible energy-efficient production scenarios of specific parts. It has to be considered that separate considerations of the factor energy have a direct impact on the factors costs, quality, and time. The optimizations were carried out in the research project reBOP and furthermore evaluated by Krueckhans [11] and Khalaf [7] based on a common origin scenario. This scenario is based on actual production parameters, which were used for the operation of the plant.

The technical and organizational optimization steps, considering adjusted production parameters, variations of chain linking, furnace mode, minimum dwell, and curing time (described more detailed in [12]) lead to four other scenarios with appropriate parameters focusing cost, quality, time, and also energy. The graph (see Fig. 6) represents the deviation from the original scenario. In a final evaluation the four different strategies are compared in terms of their compliance with each main goal. Target compliance in this context describes the deviation of the current target to the respective previously determined optimum value.

With this tool the plant operator is able to address various customer requirements. If a customer needs its components very quickly (optimum time) the plant operator can apply the simulation results. The simulation model in combination with performance measurement systems gives detailed information about the degree of achievement of the other described factors time, cost, quality, and energy. Also, the increasing demand for emerging “green” produced components can be better satisfied by the system operator.

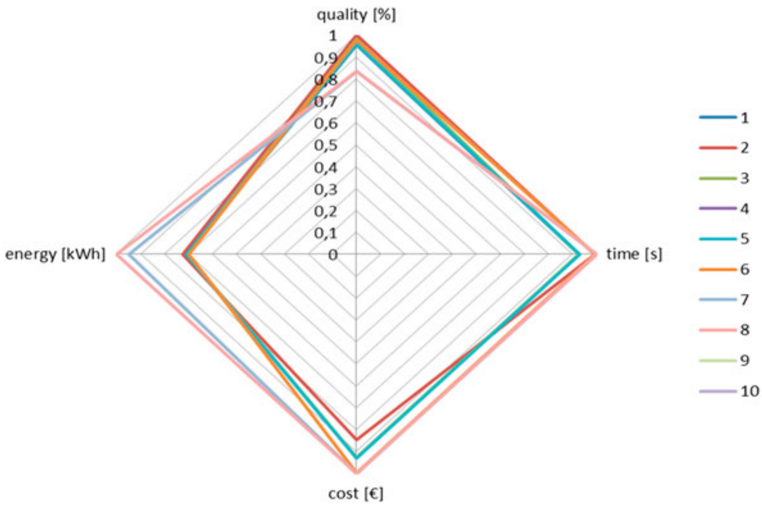


**Fig. 6** 10 different scenarios showing settlement of claims [7]

## *5.3 Changes and Results of the Members of the Consortium*

The company Air Liquide GmbH Germany aspired energy optimization of the $CO_2$-cleaning process, improved plant availability, and a maximization of the overall life time of the components. Bosch Rexroth AG has developed resource-efficient drive solutions that have been specially adapted to the conditions of the test scenarios. The solutions were successfully adapted to other applications of the company. Another benefit for the Bosch Rexroth AG is the gained experience in the use of simulation software for the assessment of drive concepts and solutions in engineering and design phase. Simulations will now provide information about functional and energetic aspects. The manufacturer BSN Thermprozesstechnik GmbH has developed—based on the identification of energy intensive consumers—more efficient and process specific furnaces. Dieffenbacher GmbH & Co. KG optimized the press hardening plant on basis of resource monitoring and plans to adapt the results to other presses in a close cooperation with Bosch Rexroth AG. With the development of marketable concepts, the foundation for the creation of competitive advantages in the area of resource-efficient presses has been placed. Schneider Electric GmbH enlarges the leadership in the area of energy efficiency by the developed user-oriented energy management and promotes the proactive marketing within this market segment. IT-company Rockwell Automation Solutions GmbH enables plant operators to save significant resource savings by using the developed adaptive system.

Further dispersion of knowledge is assured by the business model of services for the external resource efficiency monitoring of Platos GmbH. Other companies have the opportunity to optimize their production and plan it more efficient by implementing the validated visualization tool [6].

# 6 Extended Focus Within the Project Rebas

## 6.1 Introduction to Rebas

Successor project rebas started in September 2012 with five industrial partners. In the course of rebas procedures and measures for lasting reductions of resource consumption for interlinked production within the food sector are originated. The rebas-approach consists in a detailed analysis of all types of crude, operating, and auxiliary material affected by focused production process. This "track and trace"-procedure will guarantee a broader comprehension of the direct and indirect nexus of resource flows, initiated by the main process. So even airing and packing, but also and the quantity of coolant or spare parts used will be scored. Within fine-grained sankey-analysis losses through leakage and waste, but more to the point inefficiencies within the processes will be revealed, constantly linked to the current degree of added value through the process.

Focal objective of rebas are two independent German breweries. This project-inherent doubled validation guarantees a high level of transferability. The filling lines, which are addressed in rebas, are very different and though are mirroring the situation of existing production plants in the field. Not only age and homogeneity of components are differing but also the level of certification of these plants. One brewery is certified correspondent to DIN ISO 9001 and the other one correspondent to DIN ISO 50001. Both facilities are, according to the breweries, working very reliable, and efficient. Addressed problem is that this estimation is not based on clear defined, comparable data, so within rebas both facilities will be made comparable through retrofitting the filling plants with essential parts for instrumentation, control and automation. Linking the plants at a manufacturing execution system (MES) ensures spotting of the specific nexus of effects on component-level under the same assumptions.

To ensure the overall goal specific steps and gates were defined: To monitor the prevailing process-consumption properly, existing measuring system of both breweries will be complemented with required enhancements. Furthermore existing key performance indicators (KPI) will be adapted to describe the current state of the filling plant and it's relevant components. Preliminary studies and results, elaborated in the reBOP-project, will ascertain the critical consideration of essential solicitations for a valid model. Generated data will directly be processed in MES to resource-indulgent operating points for considered process chains. This will be done by a strict analysis of existing nexus of effects from single components combined with an evaluation of specific load status and dominant resource-consumption. To ensure that all data are up-to-date this processing will be done even before gathering them in a superordinate database.

This analysis is considered as the basis for a complex simulation tools for process chains. Another unique feature is the integrated learning-loop of this tool. In other words the tool will be validated and optimized with genuine system responses by itself, turned in parallel-connected to normal operational phase. Self-adapting resource-optimal operating points of focused plants are measurable results of this approach. Through be available at the stage of blueprinting new production plants these operating-points will be basis for a next generation of less resource-consuming production plants. While designing new components first simulations will be run to predict further specific resource-consumptions.

## 6.2 Novelty of Integrated Simulation Model

Conceptualized simulation model employs an unique multilayer-architecture. Resource-specific layers, e.g., just containing detailed descriptions of water as a separate resource flow, can be set as leading optimization parameter. Additional layers can be chosen to set up an interconnected simulation and optimization parameter. Another set of layers consist of component-specific values. So even single components and there operating points can be set as leading parameters. Basis for this practical approach are realistic 3D-layouts of focused plants and detailed sankey-diagrams. User interaction intuitive follows a realistic portrayal of the well-known production facility and the level of detail can be adapted to prevailing needs—unnecessary complexity is avoided.

The process-inherent nexus of effects is the most valuable and most critical point at once. This leads to further novel functions, like quick load curve analysis and automatized detection of the deviation regarding previously determined optimization-methods and –algorithms. All features can be assessed with a very quick response time, with just a small latency. To be the result of the integration of MES before writing affiliated data in a database. Database-functions and MES-functions will be done parallel in two separate units, combined after analysis of data. This tier of simulation is bound to the MES and assesses all data almost process-parallel, to ensure the self-learning loop, and surveillance of derivation. Continuous improvement through direct plant-feedback and iterative evolution of prior unspecified operating-points, even after modifications of the production process are further results.

Favored self-learning loop, even regarding not considered states or combination of states induce a reconsideration of finite states, as downtime, ramp up, or production. Combination of states matters states, like %-load, are prerequisites for establishing realistic resource-optimized operating points (Fig. 7).


**Fig. 7** Partners of the rebas project

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## References

1. Gesellschaft F (2008) Energieeffizienz in der Produktion—Untersuchung zum Handlungs- und Forschungsbedarf
2. Meier H (2010) Deutsche Standards Grün produzieren. Verband Deutscher Maschinen- und Anlagenbau e.V. Köln
3. Bialdiga K (2008) Studie: Firmen verschwenden Energie, in: Financial Times Deutschland, Gruner+Jahr
4. Tscheche JR (2008) Mehr Ressourceneffizienz in der Produktion—der Schlüssel für zukunftsfähiges Wirtschaften. Vortrag Wien
5. Statistisches Bundesamt (2011) Entwicklung von Energiepreisen und Preisindizes. Eurostat, Bundesamt für Wirtschaft und Ausfuhrkontrolle, Mineralölwirtschaftsverband
6. Kreimeier D, Khalaf S, Krings R (2012) Effiziente Produktion durch ressourcenorientierte Bewertung und Optimierung von Prozessketten. Buchveröffentlichung des Verbundprojektes reBOP, VDMA
7. Khalaf S (2012) Entwicklung eines Vorgehensmodells zur Erstellung energieeffizienter Fertigungsstrategien für verkettete Fertigungssysteme. Schriftenreihe des Lehrstuhls für Produktionssysteme, Shaker
8. Meier H, Khalaf S, Krückhans B (2011) Mit Materialflusssimulation zu effizienteren Prozessen. Productivity Management, pp. 32–35
9. Westkämper E (2006) Einführung in die Organisation der Produktion. Springer, Heidelberg
10. Neugebauer R, Westkämper E (2008) Energieeffizienz in der Produktion", Untersuchung zum Handlungs- und Forschungsbedarf. Abschlussbericht, München
11. Meier H, Khalaf S, Krückhans B (2012) Simulationsprozess für energieeffiziente Produktion. IT & Production, pp. 80–83
12. Kuhn D (2008) Energieeffiziente Produktion wird Realität. In: MaschinenMarkt Deutschland Innovativ, Sonderausgabe, 11/2008

# Methodical Approach to Identify Energy Efficiency Measures in Factory Planning Based on Qualitative Analysis

**Egon Müller, Manuela Krones and Jörg Strauch**

**Abstract** Energy efficiency has become an important objective for industrial companies and its importance is constantly rising. Factory planning plays an important role to reach the challenging goals for energy efficiency, because energy consumption can be influenced at early planning stages more effectively. Existing methods with the goal to increase energy efficiency can only be used during factory operation, because they need detailed quantitative insights into a process. Furthermore, they mainly provide scientific support for the analysis rather than for the identification of improvement measures. Therefore, a concept has been developed to systematically identify energy efficiency measures on the basis of qualitative information about a process. The basic idea is to define fundamental energy efficiency approaches and to make them available for factory planning participants in a systematic and structured manner. The overall concept and the steps that are necessary for the development of this concept are presented in this paper. The approach is explained by means of a case example dealing with internal transport planning, which represents an important part of factory planning. Based on this, potentials and limits of use as well as further research needs are deduced.

## 1 Introduction

The importance of energy efficiency is constantly rising due to ecological, political and economical reasons. From an ecological point of view, the International Energy Agency shows still increasing $CO_2$ emissions and an ever decreasing chance to reach the 450 Scenario, which means to limit the concentration of

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greenhouse gases in the earth's atmosphere to 450 parts per million [1]. These challenges have led to a strong integration of the topics energy and environment into political strategies. For example, the European Union set ambitious goals for energy generation and use. The mid-term strategy "Energy 2020" aims at a 20 % reduction of greenhouse gas emissions, a 20 % reduction of energy consumption and a 20 % share of renewable energies until 2020 [2]. A long-term strategy is recorded by the "Energy Roadmap 2050", which includes, among other things, an 80–95 % reduction of greenhouse gas emissions until 2050 [3].

In the EU, industrial energy consumption mounts up to 25 % of total energy consumption. Accordingly, industry plays an important role in the achievement of the fore-mentioned goals. Besides, industrial companies have a strong motivation to increase energy efficiency due to economic reasons. The European average prices for gas rose by approximately 70 % and the average prices for electricity rose by approximately 45 % since 2005 [4]. The share of energy costs at total industrial costs varies considerably between different countries and sectors. The worldwide average, with about 12.3 %, is remarkable [5].

In practice, the realization of measures to achieve the energy efficiency goals requires action of every involved discipline. Past efforts mainly focused on improving energy efficiency for individual components (e.g., energy-efficient motors). However, the efficiency of a system depends not only on the efficiency of its components. Thus, the complex interrelationships between products, processes and resources need to be considered in order to increase energy efficiency on factory level. The importance of factory planning is further emphasized because of its early planning stages that form the basis for later energy consumption in a factory. However, this opportunity is also a challenge because of several issues: First of all, the various interrelationships in a factory lead to an increasing complexity of planning problems. Secondly, there are many degrees of freedom, in case a system is not yet determined. Furthermore, there are often limited possibilities for energy measurements in order to identify improvement opportunities. Finally, factory planning usually takes place in form of interdisciplinary projects.

Until now, there is a lack of methods and tools to integrate energy efficiency in factory planning processes. Therefore, a concept to identify and implement energy efficiency measures holistically and systematically has been developed [6]. The further development of this concept and steps to its implementation are presented in this paper. The remainder of the paper is organized as follows: An overview of the state of the art of energy efficiency-oriented factory planning is given in Chap. 2. The overall concept for the presented methodical approach, called "Energy Efficiency Model", is presented in Chap. 3 and will be detailed in some selected tasks in Chap. 4. A case example for the basic understanding of the methodical approach is presented in Chap. 5. Finally, Chap. 6 comprises the conclusion reflecting future research work.

## 2 State of the Art of Energy Efficiency-Oriented Factory Planning

Factory planning in the narrow sense has the task to plan a factory including all functions associated with production [7]. In a broader sense, the definition of factory and project objectives, the location selection as well as the planning of external logistics also belongs to factory planning. Furthermore, it can also include issues of factory operation, i.e., during the production phase. This wide field of application leads to a high complexity and variety of planning tasks. To handle this complexity, factory planning is characterized by using prepared technical building blocks and organizational solutions to design, dimension, structure and configure a system [8]. As the requirements of factory systems can be very diverse, factory planning usually takes place in planning projects with interdisciplinary participants.

For the last decades, many future visions for factories have been developed in the context of sustainability, e.g., emission-free, resource-efficient, and energy-independent factories. However, the methodical support to reach these visions is not yet developed enough. Anyway, there are tools in different fields of application to support factory planning participants in increasing energy efficiency. One possibility to distinguish them, namely into practice-oriented guidebooks, energy efficiency principles and energy efficiency methods, is presented in the following (see also [6] and [9]).

Practice-oriented guidebooks collect energy efficiency measures tailored to industrial sectors or technologies (e.g., compressed air). These are mainly published by institutions aiming at energy efficiency or ecology (e.g., energy agencies, environment departments). With the help of industrial case studies including needed investments and energy or cost saving effects, the guidebooks represent support that is close to practical application. However, the identification and realization of measures is not described in a systematic way. Furthermore, the connection to a sector or technology is the only criterion for assigning measures to a user.

The energy efficiency principles result from generalizing and structuring energy efficiency measures. This leads to an increasing systematic, but it may also result in a decreasing applicability for practitioners. Energy efficiency principles can be regarded as checklists to examine what principles for increasing energy efficiency are already considered in a factory system and which still need to be considered, respectively. These are mainly published by research institutions or companies with energy services sectors, who apply the principles together with their customers. Examples for energy efficiency principles are shown in Table 1.

A special emphasis should be put on the third category, energy efficiency methods, because they provide methodical approaches to analyze and optimize processes and systems regarding their energy efficiency. The methods differ especially regarding their purpose and results as well as suitability for different processes. However, most of them have in common that processes are analyzed in

**Table 1** Selected energy efficiency principles

| Authors | Erlach [17] | Müller and Löffler [18] | Verl et al. [19] | Bosch Rexroth [20] |
|---|---|---|---|---|
| Energy Efficiency Principles | Manufacturing at an optimum operating point | Substitution of energy sources | Optimization of the process chain | Energy-efficient components |
| | Reducing energy demand of resources by technical improvements | Reduction of energy demand | Optimization of the technology of individual process steps | Energy recovery |
| | Minimizing the energy consumption of resources during stand-by operation | Increase of efficiency of equipments | Permanent structural measures including component selection | Energy on demand |
| | Minimizing energy consumption during turn-on and turn-off | Reduction of process losses | Energy-optimal operation and control | Energy system design |
| | Energy recovery | Energy recovery | | |
| | Leveling energy consumption by smoothing the peak energy | Direct use for heating | | |
| | Laying down an energy-efficient processing sequence for the largest energy consumer | | | |
| | Synchronizing energy supply and energy consumption | | | |

detail with the help of quantitative energy data. These data are used to compare processes or systems regarding their energy consumption, to identify areas of high consumption or low efficiency as well as to deduce improvement measures for these areas. Regarding the application in factory planning tasks, there is often the problem that quantitative energy data cannot be collected—at least not as detailed as necessary. Thus, the concept "Energy Efficiency Model" was developed in order to identify energy efficiency measures based on qualitative analysis.

## 3 Overall Concept "Energy Efficiency Model"

The basic idea of the concept "Energy Efficiency Model" is to use physical principles, which describe the underlying causes for energy consumption, in order to define fundamental energy efficiency approaches. Because of the physical basis, these can be applied to different industrial processes. One easy example is the fundamental approach "reducing mass", which is used e.g., for transport processes (as the reduced mass leads to reduced mechanical work) and for melting processes (as the reduced mass also leads to a reduced need of head quantity). The existing energy efficiency principles (Chap. 2) are a starting point to generate fundamental approaches.

