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(Eds.)

Advances in Production Management Systems

The Path to Intelligent, Collaborative and Sustainable Manufacturing

IFIP WG 5.7 International Conference, APMS 2017
Hamburg, Germany, September 3–7, 2017
Proceedings, Part I

1 Part I

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Preface

We live in exciting times. The technological revolution in information and communication technology has been going on for several decades already and there seemingly is no near end in sight. The possibilities for industrial companies are enormous, but so are the challenges.

The globalized economy has done its fair share in reducing extreme poverty levels. The United Nations report that the target of reducing extreme poverty by half was met five years ahead of the 2015 deadline: more than 1 billion people have been lifted out of extreme poverty since 1990.

The environmental burden humankind puts onto our planet is becoming bigger and bigger, threatening eco-systems and our own well-being in the future. Industrial companies are affecting, and affected by, all three environments. In fact they contribute significantly both to poverty relief by employing hundreds of millions of people but also to the ecological challenges we are confronted with by exploiting natural reserves and by their emissions to the environment.

Thus, the question of how to find the path to intelligent, collaborative and sustainable manufacturing is of eminent importance.

We invited experts, academics, researchers, and industrial practitioners from around the world to the Advances in Production Management Systems Conference 2017 in Hamburg, Germany, to contribute with ideas, concepts and theories. A large international panel of experts reviewed all the papers and selected the best to be presented and to be included in these conference proceedings.

In this collection of papers, the authors share their perspectives as well as their concepts and solutions for the challenges industrial companies are confronted with and the great opportunities new technologies, collaboration and the developments described above offer.

The chapters are organized in two parts

- Smart Manufacturing (Volume 1)
- Collaborative and Sustainable Manufacturing (Volume 2)

We hope that our readers will discover valuable new ideas and insights.

The conference was supported by the International Federation of Information Processing and was organized by the IFIP Working Group 5.7 on Advances in Production Management Systems.

We would like to thank all contributors for their research and for their willingness to share ideas and results. We are also indebted to the members of the IFIP Working Group 5.7 for their support in the review of the papers.

September 2017

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IFIP WG 5.7 Advances in Production Management Systems

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Strategizing for Production Innovation

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Abstract. Manufacturing firms are constantly evolving to accommodate new customer requirements as well as emerging technologies, materials, processes and equipment. As a consequence, a broad range of production innovation opportunities arise for manufacturing firms to produce their products in smarter, more flexible, agile and sustainable ways. This paper proposes a strategic planning framework for "production innovation" and discusses its implications for the evolution of companies-specific production systems and competitive advantages.

Keywords: Production innovation · Process innovation · Production capabilities · Manufacturing · Competence · Readiness levels · Maturity

1 Introduction

Production Innovation [1] is a concept describing on-going re-engineering processes and a core-organisational culture in itself. It aims to evolve product and production engineering from prevalent trends of 'continuous improvement' towards 'continuous innovation'. This, in order to retain and emphasize the competitive advantage of any manufacturing firm by adopting and developing the next generation manufacturing and processing technologies as well as working methods ahead of competition. *Production Innovation* involves constant monitoring and evaluation of the advances in research and technology development in the areas of production management systems and related technologies and working methods. This also includes the assessment of such technologies and working methods readiness for adoption at the shop-floor. Moreover, *production innovation* considers the upgrade and/or renewal of the 4 M (man, material, machine and method) in order to strengthen the productivity and resource efficiency of a production system.

This paper proposes a strategic planning framework for "production innovation" based on the identification, development, integration and adoption of the appropriate production, organisational and financial capabilities, at their proper readiness level, in a manufacturing firm's shop-floor. The goal is to not just enable a new manufacturing competence or to bring an existing one to its next level within a manufacturing firm, but also to support the maturing (mastering) of such new or improved manufacturing competence.

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This initial research work was developed based on a literature review and interviews with academic and industrial experts in advanced production management systems.

2 Basic Concepts

An underlying concept, *Process Innovation* [2] refers to implementation of a new or significantly improved production or delivery method (including significant changes in techniques, equipment and/or software) in order to acquire a new or increase a current production or service capability in a manufacturing or logistical system, which must lead to added value for the firm (company value) and its value chain (value chain value).

Within the definition of process innovation, *company value* is defined as the benefits perceived from a process innovation by the different departments of a manufacturing firm (inner-added value). *Value chain value* is defined as the benefits perceived from that same process innovation by the members of a manufacturing firm's value chain due to its increase of company value (inter-added value). This could be in terms of e.g. saving time, reducing risks, reducing costs, improving quality, increasing variety, reducing efforts or simplifying, organising, integrating and connecting things, etc. In the end, it is about creating positive environmental, economic and social effects in the operating model of a manufacturing and/or logistical system at intra- and inter-organisational level.

Furthermore, a *production capability* (also called 'manufacturing capability') must be understood as a unique combination of tools, materials, methods and people engaged in producing a measurable output within the framework of technical, physical and financial limitations of a manufacturing firm. Since 'production capabilities' require people, 'organisational capabilities' for innovation in a manufacturing firm must be also considered in order to realize a 'production innovation'. *Organisational (workforce) capabilities* refer to socially complex routines determining the effectiveness | efficiency with which manufacturing firms (*cf.* their workforce) can transform learning and knowledge into actionable operational working methods. Moreover, the development of production and organisational capabilities in a manufacturing firm relies on its *financial capabilities.* This encompasses knowledge, attitudes, skills and behaviours of their stakeholders with regards to the required investment, and available financial instruments to invest in production equipment (technology) acquisition and education/training programs (workforce).