The goal is to provide appropriate energy efficiency approaches to a planning situation, which needs to be described on a qualitative basis by the user. The overall concept consists of seven components, which are detailed in the following (see Fig. 1). The starting point is a difference between the current condition (1) and the aimed condition (2) corresponding to the systems engineering process [10]. The aimed condition focuses on goals (e.g., energy efficiency) subordinate to the strategic objective system (3) which is defined by the strategy of sustainable development. For that reason, the physical approaches need to be extended by other approaches, e.g., use of renewable resources. The user accesses the fundamental energy efficiency approaches (4) by describing the planning situation with the help of the user interface (5) The approaches are on different levels of detail, e.g., the above-mentioned approach "reducing mass" versus special approaches like dimming lighting in dependence of daylight. Furthermore, they are structured according to different criteria (e.g., object area, influenced energy carrier) in order to assign them to the specific planning situation of the user. The approaches are linked to additional knowledge components (6) which include useful information about the approaches' application, e.g., best practice, experience values for the achievable effects. Different professions are integrated (e.g., technology, factory planning, logistics, management, materials) in order to consider the interdisciplinary requirements of factory planning projects. The "Energy Efficiency Model" is linked to a qualification system (7) in order to provide training and education for both students and practitioners. The platform, in which the qualification will take place, is the "Centre of Energy Competence—Logistics and Factory Planning", which is currently being developed [6].

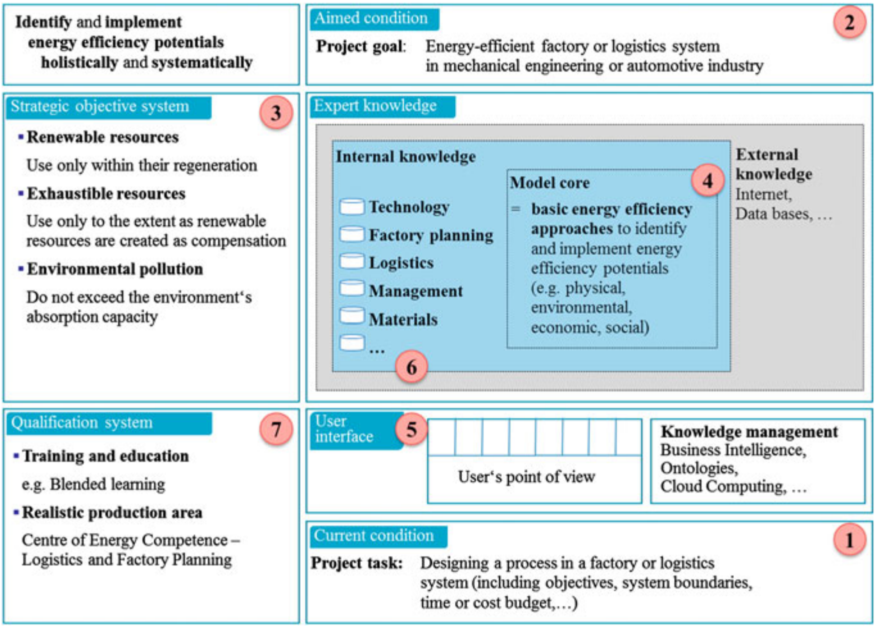


**Fig. 1** Concept "energy efficiency model" [6]

Several tasks need to be fulfilled in order to realize the concept "Energy Efficiency Model". At first, a basic collection of energy efficiency approaches needs to be established using literature as well as own experiences and measurements. Then, the process of assigning approaches to the respective planning situation, which will proceed in the background, i.e., not influenced by the user, is to be developed. The following process steps are currently under development: analysis of the planning situation, identification of physical parameters, assignment of approaches and structuring of the additional knowledge components. The first two steps are described in more detail in the next chapter.

## 4 Description of Selected Tasks Within the "Energy Efficiency Model"

### *4.1 Analysis of the Planning Situation*

The first step of the procedure model consists of describing the planning situation in order to assign suitable energy efficiency approaches later on. It is accentuated that—in contrast to most of the existing methods (see Chap. 2)—there is no need to collect energy consumption data of an existing system. A central criterion for the description of the planning situation is the level of abstraction the planning object is assigned to, because this leads to an increasing system complexity and increasing possibilities for energy efficiency measures.

Literature provides different possibilities to distinguish levels of abstraction, e.g., factory level, department level and unit process level [11]; macro-level (whole factory), meso-level (production processes), and micro-level (production machines) [12]. More precise classifications are proposed in [13], namely supply chain network, factory, production area, group of workstations, workstation, as well as in [14], namely enterprise/global supply chain, multi-factory system, facility, line/cell/multi-machine system and device/unit process. Further research is needed to analyze the applicability of these or other classifications for the analysis of the planning situation, i.e., an examination how precise the classification needs to be in order to assign appropriate energy efficiency approaches.

## 4.2 Identification of Physical Parameters

After identifying the object area, physical parameters can be identified on a low level of abstraction (see Sect. 4.1). This level can be reached either by the user's definition or by continuous splitting of the actual planning object. A hierarchical approach is recommended in order to identify and describe relevant physical parameters. Therefore, the objective needs to be defined first, e.g., energy consumption over a defined period of time. The objective can also be an energy performance indicator consisting of an energetic objective and other objectives (e.g., number of parts produced). Then, the energetic objective is analyzed in a continuous refinement starting with a generic description. Again, there are many different possibilities for this generic description in literature, mainly in the area of machine tools. For example, Duflou et al. propose a division of the total energy demand into active energy theoretically needed, additional energy demand of the machine tool and energy demand of peripherals [14]. Rahimifard et al. suggest a similar division into indirect energy and direct energy, whereas direct energy is further divided into theoretical and auxiliary energy [15].

However, differentiating additional energy demand (or auxiliary energy) from energy demand of peripherals (or indirect energy) is only possible with a clear distinction between the relevant system and its surrounding. Considering factory systems rather than manufacturing systems, this distinction cannot be done sharply, because peripheral devices, e.g., ventilation, can also represent the relevant object area. That is why, a division into work for processing $W_{process}$, work for auxiliary devices $W_{aux}$ and losses work $W_{loss}$ is suggested here (following [13]). The work for processing includes the energy demand for the desired output of a process, which can be a manufacturing step, but not necessarily has to be one—in contrast to the aforementioned approaches. The work for auxiliary devices covers energy demand for all other devices, e.g., control, lubrication system. The losses work includes the physical work due to conversion between energy forms or energy carriers. The assignment of energy consumers to these categories clearly depends on the definition of the relevant system.

The continuous refinement of objectives can be continued with parameters that are specific for the relevant object area. Afterwards, the parameters are divided into control and disturbance variables according to the influence opportunities of the user, i.e., control variables can be influenced, whereas disturbance variables cannot. The identified control variables form the basis for deducing energy efficiency measures that affect these variables.

## 5 Case Example: Internal Transport Planning

For better understanding of the function and the procedures of the "Energy Efficiency Model", an example of internal transport planning is given in this chapter. The exemplary current condition is an internal transport process of small load carriers realized with an automated guided vehicle (for this use case see also [16]). The object can be assigned to the level unit process, micro-level, workstation and device, respectively (see Sect. 4.1). The task is to increase energy efficiency without need for investments, i.e., during factory operation. The objective energy efficiency is expressed by the specific energy consumption as quotient of the electrical energy consumption and the transport effort. The transport effort, in turn, is the product of transport distance and transported mass.

Using the generic description of Sect. 4.2, the energetic part of the objective, the electrical work $W_{el}$ is analyzed in a continuous refinement (see Fig. 2). This analysis is performed in high detail for demonstration purposes. The work for processing corresponds to the mechanical work for transport. The work for auxiliary devices consists of energy demand for control and navigation systems. Finally, losses work occurs due to the conversion of electrical energy into mechanical energy.

The next step is to divide the parameters into control and disturbance variables according to the restrictions of the project task. Since there is the need to avoid investments, a substitution of components (e.g., drives) is not possible. Hence, all parameters that are determined by the vehicle (stand-by power, losses power, rolling resistance coefficient and mass of the vehicle) are disturbance variables. All other parameters can be controlled directly or indirectly, whereas the direct control means the most precise level of the continuous refinement. These parameters are transport distance, operating time, stand-by time, number of acceleration operations, mass of transported goods and the velocity (boldly highlighted in Fig. 2). Then, appropriate energy efficiency approaches, which influence the control variables, are assigned. Table 2 shows these approaches as well as the parameters affected. The directly influenced parameter characterizes the parameter at which the approach aims. Further effects are summarized by indirectly influenced parameters.

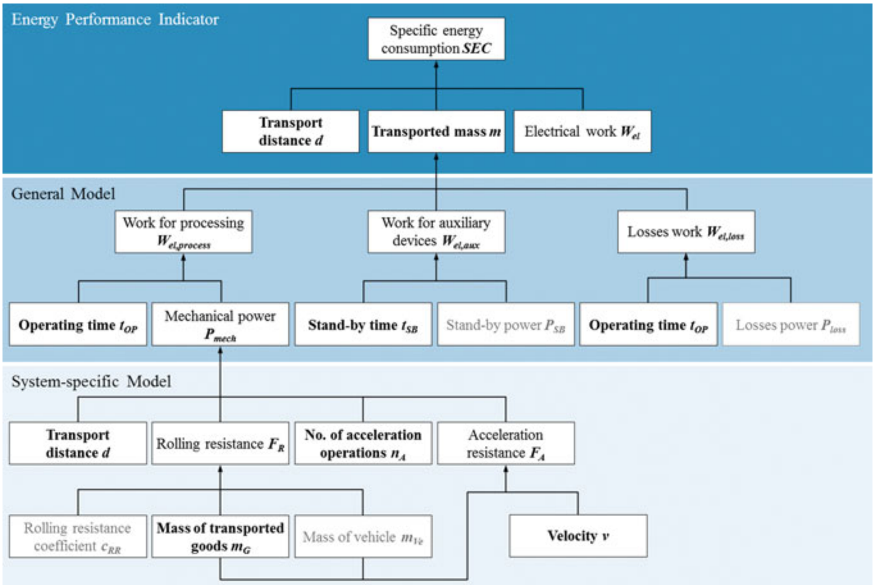


**Fig. 2** Influencing variables on the objective specific energy consumption for the case example, (control variables are *bold*, disturbance variables are *grey*). The indirect relationships are omitted for better clarity. Therefore, the variable "transport distance" is listed twice

**Table 2** Assigned energy efficiency approaches for the case example (selection)

| Energy efficiency approach | Directly influenced parameter(s) | Indirectly influenced parameter(s) |
|---|---|---|
| Reducing acceleration and braking operations | No. of acceleration operations $n_A$ ↓ | Operating time $t_{OP}$ ↓/↑ |
| Reducing empty runs | Transport distance $d$ ↓ | Operating time $t_{OP}$ ↓ |
| Reducing mass | Mass of transported goods $m_G$ ↓ | |
| Reducing transport velocity | Velocity $v$ ↓ | Operating time $t_{OP}$ ↑ |
| Summarizing transport processes | Transport distance $d$ ↓ | Mass of transported goods $m_G$ ↑<br>No. of acceleration operations $n_A$ ↓ |

Besides the energy efficiency approaches, the user also receives additional knowledge components that include information on the effects of applying the approach. A special emphasis should be put on contrary effects on the objective, e.g., considering the approach "Summarizing transport processes", which reduces the transport distance, but increases the mass of the transported goods. Although the contents of the additional knowledge components cannot assess the implications of this contrary effect on the objective in general, they point out these interrelationships to the user.

## 6 Conclusion and Further Work

In this paper, a methodical approach to identify energy efficiency measures with the help of qualitative analysis was presented. It is based on the idea of defining fundamental energy efficiency approaches and assigning them to a defined planning situation or project task. In contrast to existing methods for energy efficiency analysis and improvement, there is no quantitative data needed and the focus is put on improvement rather than on analysis. Due to the low requirements on input data, the advantage of the approach lies in its manageability.

A case example dealing with internal transport planning showed the potentials of the application. Helpful energy efficiency approaches could be identified with only little description of the current condition. The limits of the approach are reducible to the general character of the approaches. However, it is expected that factory planning participants can use the "Energy Efficiency Model" to increase energy efficiency of their planning solutions.

In further research, the demonstrated steps that are necessary to develop the "Energy Efficiency Model" are refined and detailed. Special focus lies on the formal description of the assignment of the approaches to planning situations. The created energy efficiency knowledge will be transferred to qualification modules for students and practitioners in the "Centre of Energy Competence—Logistics and Factory Planning".

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## References

1. International Energy Agency (2012) World energy outlook 2012. Paris, France
2. Council of the European Union (2007) Presidency conclusions. Brussels, Belgium. http://register.consilium.europa.eu/pdf/en/07/st07/st07224-re01.en07.pdf. Accessed 26 Nov 2012
3. European Commission (2012) Energy roadmap 2050. Luxembourg, Luxembourg. http://ec.europa.eu/energy/ publications/doc/2012_energy_roadmap_2050_en.pdf. Accessed 26 Nov 2012
4. European Commission (2012) Energy statistics—prices. http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/ data/main_tables. Accessed 26 Nov 2012
5. United Nations Industrial Development Organization (UNIDO) (2012) Industrial development report 2011: industrial energy efficiency for sustainable wealth creation—capturing environmental, economic and social dividends. http://www.unido.org/fileadmin/

user_media/Publications/IDR/2011/UNIDO_FULL_REPORT_EBOOK.pdf. Accessed 7 Dec 2012
6. Müller E, Krones M, Hopf H, Arndt R, Strauch J (2012) Identifying and responding to energy efficiency improvement opportunities in factory planning. In: Proceedings of 22nd international conference on flexible automation and intelligent manufacturing (FAIM 2012), Helsinki/Stockholm, Finland/Sweden, pp 365–372
7. The Association of German Engineers (VDI)—Society for Production and Logistics (GPL) (2011) VDI 5200 factory planning, Part 1: planning procedures. Beuth, Berlin, Germany
8. Schenk M, Wirth S, Müller E (2010) Factory planning manual—situation-driven production facility planning. Springer, New York
9. Müller E, Strauch J, Krones M (2011) Energieeffizienzpotenziale systematisch erkennen und erschließen—Konzept für ein planungsunterstützendes wissensbasiertes Energieeffizienzmodell. Tagungsband 14. Tage des Betriebs- und Systemingenieurs (TBI)—Nachhaltigkeit in Fabrikplanung und Fabrikbetrieb, Chemnitz, Germany, pp 67–76
10. Blanchard BS (2008) Systems engineering management, 4th edn. Wiley series in systems engineering and management
11. Bogdanski G, Spiering T, Li W, Herrmann C, Kara S (2010) Energy monitoring in manufacturing companies—generating energy awareness through feedback. In: Proceedings of the 19th CIRP international conference on life cycle engineering, Berkeley, California, USA, pp 539–544
12. Schuh G, Burggräf P, Welter T, Kamp S (2012) Ressourceneffiziente Fabrik- und Produktionsplanung. In: Proceedings of the international chemnitz manufacturing colloquium ICMC 2012, 2nd international colloquium of the cluster of excellence eniPROD, Chemnitz, Germany, pp 29–40
13. Müller E, Engelmann J, Löffler T, Strauch J (2009) Energieeffiziente Fabriken planen und betreiben. Springer, New York
14. Duflou JR, Sutherland JW, Dornfeld D, Herrmann C, Jeswiet J, Kara S, Hauschild M, Kellens K (2012) Towards energy and resource efficient manufacturing: a processes and systems approach. CIRP Ann Manuf Technol 61(2):587–609
15. Rahimifard S, Seow Y, Childs T (2010) Minimising embodied product energy to support energy efficient manufacturing. CIRP Ann Manuf Technol 59(1):25–28
16. Müller E, Hopf H, Krones M (2012) Analyzing energy consumption for factory and logistics planning processes. In: Proceedings of the APMS 2012 international conference—advances in production management systems—competitive manufacturing for innovative products and services, Rhodes Island, Greece
17. Erlach K (2011) Increasing energy efficiency using energy value stream mapping. National energy efficiency conference and EENP awards ceremony, Singapore, http://app.e2singapore.gov.sg/DATA/0/docs/NEEC%20&%20EENP% 20Award%20Ceremony/26%20Klaus%20Erlache_neeconf.pdf. Accessed 4 Dec 2012
18. Müller E, Löffler T (2009) Improving energy efficiency in manufacturing plants—case studies and guidelines. In: Proceedings of 16th CIRP international conference on life cycle engineering (LCE 2009), Cairo, Egypt, pp 465–471
19. Verl A, Westkämper E, Abele E, Dietmair A, Schlechtendahl J, Friedrich J, Haag H, Schrems S (2011) Architecture for multilevel monitoring and control of energy consumption. In: Proceedings of the 18th CIRP international conference on life cycle engineering (Glocalized solutions for sustainability in manufacturing), Braunschweig, Germany, pp 347–352
20. Bosch Rexroth AG (2012) Rexroth 4EE—Rexroth for energy efficiency. Lohr am Main, Germany. http://www.boschrexroth-us.com/country_units/america/united_states/en/Industries/machine_tool/a_downloads/4EE_Brochure_RE08503.pdf. Accessed 4 Dec 2012

# Evaluation of Process Chains for an Overall Optimization of Manufacturing Energy Efficiency

**Christian Mose and Nils Weinert**

**Abstract** Improving energy efficiency in manufacturing has to be considered from a holistic perspective. Investigating and optimizing manufacturing processes in an isolated manner may neglect possible energy intensive pre- and post-processes, and thus may miss an overall optimum. Instead, the whole process chain has to be accounted for being able to find an optimum for the production of a certain product. The presented method for the evaluation of process chains therefore integrates a detailed analysis of the core as well as necessary pre- and post-processes, and enlarges this approach for a factory wide optimization. Single steps of a process chain are energetically modeled using a detailed mapping of each step's energy profile, generalized by investigating the product variant related energy profiles for each machine. The result provides the base for improving the energy efficiency of a factory as well as for calculating the embodied energy of a product, fostering the energetically optimization of its manufacturing processes. Furthermore, factories in most cases produce multiple variants of similar products, requiring an optimization not for one product but for the overall product mix of the considered manufacturing site. The introduced method is therefore extended following a sustainability technology roadmap approach.

## 1 Introduction/Motivation

Climate change is widely accepted as one of the major threads today's global society has to cope with. Limiting the global warming to 2 °C has to be achieved for preserving the global environment as it is today. Higher values are estimated to cause dramatic environmental effects and will demand cost intensive actions,

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undertaken pre-emptive as well as compensating to deal with the consequences [1, 2]. Recently, at the 2012 UN climate summit at Doha, scientists announced an increase of 3.5–4 °C compared to the pre-industrialized age as inevitable, e.g., [3, 4]. Global warming, of course, is a consequence of the greenhouse effect, caused by greenhouse gases in the earth's atmosphere, especially by $CO_2$. The major source for an increased $CO_2$ concentration is the generation of energy from fossil fuels, such as coal, oil and natural gas. Common studies do forecast a significant increase of the global energy demand, expecting the total required energy to double until 2050, while demand for electrical energy will already be doubled in 2030 [5], displaying the urgent need of taking action for cutting environmental burdens.

On global scale, more than half of the final energy is consumed by industry (52 %, [5]), while for example in Germany the share is at about 40 % of primary energy [6]. For industry as the major energy consumer, the need for saving energy and increasing energy efficiency is evident. Additionally, from the economic perspective, companies may not neglect rising energy prices, which steadily enlarge the share of energy expenses contributing to the overall production costs [7, 8]. Furthermore, the perception of sustainability-related company activities is steadily rising among customers and employees. Industry, as a consequence, is more and more required to extend actions on conserving the environment, for maintaining a positive customer perception.

Industry's major share of energy usage goes into the manufacturing of products. Product creation in general is the result of applying a series of different processes in a certain order to form a process chain. Process chain adaptations through implementing process alternatives as well as shortening process chains are estimated to provide saving potentials of up to 30 % of the energy applied [6].

Typically, a process chain contains certain core processes, which add the major share of value to the product, and additional pre- and post-processes, which are required to conduct the core processes, e.g., by preparing a work piece for a core process step. Thus, by choosing core processes, additional process steps are unavoidably inserted into the process chain to result in a seamless chain of manufacturing processes. Consequently, when investigating the energy demand of process chains, not only the core processes have to be considered, but the energy required for both, core and enabling processes.

While a process chain depicts the steps necessary to add value to raw material for manufacturing one particular product, a factory on one hand has to deal with more than just the value adding processes, and on the other hand mostly deals with more than just one product, or at least more than one variant of a product. Thus, in an economies-of-scale approach, measures for improving the energy efficiency of a production environment are likely to achieve severe savings throughout the lifetime of a process applied in manufacturing. Consequently, designing energy efficient process chains will cut down the energy required significantly, especially if multiplier effects are met through high lot sizes. In this paper, a methodology for designing energy efficient process chains is introduced.

Altering process chains in many cases implies an adaptation of production equipment. Consequently, the energy-aware optimization of process chains, and thus of factories, has to take into account a mixture of different products, representing the entirety of products manufactured by the considered plant. Since in an industrial environment, each improvement measure has to convince in an economical way, meeting affordable amortization times is required when replacing equipment by more efficient machinery. For integrating this economical perspective with an energy aware process chain design, the design methodology introduced afore is enhanced with a technology roadmap approach in Chap. 4.

## 2 Energy Profiling of Process Chains

### *2.1 Information Demand*

Recent research in the field of energy and resource efficiency in manufacturing reveals lots of areas for improvement and optimization, from the selection of technologies to machine components, and from energy intense to processes with a low energy density [9, 10]. Common Life Cycle Assessment (LCA) methodologies tend to focus on a particular product. Within these boundaries it seems natural to concentrate on the lifecycle phases with the highest impact for optimization. For a great share of technological products, the use-phase is the dominant one regarding energy consumption. Thus, modifications on the product that have a use-phase impact are mostly to be addressed in product development. Knowing this, one could come to the conclusion that optimizing one of the non-dominant life cycle phases in the direction of energy efficiency improvements should not be an important field of action [11]. On the other hand, for a manufacturing company the area for instant activities can be found along the whole supply chain, and in particular in manufacturing itself. Increasing efficiency is a key for economical growth, increased competitiveness in general and regarding energy and material for sustainability. The particular influence a company has on manufacturing processes depends on the degree of vertical production range, which is often fluctuating over time, especially when considering new manufacturing technologies.

To come to a more holistic view, a process chain approach is introduced to tackle this field. When investigating alternative technologies regarding their energy demand, it can be realized that there are key processes that require and define a series of pre- and post-processes within the process chain. Therefore, optimizing the largest consumer solely is only the most obvious approach, but not sufficient when targeting at an overall minimum.

When evaluating a process chain of the manufacturing phase during a life cycle analysis (LCA), one gets to the point where common available database information on material- and energy flows is not detailed and accurate enough to support an analysis on manufacturing level. Reference values used in LCAs (e.g., per kg of product) indicate that the focus of the kind of analysis lies on resource extraction and process industries, rather than on discrete production. The level of detail available for material- and energy flow is not sufficient to be used to determine the difference in eco impact of different technologies or processes. For example, different particular processes out of the same kind of manufacturing operation like water jet cutting vs. laser cutting are not differentiated in general. Even fundamental manufacturing processes differ greatly in terms of energy demand, regarding the magnitude of the process as well as a difference in the type of implementation and the shares between primary and secondary functions, respectively secondary consumers (e.g., fixing, pre-heating, suction systems etc.), which are relevant for running production equipment, and display a significant share of the overall consumption [12–14].

The lack of available information on energy demand usually requires measuring to determine the energy demand of processes as well as approximations for possible modifications within a process chain. The energy demand of a process is the combination of all devices utilized for the particular process. Not only the core technology but also the accessories may contribute a great share [15]. Therefore considering the physical fundaments of a core process only will not lead to the full picture. In addition it is not just the value adding process that has to be considered. It can be concluded that energetically profiling a manufacturing station has to consider the energy demand for all different machine states [16]. This also has to include the consideration of different machine parameters, depending on their impact and significance. The process energy demand needs to be calculated as a meaningful normative value that is process specific and can be related to a particular product's attribute. As an example, the energy demand for welding needs to be considered per welded length instead of per product mass. Thus, product specific characteristics originating from product design are considered in estimating the energy demand for a particular process chain. A further requirement on gathering information on process energy consumption arises from the structure of production planning. On a timeline, process chain design takes place before the process chain is actually implemented and production takes place, which makes detailed measuring of the final process chain impossible.

Deriving the requirements from what was discussed above, energy profiling of process steps has to be based on process specific energy consumption data. This has to include the possibility to distinguish between different equipment and manufacturing technologies performing the same manufacturing task. The energy model for one process step has to be scalable in terms of information density, or information resolution, in accordance with the product's specific characteristics. A production process consists of different phases, for example set up and loading, processing and unloading. Therefore, not only the main processing phase has to be included in estimating the energy demand, but also the energy consumed by primary and secondary consumers during non productive times. Furthermore, product specific characteristics have to be considerable in energy profiling. Taking a welding application as an example, the welding length has to be easily defined as a parameter, since similar products might significantly differ in the length of welded joints. Further it has to be made possible to model certain process steps individually, when one step significantly differs from a standard process.

## 2.2 Energy Blocks-Methodology

For meeting the requirements toward energy consumption modeling of process chains, the EnergyBlocks-Method (Overview given in Fig. 1) is applied. The method is based on the segmentation of production equipment's power profiles according to the different operational states the equipment can operate in. Operational states, in this understanding, are for instance stand-by, processing using certain process parameter settings, or rapid axis movement. Each segment, now referred to as EnergyBlock, represents the energy consumption within the related operational state as a time based mathematical model. Thus, not only an average consumption value is available, but also a high resolution time dependent profile in case a detailed analysis is required, for example if peak consumption is relevant for investigations. Possible data sources for building up an EnergyBlocks-Database could reach from estimations over simulations to real measurements on production processes [17, 18].

Any production task can be understand as a series of operational states the production equipment is set to, e.g., as defined by the control program. For modeling the energy demand of any production task, EnergyBlocks have to be arranged in the respective order, forming an EnergyBlocks-Sequence, regaining an estimated energy profile of the task fulfillment. By applying this for each process step of an investigated process chain, a chain-wide energy consumption model can be set up. Depending on the required demand of accuracy, the modeled profile can be used for power analysis, or can easily be integrated for using average energy consumption values, e.g., per process step.

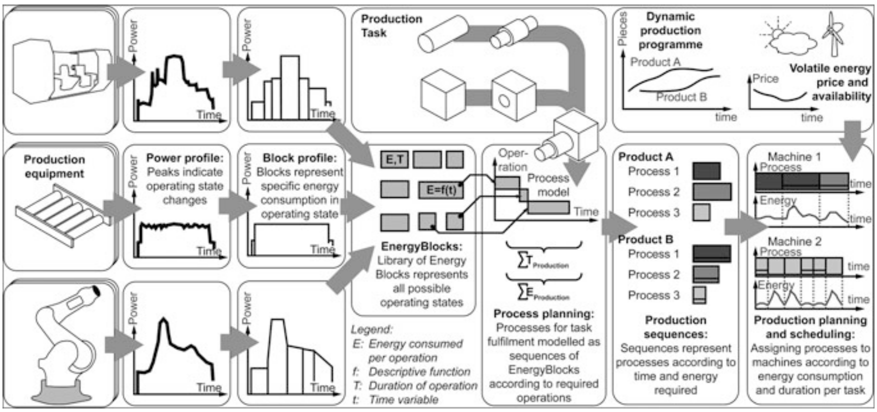


**Fig. 1** Overview of the EnergyBlocks energy consumption modeling methodology [18]

Further, predefined sequences for standard applications can be used, e.g., the application of a welding seam for a defined length can be modeled as a single sequence, including for example necessary robot movements from and to a home position towards the work piece, the robot movement during welding as well as the welding process itself. For the estimation, this sequence would be applied according to the overall length of the welding seam of the work piece, only having to adjust the duration of the block applied for welding.

## 3 Process Chain Design

Only when process specific data is available it is possible to evaluate and rank different processes concerning their energy demand. The ideal process chain for minimum use of energy is not necessarily the one utilizing the most energy efficient technology for every particular process, but the one having the lowest overall energy demand.

Assembly, as a core process in manufacturing products, and joining as the essential process within assembly is used as an example for explaining the approach. Targeting the overall minimum of energy utilization the example is meant to show the wide spectrum that it is applicable for. Joining is a wide field, containing very different technologies and applications and is therefore suitable for demonstration. Furthermore, a joining process chain, even when focusing on welding, like within this example, can be understood as a chain containing other widespread technologies as pre- and post processes, like cutting and machining.

The definition of a joining process chain follows a procedure like depicted in Fig. 2. Starting point for the described procedure is the design function of a joint. Realizing a function defined during product design starts with analyzing the specification of both, the final component as well as the joining it contains, regarding requirements and constraints. The joining has to fulfill certain requirements and service conditions that have to be assured by the type of joining and throughout the lifetime of the component. Depending on the particular specification, the degrees of freedom within the definition of the joining may vary. The selection and number of feasible technologies is very much depending on material attributes as well as physical attributes like the geometric shape [19]. After defining the joint type, consisting of the joining principle as well as the a type of contact [20], it is possible to come to a limitation of suitable joining technologies out of the sum of all possible solutions. The number of possible solutions is reduced by the technologies not fulfilling the constraints described and defined within the previously analyzed steps. For each technological possibility suitable joint configurations can be selected within the next step, considering all defined constraints. Having suitable joining technology shortlisted and defined fitting joint configurations within the following step, it is now possible to select the required processes for preparation as well as post-processing. Especially the joint configuration in combination with the joining technology is essential for describing the parts geometry and therefore all subtractive manufacturing technologies required as joint preparation. In addition to the components shape, there are many additional properties that need to be considered. The materials surface or structural treatment like other aspects for the joint covering chemical, physical as well as metallurgical properties might require certain pre- and/or post-processes within the process chain. For sake of explanation the processes discussed here do cover only shape and subtractive technologies but can similarly be transferred to other properties and processes. The targeted outcome of this is the definition of multiple suitable as well as generally feasible alternative process chains for a particular joining. The alternative chains are meant to be variants for basically a similar resulting part that fulfills all given requirements, but shall differ regarding the utilized

- core technology (depicted as "circle" in Figs. 2 and 3), e.g., welding process,
- pre- and post process technologies (depicted as squares and rectangles), e.g., joint preparation,
- number of process steps (pre- and/or post-processes),
- manufacturing equipment, e.g., milling machine,
- combinations of these variations.

One example of just two alternatives is depicted in Fig. 3. Similar requirements can be fulfilled by cutting parts out of a sheet of aluminium with a water jet cutting process, followed by a joint preparation through milling and joining the components with a gas metal arc welding (GMAW) process. The depicted alternative is a laser cutting process for the same aluminium sheet, followed by a friction-stir welding (FSW) process. Both process chains start with the same base material and don't differ for previous process steps, and can therefore be looked at as if both where starting with the cutting process.

After defining technological suitable process chains, the available alternatives have to be evaluated taking into account ecological as well as economical criteria. For the economical side conventional procedures well established are applied, referred to as economical assessment, in the bottom center box in Fig. 2. The overall ecological perspective then is achieved by the integration of the conventional results and on the energetic profiling and evaluation. For the energetic profiling of the process chain alternatives, the EnergyBlocks method is applied. Process specific data that is described by the processes' EnergyBlocks are used for approximation of the overall energy demand along the defined process chains. Thus, a scalable level of detail is achieved, which can be decreased as well as increased depending on the scope and time available within the planning phase. With this overview it can be decided which combination of single processes stands for the lowest energy demand for the analyzed joint.

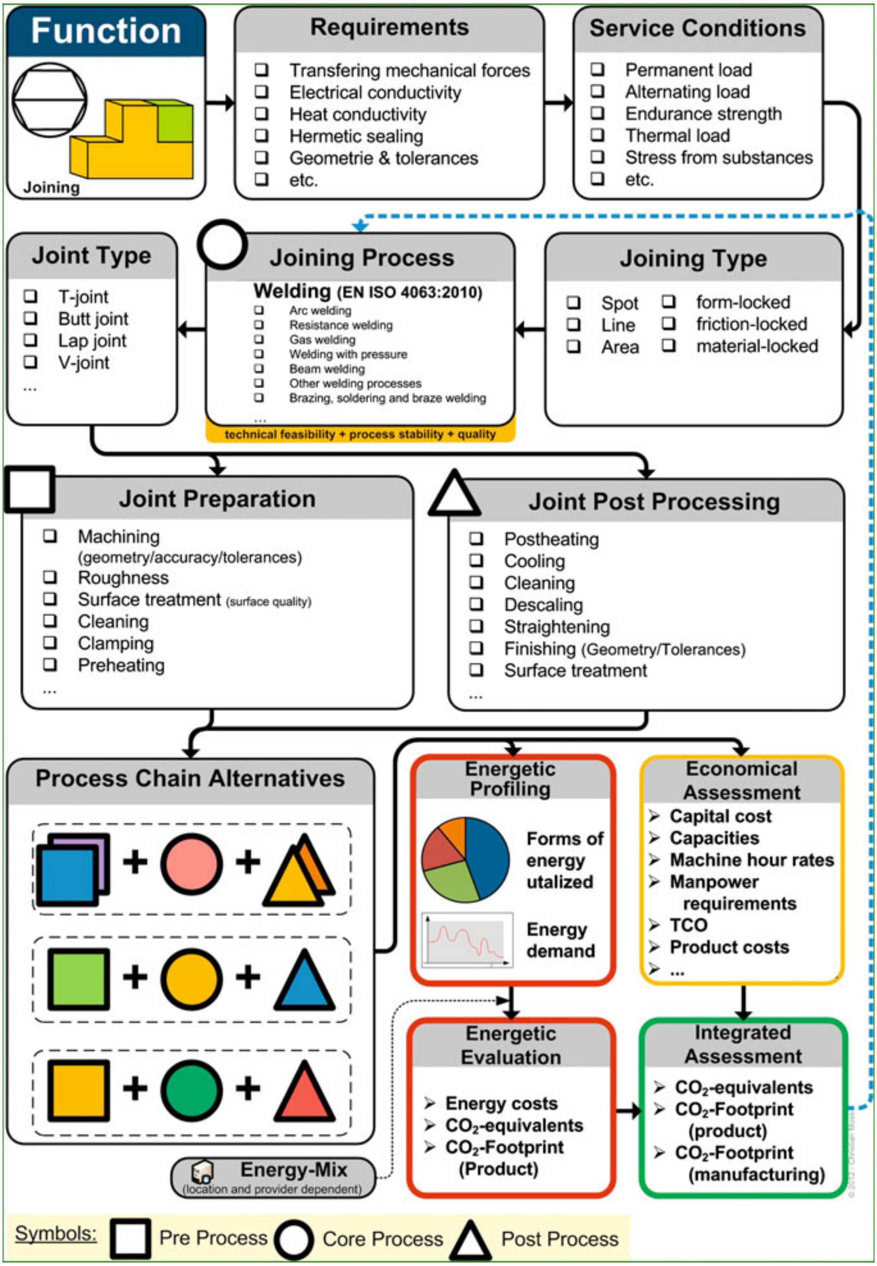


**Fig. 2** Process for defining and evaluating process chains for the example of joining processes

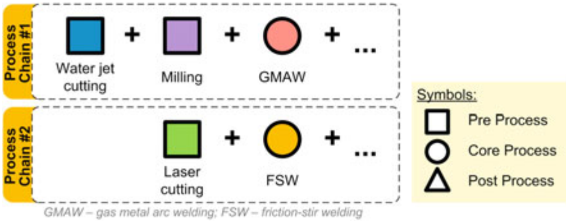


**Fig. 3** Example for alternative joining process chains containing pre-processes

# 4 Plant Perspective

## *4.1 Plant Dilemma*

Enhancing the approach further, one needs to consider that optimizing the manufacturing phase of an existing as well as of a new product cannot be investigated in an isolated manner. In a manufacturing plant context, it has to be considered as part of a relatively complex environment where several products or product variants and therefore manufacturing phases meet.

In Fig. 4 three process chains of three different products are depicted and arranged in parallel along a products lifecycle. Focusing the manufacturing phase, only processes from this phase are shown, despite the fact that the overall process chains will be much longer. Work stations are highlighted, covering certain process steps that can be understand as the implementation of a particular manufacturing technology, which is required at a certain point within one or more process chains for manufacturing. A plant covers a certain segment of the process chains, generally including several work stations. Process steps not covered by the plant can be understood as either outsourced processes respectively purchased services or components.

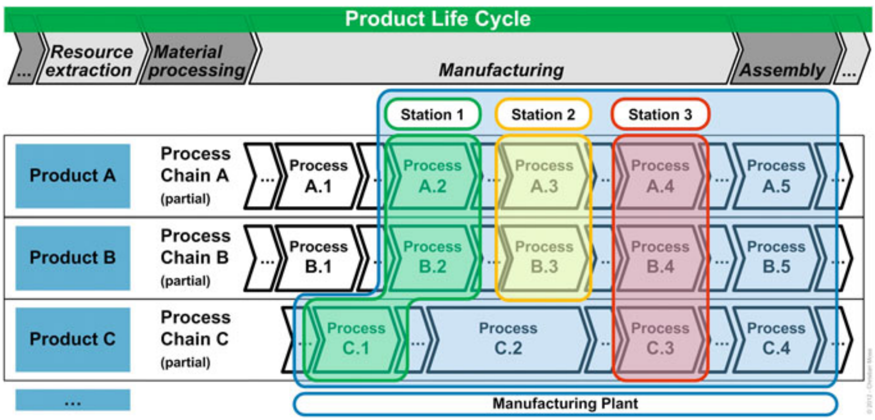


**Fig. 4** Plant perspective on products' process chains and manufacturing station

The economic optimization nowadays has led to a production planning behavior of highly loading manufacturing stations with the purpose of lowering the manufacturing costs. Therefore on manufacturing equipment it is common practice to use the equipment for processing a product mix to achieve the maximum equipment utilization. Changing process technologies in most cases requires equipment to be replaced. Introducing the replacement as a modification for one solely product will have an economical impact not only on the modified production process but also on the factory's remaining product mix. This is caused by increased capacities which lead to a lower utilization of the workstations, and by required investments for new process technology. These effects result in higher manufacturing costs, and make ecological induced process adaptations both expensive and risky. Investing in environmental benign technologies therefore becomes economical malicious in multiple way and can be seen as a dilemma.

## *4.2 Sustainability Technology Roadmap*

Although designing more energy efficient process chains is possible by using the presented methodology, a great challenge is the implementation when facing today's predominantly economically driven decision making in production planning. Single measures for raising production sustainability or lowering a factory's $CO_2$ footprint in most cases are still economically disadvantageous. Today's predominant investment time frames are hardly to be combined with $CO_2$ reductions requiring long amortization times. Targeted payoff periods which are derived from the pressure for rationalization do not leave much space for investing in sustainability improvements at the same time.

However, environmental performance of products and deriving from there to companies and factories increases in society's perception. With a growing demand for more transparency on one hand, and environmentally consciousness on the other, sustainability becomes a competitive advantage. It is evident, that in the long term sustainable production will become a necessity but also a matter of course for manufacturing companies.

As many of the identified more sustainable solutions are already economical bearable—just not in short term—it is necessary to find a way for harmonizing economical and ecological objectives. The required harmonization (as started in product development for the use phase (see "Eco Care Matrix" in [11]) has to be started on factory level, based on the design and selection of process chains. As a tool for the systematic development of one's current manufacturing competences and technologies toward sustainable production, alternative process chains of different products have to be implemented stepwise, following a sustainability technology roadmap. When defining this roadmap, innovation as well as investment cycles have to be considered.

Following a roadmap based approach fosters an adjusted planning of investment and innovation cycles. Investments for new technologies have to be adjusted with times of technology readiness in a meaningful way, what in an individual case could mean to adapt an existing process chain later than reasonable from an energy consumption perspective. To smoothen the transition towards a more energy—and resource efficient production on the other hand, combined investments for production technology need to be considered.

A practical example for this idea is purchasing a milling center for modernization or extending capacities of manufacturing processes, which contains an optional extension for Friction Stir Welding (FSW), a compared to milling congener joining technology. The milling center will be used for a period comparably long to the average production period of a product, and thus the existence of a particular process chain. In this example, the FSW ability will cause a higher invest at the time of purchase, although the process is not being implemented at that time. However, by providing the FSW option, this energy efficient technology can be implemented for joining purposes later (following the sustainability roadmap for manufacturing), and then—when being implemented—with a significantly lower invest as if purchasing a FSW-single purpose machine at that point in time. Overall, this example illustrates the strategy for a smoothened transition from the current to a future technology and competence state of a factory, respectively company.

## 5 Conclusion/Outlook

Facing the given need for raising energy efficiency in production, a method for evaluating process chains has been introduced in this paper. The method explicitly integrates the combined investigation of the core processes, mainly responsible for adding value to the product, and the pre- and post-processes, e.g., necessary to prepare a product for the core processes. Starting from generating alternatives for designing a process chain, these are investigated by estimating the demand of energy required for each process step. In combination with an economical assessment of the process chains investigated, selecting the most suitable alternative for implementation is allowed.

Furthermore, since most factories are producing a mix of different products, an energetically optimal process chain for only one product is hardly to be implemented under economical sound conditions. The process chain evaluation method therefore is enhanced for defining factory wide solutions, using a Sustainable Technology Roadmap approach.

For coping with the current situation of environmental threads, in the future solely energy efficiency improvements will not be sufficient for saving the earth's climate. A solution for avoiding global warming can only be found as a combination of energy efficiency activities combined with further approaches, e.g., a wide establishment of renewable energy sources. Further, innovative concepts like developing $CO_2$ from a hazardous substance into a valuable raw material in what has been introduced as a Green Cycle economy [21] have to be pursued intensively.

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# References

1. The Economics of Climate Change (2006) Stern-report. Cambridge University Press, Cambridge
2. Potsdam Institute for Climate Impact Research and Climate Analytics (2012) Turn down the heat—why a 4 °C warmer world must be avoided
3. Vogt E (2012) Katastrophe voraus, Klimakonferenz in Doha. Süddeutsche Zeitung (SZ), München, 27 Nov 2012
4. Mihm A (2012) Doha—Wenig Erfolgschancen vor dem Weltklimagipfel. Frankfurter Allgemeine Zeitung (FAZ), pp 12–14, 25 Nov 2012
5. Energy Information Administration (EIA) (2011) International energy outlook 2011
6. Neugebauer R, Westkämper E, Klocke F, Spath D, Schenk M, Michaelis A, ten Hompel M, Weidner E (2008) Energieeffizienz in der Produktion, Untersuchung zum Forschungs- und Handlungsbedarf
7. Energiepreise und Unternehmensentwicklung in Baden-Württemberg (2009) Industrie- und Handelskammer Heilbronn-Franken, Hochrhein-Bodensee, Karlsruhe und Ostwürttemberg
8. Brüggemann A (2005) KFW-Befragung zu den Hemmnissen und Erfolgsfaktoren von Energieeffizienz in Unternehmen. KFW Bankengruppe, Publikation der Volkswirtschaftlichen Abteilung
9. Müller E, Engelmann J, Löffler T, Strauch J (2009) Energieeffiziente Fabriken planen und betreiben. Springer, Berlin
10. Duflou JR, Sutherland JW, Dornfeld D, Herrmann C, Jeswiet J, Kara S, Hauschild M, Kellens K (2012) Towards energy and resource efficient manufacturing: a processes and systems approach. CIRP Ann Manuf Technol 61(2)
11. Rohrmus D, Holst J-C, Mose C, Müller K, Schedlbauer M, Raschke U (2010) Sustainable manufacturing at siemens AG. In: The 8th global conference on sustainable manufacturing, vol 2010
12. Bunse K, Vodicka M, Schönsleben P, Brülhart M, Ernst FO (2011) Integrating energy efficiency performance in production management—gap analysis between industrial needs and scientific literature. J Cleaner Prod 19(6–7):667–679
13. Duflou JR, Kellens K, Guo Y, Dewulf W (2012) Critical comparison of methods to determine the energy input for discrete manufacturing processes. CIRP Ann Manuf Technol 61(1):63–66
14. PE International (2009) Concept description for CECIMOs self-regulatory initiative (SRI) for the sector specific implementation of the directive 2005/32/EC (EuP Directive)
15. Dahmus JB, Gutowski TG (2004) An environmental analysis of machining. In: Proceedings of IMECE2004 ASME international mechanical engineering congress and RD&D Expo, pp 1–10
16. Herrmann C, Thiede S (2009) Towards energy—and resource efficient process chains. In: Proceedings of the 16th CIRP life cycle engineering conference, pp 303–309
17. Weinert N (2010) Vorgehensweise für Planung und Betrieb energieeffizienter Produktionssysteme. Fraunhofer IRB, Stuttgart
18. Weinert N, Chiotellis S, Seliger G (2011) Methodology for planning and operating energy-efficient production systems. CIRP Ann Manuf Technol 60(1):41–44
19. Mital A, Desai A, Subramanian A (2008) Product development—a structured approach to consumer product development, design and manufacture. A structured approach to consumer product development, design, and manufacture

20. Matthes K-J (2008) Schweißtechnik - Schweißen von metallischen Konstruktionswerkstoffen. 4., akt. A. Muenchen: Fachbuchverlag Leipzig im Carl-Hanser-Verlag
21. Rohrmus D, Döricht V, Weinert N (2013) Green cycles economy and factory. Paper accepted for publication at the 20th CIRP conference on life cycle engineering (LCE), 17–19 April 2013, p. tbd., Singapore

# Green Cycle Factory

**Dominik Rohrmus, Volkmar Döricht, Nils Weinert, Jens-Christian Holst and Christoph Kiener**

**Abstract** Advancing climate change and rising prices for fossil resources and therefore industry supplies call for answers that go beyond optimizing our current use of resources and energy in production. The green cycle vision presented looks at carbon (C) for green production and green raw materials. This opens up new production models and new product markets to provide an answer for the world's hunger for materials. One driver for this development is the merging of the different energy grids. Our future vision is that $CO_2$ is the main source for green production businesses. The prerequisites will be $CO_2$-neutral forms of renewable energy and chemistry production technologies.

## 1 Introduction

As Siemens 163 year history shows, our understanding of sustainability is closely linked to our company values—responsibility, excellence, and innovation. From the very first beginning, Werner von Siemens insisted on the fulfillment of the company responsibilities for the employees, the society, and the nature. Achieving excellence, leading positions in the markets of tomorrow, and developing innovative technologies that help to ensure the future viability of modern civilization is and has always has been our vision and our challenge. The Siemens AG focuses on the mega trends [1]:

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- demographic change and healthcare;
- urbanization and sustainable development;
- climate change and energy supply;
- globalization and competiveness.

To challenge these mega trends we have a guideline: The company sustainability principles. They are setup and driven by the internal sustainability office and controlled by the externally staffed sustainability board. It aims at the fulfillment of social responsibility and environmental preservation globally, both geared towards long term company economical success, which is a key function of any company [1]. Social responsibility is the Siemens commitment toward the societies in which we are active to help as many people as possible to gain access to essential goods, both today and in the future: food, jobs, security, energy, and affordable healthcare. This is important since companies are mainly successful in societies in which people enjoy a certain level of prosperity. The products and solutions within our environmental program and the greater company portfolio acknowledge the need to preserve the fundamentals of human life in order to remain successful over the long term [2]. Siemens wants to help maintain a healthy world, one in which natural resources are protected and the needs of future generations are respected by environmental conservation. The Siemens sustainability goals are to establish a substantial equilibrium between the planet and the people. This equilibrium is to be achieved with a profit orientation from the business point of view (see Fig. 1). The Siemens Sustainability Board defines and guides business activities for this purpose [1].


**Fig. 1** The Siemens AG sustainability definition

## 2 Motivation for "Green Cycle Factories"

The energy and resources consumption of the developed civilizations and the new emerging populations in Asia and South America is one of the main threats for the ecological systems globally [3, 4]. The so called rebound-effect, i.e. the situation that increasing production capacities worldwide over-compensate efficiency achievements of existing production sites, intensifies the consumption situation largely [5]. Not only green house gas emissions like $CO_2$ as a consequence of fossil combustion have to be named, but also the environmental impairment raised by the increasing extraction of natural resources [6, 7]. Consequently, the excessive use of energy not only threatens the environment but strongly influences the social dimension of the human existence and thus, the ability to increase the global living standards [3]. Unfortunately, growing prosperity of societies has always been linked to increased energy consumption [7]. At the same time, the economical challenges due to the increased worldwide demand of the limited available resources become observable.

In 2007, 457 EJ (1 Exa J = 1,018 J) of primary energy were consumed worldwide, the share of final energy used for industrial applications have been 195 EJ. About two-fifth of the total primary energy are converted into electrical energy, with an increasing tendency in the emerging markets. The required energy is estimated to double globally until 2050, while the electrical energy demand will already be doubled in 2030 [8, 9]. The industrial production as an important indicator of the national industrial activity is responsible for up to 40 % of the total $CO_2$ emissions worldwide [10]. On the other hand, an isolated chemical industry example in parts of Iceland achieved the reduction of $CO_2$ emissions to close to zero for a competitive mid-size industrial production [11].

The efficiency of manufacturing processes specifies how efficient resources are used to add economic value to the company, i.e. it is the economic relationship between the resources input and the product output. Today, the increasing scarcity of natural resources as well as the market critical raw materials and resources supply [6] account for an average of 40 % of the total manufacturing costs. The energy and water supply add to this with the small share of 10 %. Both together compare significantly to the share of about 20 % for labor costs (see Fig. 2) [12,

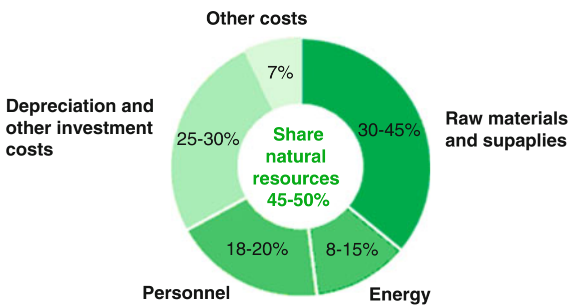


**Fig. 2** Manufacturing industry cost structure

13]. In the future, when the energy efficiency improvement measures available today are widely implemented, the industry will face a limited energy savings potential relative to the possible efficiency measures of today compared to the households, the transport and the tertiary sector [12], because advanced efficiency measures become increasingly expensive [14]. For the European industry the energy saving potentials decrease in 2020 to about 6 % (estimation range is 5.9 % to 6.6 %) compared to the baseline scenario, which is presented in [14].

The presented dialectic situation yields a possible future scenario in which the energy from renewable sources as well as the scare raw materials supply will be addressed in a combined way. One approach to achieve this scenario is the green cycle model, i.e., an integrated novel view on renewable energy and production cycles. It enables new production optimization concepts that are scalable from small to large businesses. Our proposed solution for production is the green cycle factory.

## 3 The Concept of Green Cycles

It is possible to open additional market potentials by solutions based on the so-called green cycles. The novel green cycles will foster a complementary market to the existing energy efficiency optimization und supply shift markets, which are the main drivers for the currently innovative energy aware products and production solutions. We define green cycles as the imitation of natural processes from the biosphere in terms of technical (synthetic) means. In nature, two cyclical processes are crucial: the water cycle and the carbon cycle [15]. It is remarkable that in nature (almost) no heavy-metal cycles exist. The new green cycle concept developed within the Siemens AG Cooperate Technology is depicted in Fig. 3 [16].

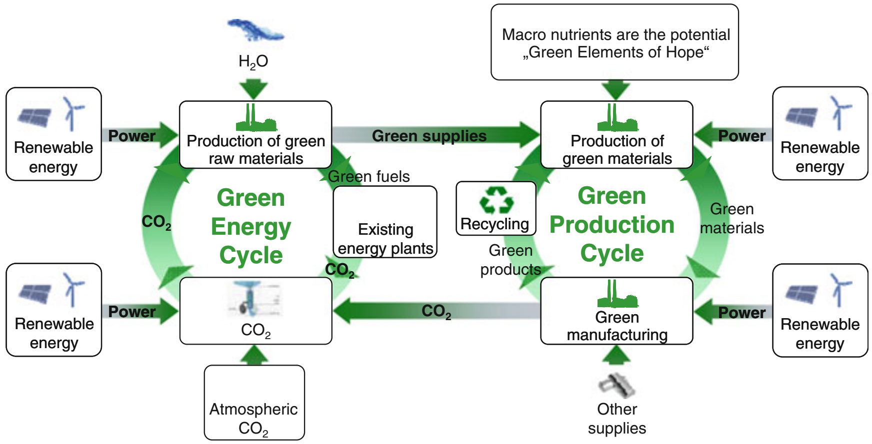


**Fig. 3** Green cycles in the Siemens definition

To run the green cycle a considerable amount of electrical energy is needed. The quantity of $CO_2$ fixed in a green cycle, i.e., converted from gas to liquid fuels can be demonstrated by an existing chemical industry example: It takes about 8 MWh of electrical energy for an electrolysis technology combined with a Methanol synthesis to fixate one metric ton of $CO_2$ in about 3/4 metric ton of synthetic raw material, e.g., fuels. This is equivalent to the annual power consumption of about 2000 three-person households, or the hourly production of two 4 MW wind turbines. This cycle approach generates all required aspects to shift to a 100 % renewable energy economy by not emitting but consuming $CO_2$ as a raw material source. We define this the green energy cycle (see the left part in Fig. 3).

Beside the green energy cycle there exists a directly linked green production cycle, which yields a novel combinational view (see the right part in Fig. 3). The green production cycle takes hydrocarbons, oxygen, and hydrogen from the green energy cycle as well as so-called "green elements of hope" [17] as input resources for the production of green materials and products, e.g., plastics. This green production cycle requires different ways of product design and production technologies that are focusing on molecular layers of the carbon materials and the technology that is required to produce these layers. The scarcity of specific metals is becoming one of the most urgent global problems, comparable with the energy scarcity [6]. The peak oil situation is analogously transferable to certain mineral resources [18]. A particularly feasible approach is the substitution of scarce metals by most abundant elements [6]. This requires advanced engineering sciences as well as disciplines like agriculture and biosciences. The green elements of hope contain all macronutrients of life and lack heavy metals. We propose that carbon-based materials are a complementary source of interest for alternative green materials and alternative production processes.

## 4 The Merge of the Energy Grid

In highly industrialized countries like Germany four different energy consumer groups can be identified: large-scale, industry, small-medium enterprises, and private households. Each consumer group is usually centrally supplied by energy with different prices that vary drastically. In addition, the grid transmission prices, which are by a high degree influenced by governmental actions, vary in a similar way. Considering the worldwide trend of decentralized energy supply, these grid transmission prices increasingly become volatile since certain consumer groups, beginning with private households, will reduce the consumption of energy provided by centralized grids.

A single company can simultaneously belong to the large scale, industry, and small-medium enterprises energy consumer group per energy type respectively form. Energy forms are electrical, gas, mineral oil, heat, and further energies. Hence, companies face the problem of being tied to different price scenarios. This yields a multidirectional understanding of energy supply for these consumer

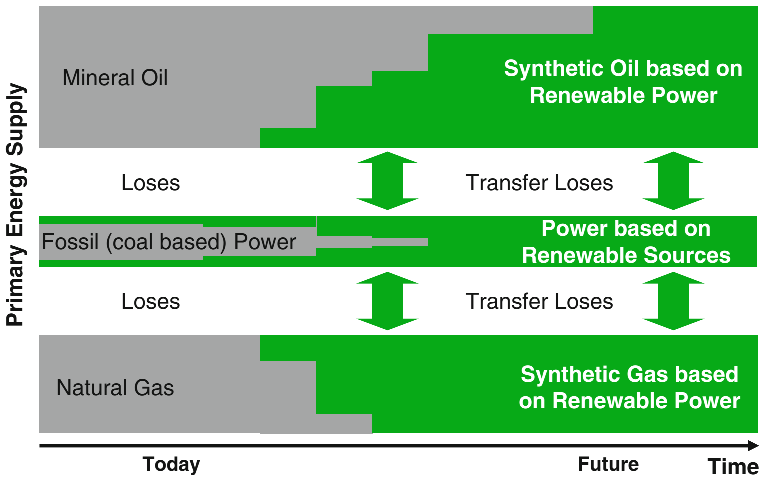


**Fig. 4** The energy grids merge in the future

groups. It becomes market attractive to convert energy from one form to another if decentralized electrical energy production is possible and available at cheap prices. In other words, currently the primary energy such as gas, coal, or mineral oil is converted in electrical energy. In the decentralized setup this is different because the supply from centralized grids is more expensive than decentralized produced energy. In other words, the scenario becomes inverted because the decentralized renewable electrical power is cheaper than any other energy form. The path to this new energy future is displayed in Fig. 4.

## 5 Green Cycle Factory

A green cycle factory is defined as a plant that has no negative impact on the global or local environment [16]. By this definition a production site or a production network aims to meet the triple bottom line of the sustainability definition of the Siemens AG [1]. Green cycle factories focus on environmental and economical targets. In general, the business of these factories is described as green if it matches the following criteria:

1. It aims to supply environmentally friendly products or services that replace the demand for non green products and/or services.
2. It uses high energy efficiency solutions in all of its business processes.
3. It mainly uses renewable power and supplies based on renewable energy.
4. It emphasizes on the implementation of recycling heat, water, energy supplies, and materials in the factory.
5. Green factories use exhaust gases like $CO_2$ as a resource.

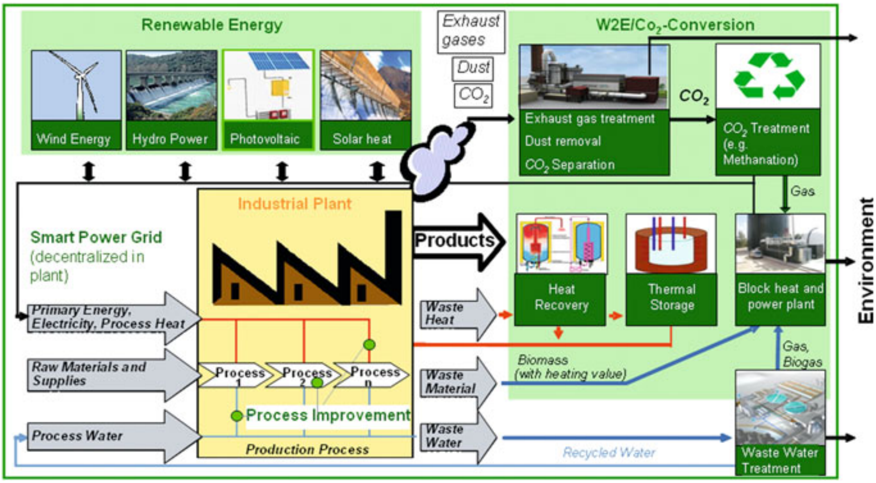


**Fig. 5** Green cycle factory elements

The green factory can help to meet the needs of the current world without compromising the ability of the future generations to address their own needs [1, 19]. It emphasizes the transformation process of achieving the design of products and production processes that use the advantages of carbon, hydrogen, oxygen, and additional elements. The most important elements of a green factory are depicted in Fig. 5. These are renewable and $CO_2$-neutral electrical energy sources, suitable production processes and facilities, and additional chemistry processes that realize the recycling processes.

## *5.1 The Evolution of the Green Cycle Factory*

The green cycle factories can be accomplished in an evolutionary way. Three stages can be described. Each stage is essential for the next stage of the overall concept.

The first stage is the energy efficiency optimization (see Fig. 6). This covers the current activities regarding production, logistics, buildings, etc. The main goal of energy efficiency optimization is to use the limited energy resources more effectively. Since efficiency optimization processes in general are a key driver for economic growth and improved competitiveness of companies operating in global markets, the existing methods form a basis for the evolutionary extension of these processes, methods, and solutions for the new and additional energy aspects. The methods and solutions aim at emitting less green house gases than comparable predecessors while guaranteeing similar product and operation performance

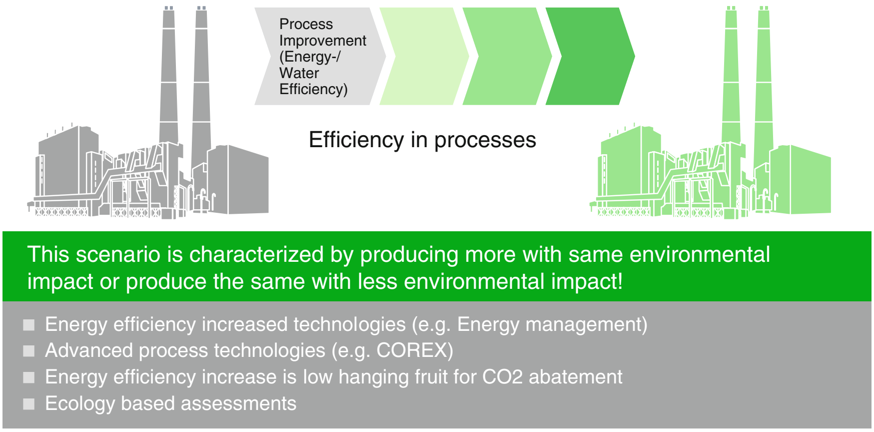


**Fig. 6** Energy efficiency optimization

compared to the not energy optimized solutions. However, the goal of zero emissions at reasonable costs cannot be reached by these approaches.

The next stage is the energy supply shift. Shifting the supply to renewable energy means primarily to switch the factory electricity supply with the related purchasing processes from fossil thermal power plants to renewable power plants. The aim is a complete replacement of the energy input by renewable energy sources and adequate smart and decentralized grid technologies.

## 5.2 *Characterization of the Green Cycle Factory*

The last stage is the new green cycle factory. It is based on the synthetic imitation of natural processes from the biosphere, i.e. plants and trees. It combines technologies that provide a negative $CO_2$ footprint over their whole life cycle and thus, form the technical core of a green cycle production. Raw materials as well as energy carriers are synthesized from carbon (C) sources like $CO_2$, using renewable electricity. Synthesized energy carriers, such as artificial natural gas (methane), are used for storing and transporting energy until the production processes take place, transferring carbon based raw materials into products. Figure 7 illustrates how to create a green energy cycle.

The following development path characterizes a green cycle factory:

- The electrical energy to maintain the cycles comes entirely from renewable and $CO_2$-neutral energy sources.
- The water from the atmosphere (assuming certain purity) is split into hydrogen and pure oxygen.

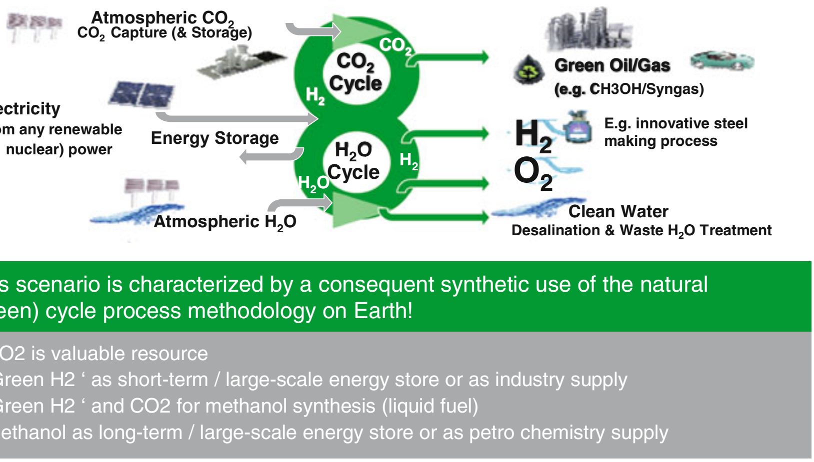


**Fig. 7** Green cycle factory final stage

- The resulting hydrogen is enriched with carbon (C) or $CO_2$ emissions from industrial waste products, processes, or best of all in long-term directly from the atmosphere [24]. It is used to produce hydrocarbon compounds.
- The hydrocarbon compounds are used, among other possibilities, for the petrochemical industry, new carbon industries, e.g. to produce new materials like carbon-fiber composites, and to generate green fuels, like methane and methanol.

A business example is given by the Island based company Carbon Recycling International, which shows that this can already be achieved cost-effectively today, assuming specific energy and raw-material cost situations [11]. Another example is the "$CO_2$rrect" project ($CO_2$ reaction using regenerative energies and catalytic technologies) from the Bayer AG, Bayer Material Science AG, Siemens AG, and other partners. Yet another example is a Bayer AG pilot plant at the Leverkusen chemical park that uses $CO_2$ as a chemical intermediate product in the polyurethane production (an intermediate product for producing plastics).

Furthermore, hydrogen can be used in a large industrial scale, for steelmaking processes like COREX. However, this application is not part of a green cycle.

There will be new possibilities for producing clean water, an important raw material for the green cycle processes. Not only raw materials, but also emissions and wastes will become more expensive in the long run as the international trading scheme for emission and waste matures [20]. In the first phase green cycle factories will be in the position to derive revenues from the carbon credit and the renewable fuel markets since exemplarily, green methanol reaches higher margins than fossil based methanol [11].

## 6 Conclusion And Outlook

Economical and ecological aspects of future production are systematically investigated and structured in a novel way. A systematic approach to define green cycle factories is presented and an evolutionary path that yields these factories is derived. The developed green cycle factory concept offers economically attractive new areas of production and product potentials that are related to new opportunities for green products and green production under the assumption of renewable energy supply as the main supply for energy.

The existing factories, the existing valuable hydrocarbon infrastructure, and even the fossil power generation plants can be well integrated and utilized in the novel concept in an evolutionary way. The goal is to achieve zero emission factories in an economically feasibly way. This requires a paradigm shift from primarily fossil and/or metal based production and products to carbon based products including the necessary new production processes. The existing product and production technologies and solutions play an important role during the transition process so that only economically reasonable green technologies will be considered at each development stage. Green fuels are among the first products to be market attractive. The $CO_2$ fixation is a goal that might not be economically feasible at the beginning of the green transition process. Rather other carbon sources from existing plants and factories will be the first carbon suppliers. The increasing speed of renewable energy technologies and renewable supply supports the green transition process and sets the transition speed. This includes the decentralized energy supply technology and market trends.

The authors recommend investigating the presented green areas further, in particular in terms of the consequences for the production and production supplies.

## References

1. http://www.siemens.com/about/en/index/strategy.htm. Accessed 11 Jan 2013
2. Rohrmus D, Holst J-C, Mose C, Müller K, Schedlbauer M, Raschke U, Weinert, N (2010) Sustainable manufacturing at siemens AG. In: CIRP proceedings of the 8th global conference on sustainable manufacturing, pp. 79–84
3. IPCC (ed) (2012) Climate change 2007: synthesis report 2007. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf. Accessed 22 Nov 2012
4. Sekretariat der Klimakonventionen (ed) (2011) Das Protokoll von Kyoto zum Rahmenübereinkommen der Vereinten Nationen über Klimaänderungen, 1997. http://unfccc.int/resource/docs/convkp/kpger.pdf Accessed 11 Dec 2011
5. Binswanger M (2001) Technological progress and sustainable development: what about the rebound effect? Ecol Econ 36:119–132
6. Diederen AM (2012) Metal mineral scarcity: a call for managed austerity and the elements of hope, 2009. http://www.tno.nl/downloads/Metal_minerals_scarcity.pdf. Accessed 22 Nov 2012

7. GLOBAL 2000/SERI (Ed) (2011) Ohne Mass und Ziel? Über unseren Umgang mit den natürlichen Ressourcen unserer Erde, 2009. http://old.seri.at/documentupload/SERI%20PR/ohne_mass_und_ziel–2009.pdf. Accessed 16 Oct 2011
8. International Energy Agency (2010) World energy outlook. IEA Publications, London
9. Cullen J, Allwood J (2010) The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy 38(1):75–81
10. Imperial College London Grantham Institute for Climate Change (2012) Briefing paper, No. 7, 2012. https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Reducing%20CO2%20emissions%20from%20heavy%20industry_Briefing%20Paper%207.pdf. Accessed 22 Nov 2012
11. http://www.carbonrecycling.is. Accessed 24 Nov 2012
12. Eco-Innovation Observatory (2012) Closing the eco-innovation gap, an economic opportunity for business. Annual report 2011. http://www.eco-innovation.eu/index.php?option=com_content&view=article&id=420:closing-the-eco-innovation-gap&catid=80:annual-reports&Itemid=210. Accessed 11 Dec 2012
13. UK Department for the Environment, Food and Rural Affairs (2012) Business benefits of resource efficiency—EV02036, 2007. http://randd.defra.gov.uk/Document.aspx?Document=EV02036_6754_FRP.pdf. Accessed 11 Dec 2012
14. ADEME/Intelligent Energy Europe (2012) Energy efficiency trends and policies in the EU 27, results of the ODYSEE-MURE Project, 2009. www.odyssee-indicators.org/publications/PDF/publishable_report_final.pdf. Accessed 11 Dec 2012
15. Olah G, Goeppert A, Surya Prakash GK (2009) Beyond oil and gas: the methanol economy, 2nd edn. Wiley, Weinheim
16. Rohrmus D, Döricht V, Weinert N (2013) Green cycles economy and factory. The 20th CIRP conference on life cycle engineering (LCE 2013)
17. Held TM, Kriegler E (2008) Tipping elements in the Earth's climate system. In: Proceedings of national academy of science of the United States of America, vol. 105, no. 6
18. BP (2011) Energy outlook 2030, 2011. http://www.deutschebp.de/liveassets/bp_internet/germany/STAGING/home_assets/assets/deutsche_bp/broschueren/broschuere_bp_energy_outlook_2030_dt.pdf. Accessed 19 Dec 2011
19. Anderson DR (2006) The critical importance of sustainability risk management. Risk Manage 53(4):66
20. Müller E, Engelmann J, Löffler T et al (2009) Energieeffiziente Fabriken planen und betreiben. Springer, Berlin

# Visualization of Energy: Energy Cards Create Transparency for Energy-Efficient Factories and Processes

**Hendrik Hopf and Egon Müller**

**Abstract** In the context of sustainability and for strengthening the competitiveness of manufacturing systems, energy efficiency becomes a more and more important objective for industrial processes. For designing energy-efficient systems and processes, new or improved tools and methods focusing energy efficiency are needed. Furthermore, detailed energy data, information, and knowledge are required for energy efficiency improvements. However, in practice, these are often not available in the appropriate form. This leads to the need to illustrate the issue "energy" in a tangible and visible form. Energy Management as an organizational instrument helps to consider energy efficiency in planning and operation tasks. Energy Labels are useful tools for benchmarking similar goods. Though, they are not available for different systems of a factory. The presented tool "Energy Cards" bundles energy data of a system and enables the transfer of energy information and knowledge in a structured and clear manner. In this article, the basic concept and the structure of the Energy Cards are described. In addition, some prototypes of digital cards are presented. An example on process modeling illustrates some possibilities of application.

## 1 Introduction

Energy efficiency has become an important objective for industrial processes because of political circumstances, increasing energy prices, the scarcity of resources, and the public awareness. Manufacturing systems have to be energy and resource-efficient for remaining competitive. Therefore, energy-efficient factory

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systems are needed. Factory planning plays a significant role for the energy efficiency of a factory [1]. In addition, facility design techniques can promote it [2]. In early planning phases the energy level of the entire system is set up. Afterwards in the operation phase, energy improvements are just possible within these borders. Thus, there is a demand for tools and methods to integrate the objective energy efficiency in planning and operation processes systematically.

In order to design energy-efficient factories, different data and information about the structures and functions of systems such as machines or facilities are important. Usually, data about functional parameters, design or quality characteristics etc. of the systems are available. However, a major deficit represents the lack of knowledge about the energetic interrelationships in the factory. In general, information about the required energy supply is delivered by the manufacturer. However, these are mostly given in different ways and there is no information about the power level or the energy consumption in different operation states. Furthermore, the access to this data is difficult. In practice, the data of machines, buildings, building services etc. is managed by different departments of the company or by external service providers with the help of specific information systems. Thus, a comprehensive energy-oriented view on the entire factory system with its subsystems is not possible.

To meet these requirements, some instruments and a concept for a new kind of a tool are presented in this article. The next chapters are organized as follows: Some instruments for providing energy information are given in Chap. 2. The basic concept and the structure of the Energy Cards are described in Chap. 3 and prototypes of digital cards in Chap. 4. An example for application in the field of process modeling is shown in Chap. 5. Finally, Chap. 6 summarizes the main facts about the current and the further research work.

## 2 Instruments for Providing Energy Information

Different state-of-the-art tools and methods are able to collect and structure energy data as well as transfer this information or knowledge to the user in an understandable way. A selection of common instruments is presented in this chapter.

To improve energy performance including energy efficiency of an organization systematically, Energy Management [3] is often mentioned as a key instrument for coordinating energy-related processes. It provides goals, responsibilities, activities and tools to integrate the issue energy in the daily operations for continual improvement of energy performance [4]. This is why Energy Management is also an important tool for energy efficiency-oriented factory planning and operation. Energy Monitoring [5] or Energy Metering [6] is a main part of Energy Management especially for systematic and continuous energy measurements. It gathers, saves and visualizes energy data of the factory operation combining hardware and software for measurements. These data can be used for planning and optimization tasks, too. It has to be considered that a big effort (energy experts, finance, hard- and software) is necessary to implement Energy Management structures or to run a comprehensive Energy Monitoring. In addition, these instruments are only used by experts like energy or facility managers. By this, the rest of personnel have no access to the energy information.

By this, different tools such as audits, checklists or action plans are also available for tasks of Energy Management. Labels can be useful, too. With the help of Energy or Eco Labels, a standardized comparison of consumer products (e.g., refrigerators, washing machines, televisions) [7], buildings [8] or cars [9] should be achieved. Currently, the scope of these labels is about to be extended for benchmarking industrial goods such as machine tools [10]. The labels divide the products of a same product group into ascending energy efficiency categories depending on a fixed benchmark. The comparability of systems based on the objective energy efficiency plays an important role for planning. Energy labels support purchase decisions through standardized comparison and classification of the product as well as the prediction of the energy demand. However, Labeling is a complex process. The challenge for standardization lies in the diversity of the regarded product group and its processes [11]. Furthermore, the Energy Labels can only be used within one product group. Though, especially in industrial environments with a lot of different processes and facilities, there are more extensive demands to provide energy transparency in the whole factory.

As a result of the first two chapters, there is a deficit in bundling and visualization of energy data, information and knowledge. For that reason, the concept of the tool "Energy Cards" will be presented in the next chapters.

# 3 Energy Cards

## *3.1 Basic Concept*

Due to the mentioned deficiencies in the systematization and the provision of energy data, information and energy efficiency knowledge, the tool "Energy Cards" [12] has been developed at the Department of Factory Planning and Factory Management within the Cluster of Excellence eniPROD®. The goal is to create transparency on the energetic relationships in the factory in a direct way at the respective object.

For this, Energy Cards are attached to the systems (e.g., plant) and subsystems (e.g., machine). The cards are uniformly structured and highlighted with a coloured frame for quick visual perception in the factory environment. On the one hand, a distinction is made according to the respective "energy type"—energy generator, converter, distributor, storage or consumer—and on the other hand according to the energy carrier. For reasons of clarity, there is an own card for each energy carrier. In this way, a system has got one or more cards. In the digital form (see Chap. 4), further information can be added easily.

The advantage of this approach is that the regarded object can be classified and compared to other objects on the ground in the factory. Both in the planning as well as in the operation phase, it is useful to get energy-related information directly from the Energy Card. This also includes measures to increase the energy efficiency. Especially for the modeling and discrete-event simulation [13] of energy flows, the cards provide necessary information. It should be noted that these energy facts are available for all persons in the factory and not only for energy experts.

Unlike Energy Labels, the Energy Cards do not concentrate on the benchmark in one product group based on a reference level. For this, international standards are needed. Instead, the Energy Cards focus on the acquisition of as many systems as in a factory to detect the entire energy flow system. This will always be done in a similar manner to support the planning and the operation phase with energy data, information and knowledge.

## *3.2 Structure of Cards*

As mentioned, the Energy Cards are uniformly structured and highlighted. They consist of several sections which will be explained on an example hereafter as shown in Fig. 1. The figure shows the toolbox with the different types and an Energy Card of an assembly machine.

In the first section, the regarded "Object" is characterized by name, type and basic function. In addition, the object is classified by the Hierarchical and Peripheral Order [14] to illustrate the interrelationships in the factory system. The regarded object is allocated in a defined factory level by the Hierarchical Order. Based on this, the factory can be assembled with these subsystems from bottom to top. The Peripheral Order structures the systems of a factory according to the dependence on the production program. Moreover, this order divides the factory in direct (value-adding) and indirect (necessary for value-adding) parts. Thus, the energy consumption can be traced to its origin backwards from the peripheral processes to the main processes. With these two orders, the object is classified as a part of the material flow system as well as of the energy flow system of the factory.

The "Energy Transformation" is described with its inputs, transformations and outputs in the next section. This includes the required energy supply and energy carriers, the incoming and outgoing form of energy, the main consumers as well as the control and disturbance variables. Furthermore, the lost energy and the required floor space indicate on the impact on the system environment and the indirect energy demands (e.g., for lighting, heating and air condition). The static information in this part is mainly needed in early planning phases for the preparation of the energy infrastructure and the factory environment. At this point, the object is described in the energy flow system with static aspects.

In the following section "Energy of Operation" the power is matched to defined operation states like power on/off, different loads, idle and standby. The definition

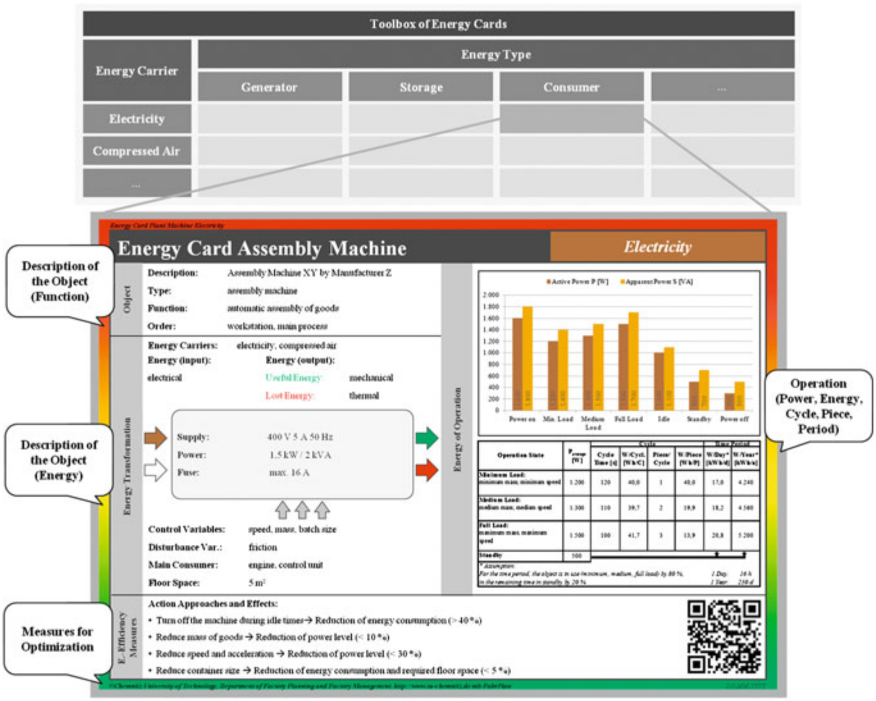


**Fig. 1** Example of an energy card

of these states can be modified for the specific use case. On this basis, the energy consumption for processing cycles, pieces or time periods are calculated as key figures. Some assumptions (e.g., working hours) are made here. They base on the specific and typical operation of the object. As stated above, the approach doesn't focus on the comparison of same systems like Energy Labels do. For this, standardized tests are needed. However, it aims for gathering energy data of as many systems as possible for consideration the whole factory. So individual operation cycles can be used but they have to represent the typical usage of the system. The key figures are needed for the preparation of the energy-efficient operation as well as for calculation and comparison of energy demands related to different bases. Both individual operating states as well as entire process chains can be considered in terms of energy demands. By this, in process modeling the energy demand can be allocated to every process chain element. Through the combination of the elements, the energy consumption of the entire process can be compared and predicted (see Chap. 5). With this section, the object can be described in the energy flow system with dynamic aspects.

"Energy Efficiency Measures" are shown in form of action approaches and their effects in the last section. These measures represent the energy efficiency knowledge. They aim at direct improvement of the energy efficiency of the regarded object both for the planning and the operation tasks. For example, the production planner should minimize the mass of the transport goods to reduce the power level. The machine operator should turn off the machine during idle times to reduce the energy consumption. For provision of further information, the QR-Code on the right side links to the Energy Information System (see next chapter, not realized in Fig. 1).

## 4 Digital Prototypes

More possibilities for the visualization of energy will be presented in this chapter. In addition to the printed version, the Energy Cards are realized prototypically as a part of a web based Energy Information System (EIS), in a digital factory model and in an Augmented Reality (AR) application (Fig. 2).

Energy efficiency knowledge in form of Energy Cards, Energy Knowledge Bricks, Energy Panels, Energy Flow Diagrams, Energy Job Instructions, and others is collected and provided in EIS. The connection between the printed cards and the EIS is established by QR codes via internal (wireless) network. Thus, mobile devices with camera and browser can be applied, too. Additionally, it is sufficient to attach a small QR code instead of the complete card to the systems. The Experimental Energy Stations, which are used for the practical qualification, access EIS by PC terminal to receive theoretical knowledge for training.

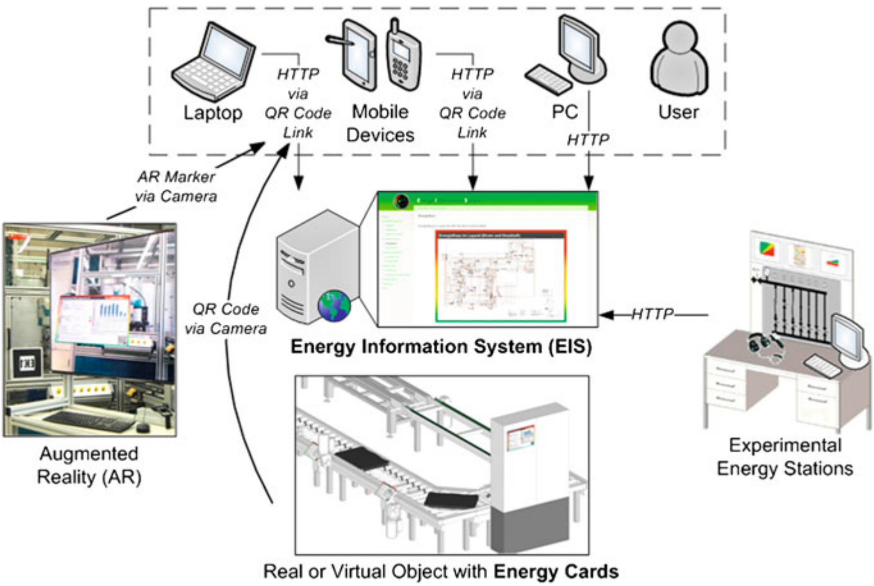


Fig. 2 Digital prototypes of energy cards

The Energy Cards are attached to the objects in the factory model in a CAD system. The cards include the same information as the printed ones. They can be accessed by navigation through the factory model. By this, the planning participants do not need to go through the real production site to get necessary information. The Energy Cards can be projected in the real environment by a special AR application. The AR visualization bases on the card models of the CAD. Again, it is sufficient to attach only the code for AR marker.

The digital Energy Cards are favorable and necessary, if there is not enough space for the printed card on the object or there is a need of a remote access or a connection to databases. In addition, further or more detailed information can be provided. Changes of data can be made faster. The integration into other planning tools, Energy Management, Facility Management or Production Control Systems is also imaginable. Real-time data as well as derived trends or key figures could be included. Thus, the cards would be generated automatically. Events like alarms for limit values could be set up or the data could be used for operation tasks. Some of these possibilities are currently tested in laboratory.

## 5 Example of Application for Process Modeling

As already described, the energy cards can be used for a variety of applications such as Energy Management, simulation or process planning and optimization. An example for the last one is described in this chapter.

### *5.1 Model of Process Chain Element*

With the help of the Energy Cards, the objective energy or energy efficiency can be considered in the planning of process chains. By this, energy-efficient processes can be modeled. The Energy Cards represent the basis for energy data, information and knowledge. For the specific use case, the actual production data such as number of pieces or working time are added for the additional calculations.

Process chains [15] describe chronological linked procedures for realizing things like orders or tasks. They consist of individual process chain elements that transform objects from an input into an output. Meanwhile, on the one hand, an increase of value of the product is achieved. On the other hand, a consumption of materials and energy as well as costs is associated with that procedure. This consumption can be matched to the individual process chain elements. This means, energy demands for the process are caused by the use of resources such as machines or facilities.

The Energy Cards submit the direct energy consumptions based on processing cycles, pieces or time periods for the needed resources of the process chain element. Besides, the regarded object (resource) is part of the whole factory. It takes up room or floor space. So, indirect energy consumptions for building services such as room heating or lighting are caused. Additionally, more inputs of other peripheral facilities like compressed air are needed. The energy consumption of these facilities can be found in their own Energy Cards. This energy consumption can also be distributed to the objects in the process chain element by allocation keys based on percentage shares or absolute floor space demands. The sum of the direct and indirect energy requirements of all resources is the total energy demand of the process chain element (Fig. 3).

## 5.2 *Model of Process Chain*

The entire process chain is set up by the connection of the elements. There are two possibilities to calculate the energy demand for the chain. Firstly, as described above and shown in Fig. 3, the indirect energy consumptions are allocated to the process chain element. This is suitable to describe the element in detail and to reduce the visible size of the process chain. Secondly, the indirect processes can be listed separately as elements of the process chain as shown in Fig. 4. Their energy consumptions are calculated as a whole or proportionally by allocation keys. The energy flow arrows are derived backwards from the main to the peripheral processes by the information of the section "Energy Transformation". The width of the arrows indicates the percentage shares. This second possibility of visualization is useful to get an extensive view on the entire process chain.

With this modeled process chain, selected individual processes or the connected processes as a chain can be optimized. Besides, energy-intensive processes or systems are identified for deeper analysis. As usual in process designing, processes are restructured or redundant processes are minimized or eliminated. But in this

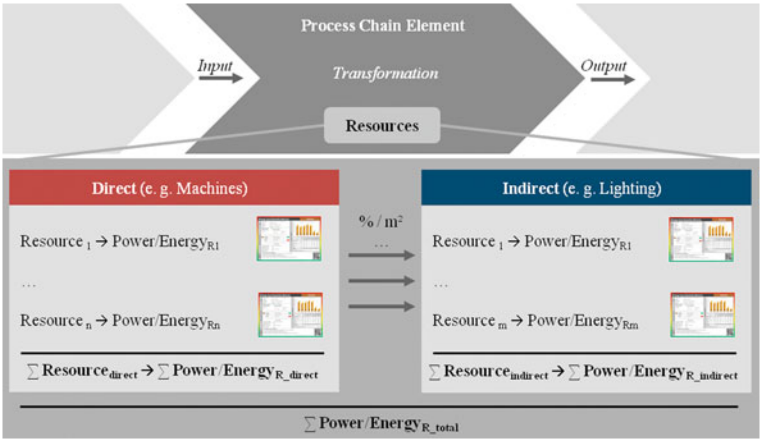


**Fig. 3** Process chain element (with integrated indirect energy)

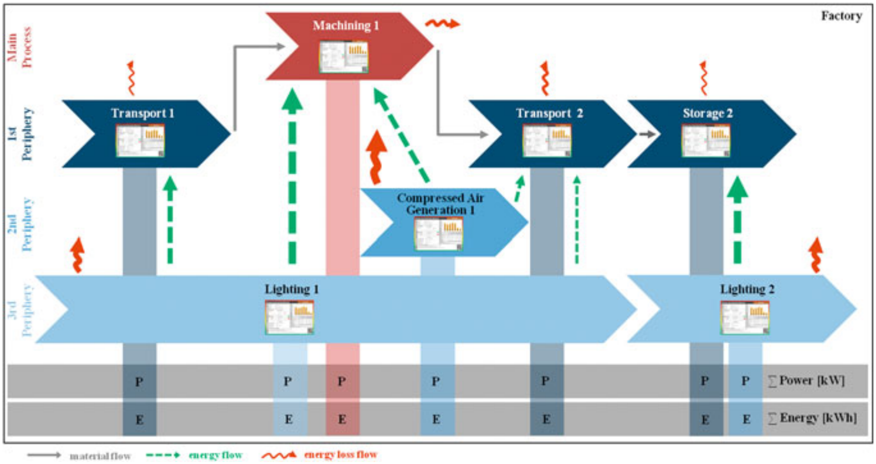


**Fig. 4** Process chain (with separated indirect energy)

case, these optimizations are done under the consideration of energy efficiency. For example, the transport systems for the process "Transport 1" in the Fig. 4 can be turned off after the transfer to "Machining 1" (energy consumption decreases). Or the facilities for "Lighting 2" can be downsized because the store does not need the same light intensity as the machining process (power level and energy consumption decrease). By comparison of energy demand and capacity, this leads to smaller sized energy supply infrastructure for "Lighting 2" (for clarity not shown in Fig. 4).

## *5.3 From Processes to Factory System*

The modeled processes determine the necessary systems (e.g., machines, facilities or building services) for realizing the production objectives. Based on this, the factory system is assembled from the individual systems.

Figure 5 shows the Peripheral Order (see Chap. 3) of the factory. As described before, the Peripheral Order divides the systems of a factory into 4 parts according to the dependence on the production program [14]. The figure includes some examples of systems which are sorted in main process, first, second or third periphery. The value-adding machines are in the main process. Systems which depend directly on the production program (products) are in the first periphery like the transport and store systems. Systems which do not depend on the products but from the systems of the main process are located in the second periphery. The third periphery consists of systems which do not depend on the main process or its systems. For example, it includes heating, ventilation and air conditioning (HVAC). By this, the factory is assembled from the main process to the peripheries. This means, the systems of the main process are determined first. After that, the systems of the first, second and third periphery are derived.

Additionally, Fig. 5 includes the material and energy links. They illustrate the complex interrelationships between the individual (sub-) systems of the factory. For clarity, the links basing on energy losses are not shown here. With the information of the Energy Cards, the demands for power, energy etc. are allocated to the main process and to the peripheries. One the one hand, every part can be regarded, estimated and optimized of its own. On the other hand, the factory as a whole of parts and systems can be considered. The shares of the parts indicate the distribution of the energy generators, converters, consumers, etc. (energy types, see Chap. 3). It should be noted that this approach allows comparing and balancing the required and the provided power. In practice, there is often no adaption of the periphery after changing of (main) processes. However, this is very important for optimizing the energy infrastructure like reducing energy losses by avoiding converting processes or oversized systems. Moreover, in further research work, the description of the complex interactions between systems, facilities, and buildings have to be expanded [16].

In conclusion, the approach does not only analyse the main process, but also the peripheral processes. A holistic view on the process and on the factory is possible. Focusing energy, the process chain or the factory system can be evaluated and optimized or compared with alternatives. Both different process and resource variations can be considered. Herewith, a planning basis is created which allows to evaluate the process in terms of energy efficiency and to predict the energy demand in the planning phase. More opportunities for designing and optimization of the process chain, e.g., according to the Energy Value Stream [17], can be realized, too. However, in contrast to it, the presented approach allows considering the structures of different energy types of the factory. Thereby, not the processes related to the product are focused, but rather the factory itself as a complex system of different energy-related (sub-) systems with their various interrelationships and interactions.

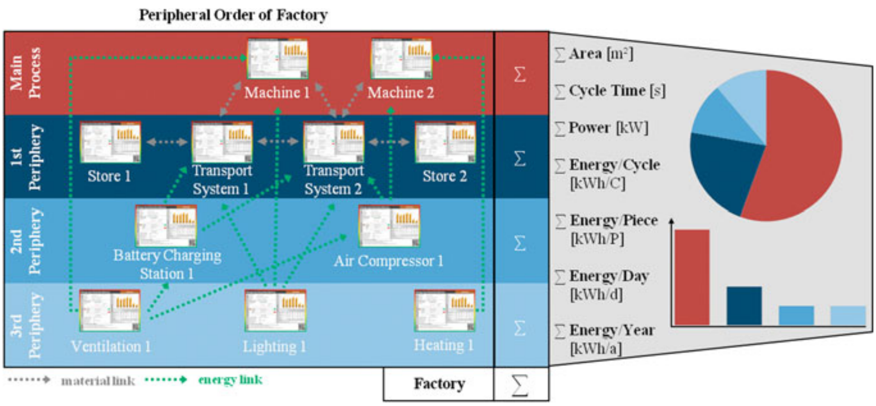


**Fig. 5** Factory system structured by peripheral order

## 6 Summary

Competitive manufacturing systems have to be energy and resource-efficient. The importance of tools and methods for energy-efficient systems and processes is underlined in this article. The major deficit—the lack of knowledge about the energetic interrelationships in the factory—is highlighted. The presented concept is one possible approach to bundle and visualize energy data, information and knowledge. With the help of "Energy Cards", the user gets different possibilities to illustrate the issue "energy" in a tangible and visible form. The basic concept, the layout and the digital prototypes are described in detail. In addition, the practical usage for process modeling and optimization is shown.

On the application side, the biggest effort is the determination of the required energy data and the deduction of energy efficiency measures. A systematic approach for analysis and evaluation of energy consumption was developed to assist in these tasks [18]. In the future, this knowledge may be supplied by the manufacturer.

On the research side, the major interest of the presented concept lies in the development of the unified structure of the Energy Cards. For this, the needed energy-relevant information in the appropriate form has to be determined for the considered use case. For strengthening the competitiveness, more information like cost or emission data can be integrated. Generally, by reducing energy, emissions and costs decrease, too. For the most practitioners, energy costs are more understandable figures than energy consumption. It isn't shown in this article because costs are very dynamic and they depend at least on political and economical influences like taxes or currency exchange rates. In terms of sustainability, the emission of carbon dioxide ($CO_2$) is also an important factor for industry. Both emissions and energy costs are related to energy, so they can be derived from the energy consumptions by equivalents. If it is necessary, key figures of emissions and costs can be easily added to the cards in this way.

Furthermore, the effectiveness for improving energy efficiency by using energy cards has to be examined. Currently, the Energy Cards are specified methodically the meet these requirements, validated by practical experiments and tested in the first industrial use cases. Further on, other applications in the field of factory modeling, energy flow simulation and Energy Management will be refined and tested in practice.

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## References

1. Müller E, Engelmann J, Löffler T, Strauch J (2009) Energieeffiziente Fabriken planen und betreiben. Springer, Berlin
2. Stephens MP, Meyers FE (2010) Manufacturing facilities design and material handling. Pearson Education International, Englewood Cliffs, NJ
3. Verein Deutscher Ingenieure e. V (2007) VDI 4602 part 1 energy management: terms and definitions, Beuth
4. International Organization for Standardization, DIN Deutsches Institut für Normung e. V (2011) DIN EN ISO 50001 energy management systems: requirements with guidance for use (ISO 50001:2011). German version EN ISO 50001:2011, Beuth
5. Hesselbach J (2012) Energie- und klimaeffiziente Produktion: Grundlagen, Leitlinien und Praxisbeispiele. Vieweg+Teubner Verlag
6. O'Driscoll E, O'Donnell GE (2013) Industrial power and energy metering: a state-of-the-art review. J Cleaner Prod 41:53–64
7. European Committee of Domestic Equipment Manufactures (CECED) (2013) The new EU energy label. http://www.newenergylabel.com. Accessed 10 Jan 2013
8. Executive Agency for Competitiveness and Innovation (EACI) (2013) Build up: energy solutions for better buildings. http://www.buildup.eu. Accessed 10 Jan 2013
9. European Commission (2013) $CO_2$ labelling of cars. http://ec.europa.eu/clima/policies/transport/vehicles/labelling/index_en.htm. Accessed 10 Jan 2013
10. Neugebauer R, Wittstock V, Paetzold J (2012) Werkzeugmaschinen energetisch vergleichen: der schwierige Weg zum Energielabel. In: Proceedings of the International Chemnitz Manufacturing Colloquium ICMC 2012, 2nd International Colloquium of the Cluster of Excellence eniPROD. Chemnitz, Germany, pp. 485–509
11. Gaussin M, Hu F, Abolghasem S, Basu S, Shankar MR, Bidanda B (2012) Assessing the environmental footprint of manufactured products: a survey of current literature. Int J Prod Econ (in press)
12. Müller E, Hopf H, Arndt R, Krones M (2012) Energiekarten schaffen mehr Transparenz. Productivity Management 17(4):36–39
13. Wolf D, Kulus D, Dreher S (2012) Simulating energy consumption in automotive industries. In: Bangsow S (ed) Use cases of discrete event simulation: appliance and research. Springer, Berlin
14. Schenk M, Wirth S, Müller E (2010) Factory planning manual: situation-driven production facility planning. Springer, Berlin
15. Kuhn A (1995) Prozessketten in der Logistik: Entwicklungstrends und Umsetzungsstrategien. Verlag Praxiswissen
16. Despeisse M, Oates MR, Ball PD (2013) Sustainable manufacturing tactics and cross-functional factory modeling. J Cleaner Prod 42:31–41
17. Erlach K, Westkämper E (2009) Energiewertstrom: Der Weg zur energieeffizienten Fabrik. Fraunhofer Verlag
18. Müller E, Hopf H, Krones M (2012) Analyzing energy consumption for factory and logistics planning processes. In: Proceedings of the APMS 2012 international conference: advances in production management systems—competitive manufacturing for innovative products and services. Rhodes Island, Greece

# Sustainability Performance Indicators for Supporting the Realization of Sustainable and Energy-Efficient Manufacturing

**Tapaninaho Mikko, Koho Mikko, Nylund Hasse, Heilala Juhani and Torvinen Seppo**

**Abstract** The importance of performance measurement and indicators in realizing energy-efficient and, in broader perspective, sustainable manufacturing has been noticed and realized by the industry and academia. Although several frameworks for sustainability performance measurement and reporting exist, those focus mainly on corporate level and hence fail to provide adequate support for factory planning and management. This paper and the related research projects are motivated by this need to provide manufacturing companies with sustainability performance indicators that better support the realization of sustainable and energy-efficient manufacturing. The proposed paper aims to set the stage and to present the initial steps for identifying or developing sustainability key performance indicators that cover the three aspects of sustainability, economic, social, and environmental, and are linked to the improvement possibilities and measures at shop-floor level. The proposed paper contributes to the conference and the workshop by discussing performance indicators for planning and management of sustainable and energy-efficient factories. The paper presents guidelines and research needs for academia, while the related research projects intend to provide the industry with useful sustainability performance indicators for factory planning and management.

## 1 Introduction

Meeting the needs of the present without compromising the ability of future generations to meet their own needs is the often presented definition of sustainable development [1]. Achieving this objective and finding the balance between the

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continuously increasing consumption and the limited resources of our planet have proven to be difficult tasks. This is demonstrated by the observation that at present, industrial systems are not sustainable in the long term due to their growing demand and use of non-renewable resources, demonstrates that [2]. Hence, more work and information on how to achieve and realize sustainability and sustainable development is needed.

This paper and related "Visualization of Sustainability Key Performance Indicators" (VS-KPI) research project build on previous sustainability and sustainable manufacturing related research projects carried out by the authors' organizations. The state of art and the state of practice in sustainability and sustainable development as well as challenges of and needs for realizing sustainability in industry were reviewed in a national research project "Competitive and sustainable production systems and networks" and in a EU-projects "SustainValue" and "Eco-Process Engineering System for Composition of Services to Optimize Product Life-Cycle". In these projects, the need for creating new sustainability criteria and indicators and means to measure sustainability performance and success was highlighted. These were seen as the key enablers toward sustainability and sustainable manufacturing [3–5]. Then, two national research projects "Framework and toolset for developing, analyzing, and controlling sustainable and competitive production networks" and "Eco-Efficient Production" focused on methods and tools for assessing sustainability or products, processes, and production systems. Although a wide variety of such tools and methods are available, a clear need for performance indicators that assist in designing, operating, and improving production systems and processes was identified.

The current research project (VS-KPI) aims to correct the identified gaps and shortcomings in sustainability performance measurement. The research project is based on observation that currently sustainability measurement and reporting is mainly carried out by large companies in annual CSR (Corporate Social Responsibility) or Sustainability reporting. Such reports provide high level, aggregated data, but the link to improvement possibilities and efforts is missing or, at best, weak. Thus, there is a disconnection between sustainability data and reports and those capable of influencing sustainability in manufacturing and product design (e.g., product and production engineers, operators, and managers at different levels of organization). To bridge this gap, sustainability key performance indicators covering the three aspects of sustainability, economic, social, and environmental, need to be identified or developed for manufacturing and product design and for different levels within an organization. In more detail, VS-KPI project seeks to:

- Identify and/or develop set of sustainability performance indicators focusing mainly on product design and manufacturing
- Group the participating companies based on their sustainability measurement practices and needs in order to propose relevant and useful sustainability key performance indicators for the company groups.

The theoretical background covers sustainable development, sustainable manufacturing, factory planning, and management. Based on these, the role of performance measurement and indicators in realizing sustainable manufacturing is clarified. Then, the available sustainability performance indicators and frameworks are reviewed, and their usefulness in planning and managing sustainable and energy-efficient factories is considered. Finally, the need for further research and development and initial steps aiming to develop sustainability performance indicators for realizing sustainable and energy-efficient manufacturing are presented.

## 2 Theoretical Background: Sustainable Manufacturing, Factory Planning and Performance Measurement

### *2.1 Sustainable Development Definitions and Approaches*

Sustainable development has been defined in many ways, but the most frequently cited definition is "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1]." The definition highlights two aspects, first the needs and consumption, and secondly our environment's and planet's ability to meet and fulfil the needs now and in the future [1].

As the above definition indicates, sustainable development is dependent on both the consumers and the producers. This can be clearly seen in the definitions of sustainable production and sustainable consumption. The Lowell Centre for Sustainable Production [6] has defined sustainable production as "the creation of goods and services using processes and systems which are non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for employees, communities, consumers and socially and creatively rewarding for all working people." Additionally, sustainable consumption is "the use of goods and services that respond to basic needs and bring a better quality of life, while minimizing the use of natural resources, toxic materials and emissions of waste and pollutants over the life cycle, so as not jeopardize the needs of future generations [7]." These definitions also demonstrate that the actions of both individuals and companies have an effect on sustainability.

Sustainable development is typically further divided into three pillars, economical, social, and environmental sustainability. These three aspects are also referred to as "the triple bottom line" or "the 3 P's": planet, people, and profit (e.g., [1, 8, 9]). In this paper and research project, two additional aspects, technological and political, are also included and so called STEEP-framework or approach for sustainability is used [10]. The aspect of economical sustainability focuses on securing economic viability in short and long range. According to Jovane et al. [11] social sustainability can be achieved as people feel that they can have a fair share of wealth, safety, and influence. Environmental sustainability,

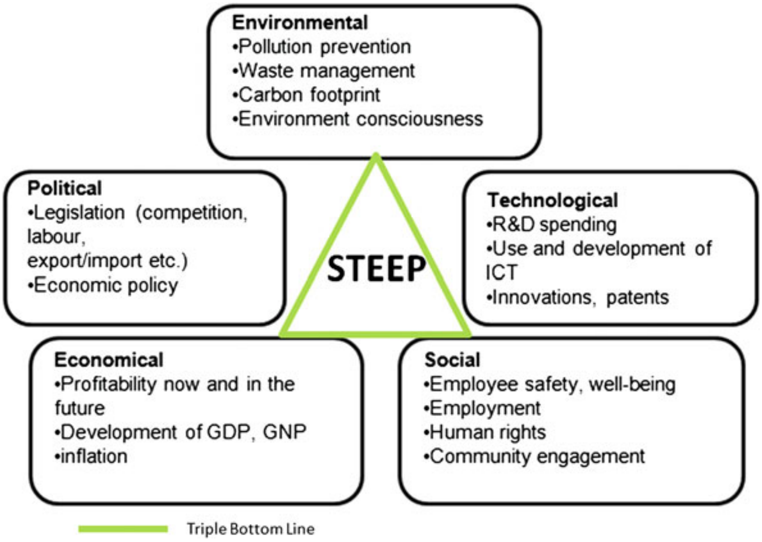


**Fig. 1** Steep framework and the triple bottom line

"seeks to improve human welfare by protecting the sources of raw material used for human needs and ensuring that the sink for human wastes are not exceeded, in order to prevent any harm caused to human beings" [12]. In addition to those three also political and technological aspects are considered. Technology can offer significant potential in sustainable development and it can be seen as an enabling and empowering aspect (e.g., [11]). Finally, the political aspect is related, for example to national or international regulations and legislation. Figure 1 summarizes the STEEP-framework and presents examples for the five aspects as well as the triple bottom line.

## 2.2 *Required Changes and Potential Advantages of Sustainable Development*

Realizing sustainable development at company level requires changes within the company and its operations, but it also offers a number of benefits and advantages. The Ad-hoc Industrial Advisory group states that pursuing and achieving the objectives of sustainable development implies changes to different areas such as technology, processes, organizational culture, and management [13]. New technologies in products and processes are needed and these can reduce the environmental effects such as material and energy consumption, and emissions generated. In terms of processes, the current trend of utilizing end-of-pipe technology for decreasing the company's environmental impact needs to be changed and the sustainability and environmental issues must be considered and improved in every phase of the production process [14]. Such improvements could focus for example on process efficiency or on increasing recycling and reuse of waste materials. Finally, from the perspective of organizational culture and management, sustainability should be regarded as a way of increasing company's competitiveness rather than as a source of additional costs. It should have a central role in company's strategy, vision and, decision making [15, 16]. One way of increasing the role and importance of sustainability and sustainable development both within a company and in relation to its stakeholders, is measuring and reporting sustainability-related initiatives, results, and performance. For this, comprehensive metrics to measure sustainability are available, for example, the Organisation for Economic Co-operation and Development (OECD) and Global Reporting Initiative (GRI) has formed a set of key metrics for companies to use. [17, 18]. Also National Institute of Standards and Technology (NIST) has examples of indicators in the Sustainable Manufacturing Indicator Repository [19].

## *2.3 Factory Planning*

Performance measurement and indicators have a key role in designing, operating, and improving factories, production systems and production processes. Several process models for planning and designing factories and production systems have been presented and all these include performance measurement as an integral part. For example, Lapinleimu et al. [20] (Fig. 2) and Vaughn et al. [21] present production system design frameworks that proceed from strategic level, i.e., corporate and business strategy, via manufacturing strategy to design decisions including layout, control systems, resources, skills, technologies, and equipment. Both frameworks and processes include performance measurement, which is relevant in piloting and implementation phase as well as in operation of the designed manufacturing system. Müller and Löfler [22] present a factory planning process that starts from analysis and project definition and includes basic and detailed engineering before implementation and usage of the factory. In this model, performance measurement is necessary in analysis phase as well as in implementation and usage phases in which the actual operation and performance of the factory is monitored and compared to the set targets.

Performance measurement and indicators are very important also in improving performance of factories, production systems, and production processes. The well-known performance improvement models PDCA and DMAIC demonstrate this. The PDCA-model consists of Plan, Do, Check, and Act phases, while the DMAIC-model includes Define, Measure, Analyze, Improve, and Control phases. In both models, performance measurement and indicators are needed in the beginning (Plan, Define and Measure phases) where the initial situation and performance as well as the improvement need and potential are evaluated and identified. Then, in the Check and Control phases, the conducted improvement efforts and changes and

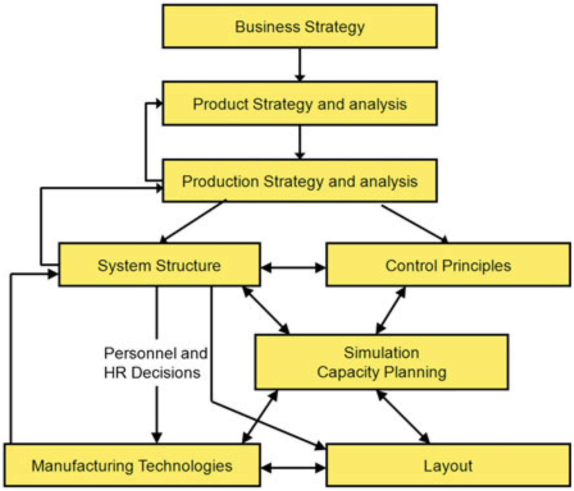


**Fig. 2** Key steps to production system design (adapted from Lapinleimu et al. [31])

the performance of the new system or process are measured and compared to the targets set at the beginning. The Check and Control phases of these models are also related to the operation and usage of production systems and processes, where constant monitoring or system and process performance and comparison to targets is necessary in order to identify need to make changes in managing and controlling the system or process. It is also important to bring both traditional productivity indicators and sustainability indicators to the decision making process. Simulation and modelling can be used to analyze the performance of the product and production system, using traditional production performance measures and also taking into account environmental sustainability-related performance measures. Integration of sustainability and environmental aspects to simulations is one of the ongoing development efforts in many research projects, e.g., Eco-Process Engineering System for Composition of Services to Optimize Product Life Cycle [23].

## *2.4 Review of Sustainability Performance Measurement and Reporting*

Individual manufacturing processes and the chain of processes they form together can be seen as an input–output system transforming the inputs to outputs. Hubka and Eder [24], in their theory of technical systems (TTS), classify the inputs and outputs into three types; material, energy, and information. In this paper, the study of environmental performance metrics is studied as an aggregated approach from machine level to corporate level.

In the category of material, material that flows thru the system and is realized as outputs is considered. Machines, tools, devices, humans, and the facilities are seen as the manufacturing resources that enable the transformation processes and therefore are not included in the category of material.

The viewpoints presented in this section are intended as the theoretical basis for structuring and developing a set of performance metrics. Behn [25] lists several important aspects of metrics which should be recognized:

- Evaluate the outcomes which are combined with the inputs and the expectations of exogenous factors
- To control the inputs which can be regulated
- Efficiency measures e.g., budgeting
- Metrics should provide almost real time data comparable with the production outputs
- Metrics should also provide easily understandable aspects of the current state of performance
- Metrics should provide the personnel significant and periodic achievement targets which give the personnel sense of collective and individual accomplishment
- Metrics should be a tool for learning as disaggregated data reveal deviances from the expected
- Metrics helps the company to improve their performance which connects changes in operations to changes in outputs and outcomes.

Additionally, performance metrics should be comparative rather than absolute assessments and it should be possible to quantify improvements [26]. Also, the ISO 14045:2012 standard takes a stance in choosing environmental indicators. ISO 14045:2012 states that indicators should present a quantitative statement. Furthermore, the standard describes the requirements for choosing indicators as follows, the increase in the production system value should represent an improved environment and decrease in environmental impact should represent improvements in production system [27].

Currently, a number of sources provide a large set of metrics. In the following is listed some of the generally accepted set of metrics. The most widely referred set of metrics are the Global Reporting Initiative (GRI G3 guidelines (80 indicators), OECD Sustainable Manufacturing Indicators (18 indicators) and EUROSTAT Sustainable Consumption and Production Indicators (15 indicators) [17, 18, 28].

Companies in general struggle to find standardized metrics and the amount of different metrics generally distract the companies from the ones which are essential for the company to measure. A review on sustainable metrics provided 41 different sets of metrics in this domain [29]. Additionally in terms of sustainable development, companies need metrics which takes a stance in terms of all the aspects of sustainable development. Typical examples of environmental performance indicators, related to the focus companies of this paper i.e., mechanical engineering industry, based on the GRI G3 guidelines, are [17]:

- Materials used by weight or volume
- Percentage of materials used that are recycled input materials

- Direct and indirect energy consumption by primary source
- Total weight of waste by type and disposal method
- Total direct and indirect greenhouse gas emissions by weight
- Significant environmental impacts of transporting products and other goods and materials used for the organization's operations.

## 3 Aggregated Sustainable Key Performance Indicator Design

Different levels of organization are responsible for different areas of manufacturing activities and therefore are interested in different performance measures. Figure 3 presents a basic view of the strategic, tactical, and operational levels of a manufacturing company.

The operational level consists of the process and production domains. The main responsibility of the people working on the shop-floor is to keep the manufacturing processes running and to create right quality at right time. Hence, metrics are needed to control the manufacturing processes to keep the behavior and characteristics of the activities within accepted limits.

The tactical level can be roughly divided into production planning and production system development. The main difference is the temporal focus. The production planning focuses on controlling and evaluating the daily manufacturing activities on the shop-floor. Production system development focuses more on how the system will manage with the changing requirements and constraints in the future. At the tactical level, the interest is on the metrics concerning on manufacturing performance and the timely flow on material and information.

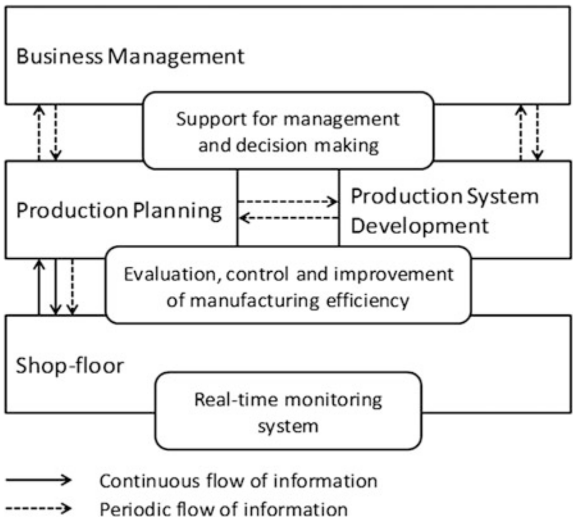


**Fig. 3** Information transfer between strategic, tactical, and operational levels

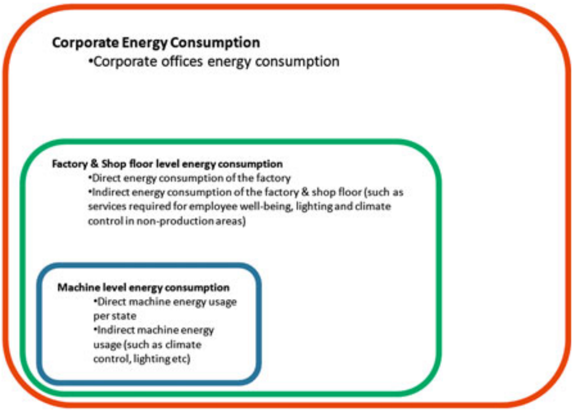


**Fig. 4** Aggregated sustainable key performance indicator design

Business management focuses is on keeping up the competence of a company on a desired level. This requires key performance indicators to ensure that the entire company follows and commits to the competitive and sustainable goals and objectives of the business strategy.

Therefore, this study suggests dividing the selected metrics to different levels throughout the company to identify the accurate measurement levels of each layer of the aggregated company metric. The presented aggregation framework in Fig. 4 identifies energy consumption as an example metric for closer inspection. The current reporting guidelines presented by Global Reporting Initiative G3 suggest companies to report the annual energy consumption. This metric itself gives very little information on actual shop-floor or machine level improvements. Therefore, the company should measure the actual consumption where and when it happens. The aggregation framework divides both shop-floor and machine level to direct and indirect energy consumptions according to the OECD metrics. It is important to divide the direct and indirect energy used to manufacture the component as part of the energy used is not required to manufacture the component rather than increasing comfort of work for the workers.

In the academic research environment we are able to measure the energy consumption of a single turning machine in real time. This paper does not itself include a case study but an example of the setup to measure machine level energy consumption is presented. The academic research environment consists of several manufacturing resources and work pieces. Each of the entities has their corresponding computer models and simulation environments. The information and knowledge of the environment is stored in local databases and in a common knowledge base. With this setup we are able to extract real time information of the setup for the case studies conducted in our laboratory. An example of a setup which a case study of energy consumption monitoring was conducted with [30],

- Gildemeister CTX alpha 500 turning machine
- Carlo Gavazzi EM21 energy meter
- Siemens 840D SL controller.

## 4 Need and Plans for Further Research

Future research in this domain focuses on visualizing the metrics to each level of the company. Our research group's intention is to make these metrics easily accessible for all personnel working in the company to gain better management of the production system in terms of its sustainability. Exact measurements in each of these levels can provide the company an in depth view of the state of sustainability within the company at any given time or interval. Thus the companies gain a better understanding where they should focus on improving efficiency in the operations as well as managing the indirect effects of their operations.

Next step in this project is to develop means to visualize each of the metrics in every stage of the presented metrics framework. Visualization is an important aspect for companies to adapt these metrics. Through the visualization the company personnel should be able to tell with more ease whether the objectives for increasing the sustainability of the company are being achieved. Additionally visualization of the metrics should yield better understanding of possibilities of improvement within the factory or process.

Finally, this goal of this research project is to conduct case studies within the Finnish manufacturing industry and support companies to adapt the use of visualized sustainability key performance indicators and enhance sustainability in their operations. The case studies are expected to take place during the last quarter of 2013 and the first quarter of 2014.

## 5 Summary

This study discussed sustainable development from the point of view of production systems. The study reviewed the general aspects of sustainable development and sustainable production, factory planning, and sustainable performance measures. This study discussed the shortcomings of the current dominant sustainable performance guidelines such as GRI and suggested an alternative approach to conduct the measurements within a company. The study suggested an aggregated framework for metrics to be adapted in different entities within the company. The entities suggested were the machine level, factory and shop-floor level and corporate level. Additionally this study suggested in dividing the entities to direct and indirect measures according to the OECD guidelines. The results of this study are not considered generic for all industries. Hence, the results cannot be directly used outside manufacturing industry. Further case studies will provide the feasibility of this approach.

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## References

1. WCED (1987) Report of the world commission on environment and development: our common future. Oxford University Press, Oxford
2. Krajnc D, Glavic P (2003) Indicators of sustainable production. Clean Technol Environ Policy 5:279–288
3. VTT (2011) Sustainability gaps and stakeholder requirements. SustainValue project deliverable. http://www.sustainvalue.eu/publications/D1_1_final_Rev1_0_web.pdf
4. Tapaninaho M, Koho M, Torvinen S (2011) Current state and future expectations of sustainable development and sustainable production in the finnish manufacturing industry. In: Seliger G (ed) Proceedings of the 9th global conference on sustainable manufacturing in Saint Petersburg, Russia, 28–30 Sept 2011. Global conference on sustainable manufacturing Berlin, Technische Universität Berlin, pp 302–307
5. Koho M, Tapaninaho M; Torvinen S (2011) Towards sustainable development and sustainable production in finnish manufacturing industry In: ElMaraghy HA (ed) Enabling manufacturing competitiveness and economic sustainability, proceedings of the 4th international conference on changeable, Agile, reconfigurable and virtual production CARV2011, Montreal, Canada, 2–5 Oct 2011. International conference on changeable, Agile, reconfigurable and virtual production CARV Berlin, Springer, pp 422–427
6. Veleva V, Ellenbecker M (2001) Indicators of sustainable production: framework and methodology. J Cleaner Prod 9(6):519–549
7. IISD Reporting Services. Oslo roundtable on sustainable production and consumption. http://www.iisd.ca/consume/oslo00.html
8. Martins AA, Mata TM, Costa CAV, Sikdar SK (2007) Framework for Sustainability Metrics. Ind Eng Chem Res 46:2962–2973
9. Elkington J (2007) Cannibals with forks: the triple bottom line of 21st century business. In: American management association, creating a sustainable future: a global study of current trends and possibilities 2007–2017
10. Schwartz P (1991, 1996) The art of the long view planning for the future in an uncertain world, first crown business edition, crown business, p 272. ISBN 978-0-385-26732-8
11. Jovane F, Westkämper E, Williams D (2008) The manufacture road: towards competitive and sustainable high-adding-value manufacturing. Springer, Berlin
12. Goodland R (1995) The concept of environmental sustainability. Annu Rev Ecol Syst 26:1–24
13. Ad-hoc Industrial Advisory Group (2010) Factories of the future PPP, strategic multi-annual roadmap. European Union, Belgium
14. Ilmola L, Linnanen L, Markkanen E (1997) Environmental know-how. Challenges of sustainability to business executives. Otaniemi Consulting Group Oy, Helsinki
15. Porter ME, Linde C van der (1995) Green and competitive: ending the stalemate. Harvard Business Review. Sept–Oct 1995, pp 120–134
16. American Management Association (2007) Creating a sustainable future: a global study of current trends and possibilities 2007–2017
17. Organisation for Economic Co-operation and Development (2001) Environmental indicators towards sustainable development. http://www.oecd.org/dataoecd/37/1/33703867.pdf
18. Global Reporting Initiative (2000–2011) Sustainability reporting guidelines version 3.1. http://www.globalreporting.org/ReportingFramework/G31Guidelines/
19. National Institute of Standards and Technology, Sustainable Manufacturing Indicator Repository. http://www.mel.nist.gov/msid/SMIR/
20. Lapinleimu I, Kauppinen V, Torvinen S (1997) Kone- ja metalliteollisuuden tuotantojärjestelmät (in Finnish). Tammer-paino, Porvoo, Finland
21. Vaughn A, Fernandes P, Shields JT (2002) Manufacturing system design framework. Massachusetts Institute of Technology, Massachusetts

22. Müller E, Löffler T (2010) Energy efficiency at manufacturing plants: a planning approach. In: 43rd CIRP conference on manufacturing systems
23. Hubka V, Eder E (1988) Theory of technical systems. Springer, Berlin
24. EPES Project (2012) State of the art analysis. EPES project deliverable. http://www.epes-project.eu/
25. Behn R (2003) Why measure performance? different purposes require different measures. Publ Admin Rev 63(5):586–606
26. Alting L (2010) The challenge and relevance of quantifying sustainability, keynote presentation. In: Proceedings of 17th CIRP international conference on life cycle engineering, LCE 2010. Hefei, China
27. ISO 14045:2012 (2012) Environmental management: eco-efficiency assessment of product systems—principles, requirements and guidelines, 1st edn. 15 May 2012, p 38
28. Eurostat Sustainable Production and Consumption http://epp.eurostat.ec.europa.eu/portal/page/portal/sdi/indicators/theme2
29. Singh RK, Murty HR, Gupta SK, Dikshit AK (2009) An overview of sustainability assessment methodologies. Ecol Ind 9:189–212
30. Lanz M, Mani M, Leong S, Lyons K, Ranta A, Ikkala K, Bengtsson N (2010) Impact of energy measurements in machining operations. In: Proceeding of the ASME 2010 international design engineering technical conferences and computers and information in engineering conference, IDETC/CIE 2010. Montreal, Quebec, Canada, p 7
31. Nylund H, Tapaninaho M, Kirman B, Koho M, Torvinen S (2012) Supporting manufacturing companies on utilizing environmental performance metrics. The 10th global conference on sustainable manufacturing, GCSM 2012. Istanbul, Turkey, global conference on sustainable manufacturing, 31 Oct–2 Nov 2012, pp 582–587

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