In this sense, *production innovation* may be defined as the process of developing or increasing a production (manufacturing) capability together with the manufacturing firm's organisational (workforce) capabilities by implementing new production equipment and deploying a new working method for it in a production environment (see Fig. 1). Intended effects are company and value chain value.

It is argued that a *production innovation* could be seen as a 'socio-technical endeavour' (e.g. an engineering project). From a technical perspective, production

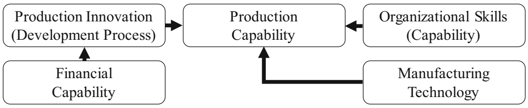

Fig. 1. Elements influencing production capability and its development

capabilities for innovation are required to develop new or improve current production equipment, and from a social perspective, organisational capabilities for innovation, such as the absorptive capability of a manufacturing firm, are needed to learn and master the use of such new production equipment and their related working method(s).

3 Strategizing for Production Innovation

To strategically work on 'production innovation' initiatives, it means to develop new or improve existing *manufacturing competences* in a firm based on the convergence of appropriate readiness levels of manufacturing technology, workforce skills and knowledge, and financial resources to invest in a production innovation project.

A (generic) production innovation project aims to acquire new or upgrade current production equipment, and to train the workforce in its use (working method), for achieving a new or defending an existing competitive advantage.

In a production innovation process (i.e. a project), two main challenges can be identified for a manufacturing firm: (a) how to achieve alignment between Manufacturing, Organisational and Financial capabilities (MOF capabilities) in a specific moment in time, i.e. a workforce with the willingness to learn and use new or upgraded production equipment acquired to create value, and (b) once enablers (equipment and workforce) for new manufacturing competence have been acquired, how are these perfected to increase their potential for creating value.

In this paper, the use of *readiness levels* is proposed as a way to assess the: (a) Readiness of innovative manufacturing technologies and/or working methods to be integrated and brought into a (real) production environment as an added value, (b) Readiness of the workforce to learn and put into systematic practice new skills and knowledge, and (c) Readiness level of the manufacturing firm stakeholders to invest in the production innovation project. The use of readiness levels aim to achieve a reliable decision-making support for stakeholders in regards to the potential to successfully integrate the needed production, organisational and financial capabilities towards 'production innovation', and consequently new manufacturing competence (see Tables 1 and 2) and later on manufacturing competence levels (see Table 3).

Furthermore, for supporting the integration process of MOF capabilities, Sauser et al. (2010) [4] have proposed an Integration Readiness Level (IRL) scale (see Table 2).

Table 1. MOF capabilities readiness levels (RL) (Adapted from [3])

RL	Manufacturing technology [3]	Organisational (Workforce)	Financial investment
1	Manufacturing principle described	Workforce competence described	Investment on production innovation project estimated
2	Concept of machinery equipment in series production described Interaction with material analysed	Skills and knowledge related to the operator competence described Interaction with equipment and software analysed.	Investment on production innovation project described (project roadmap) Production innovation project ROI analysed
3	Manufacturing principle tested (in laboratory) Impact on product design described	Working method tested (in laboratory) Impact on workstation described	Investment on production innovation project approved Budget for production innovation project detailed
4	Technology capability proven Material proven	Working method capability proven Skills and knowledge proven	Suppliers for manufacturing technology and workforce education and training identified
5	Concept of plant and production line designed (including capacity planning)	Working method designed Education and training needs identified	Production innovation project schedule defined
	Suppliers identified	Suppliers identified	Suppliers selected
6	Series capability proven	Working method capability proven	Purchases made of equipment Contracts signed for training
7	Suppliers and materials certified	Workforce certified	Full payments due
8	Low rate production demonstrated (pilot run)	Low scale working method demonstrated (pilot run)	Production innovation project ROI demonstrated
9	Start of (series) production (job nr. 1)	Start of working method usage in the shop-floor	Production innovation project ROI demonstrated
10	Overall equipment effectiveness (OEE) at comprehensive level	Overall labour (working method) effectiveness (OLE) at comprehensive level	Overall investment effectiveness (OIE) at comprehensive level

Moreover, once new manufacturing competence has been instated at the firm, it will require ‘ramp-up’ and therefore the mastering of it has a learning curve. Thus, the use of *maturity levels* is proposed (see Table 3) to rank performance of the manufacturing firm in deploying new manufacturing competence or manufacturing competence level.

Table 2. MOF capabilities integration readiness level (Adapted from [4])

IRL	MOF capabilities integration scale
1	An interface (*cf.* a production innovation project) between MOF capabilities has been identified with sufficient detail to allow characterisation of the (cost-benefit) relationship
2	There is some level of specificity to characterise the interaction (i.e. ability to influence) between capabilities through their interface
3	There is compatibility between MOF capabilities to orderly and efficiently integrate and interact in a production innovation project
4	There is sufficient detail in the quality and assurance of the integration between MOF capabilities
5	There is sufficient control between MOF capabilities necessary to establish, manage and terminate their integration in a production innovation project
6	The MOF capabilities integration can accept translate and structure information for its intended application (i.e. production innovation's project definition detailed)
7	The MOF capabilities integration has been verified and validated, and an acquisition/insertion decision can be made (i.e. production innovation project acceptance)
8	Actual MOF capabilities integration completed and production innovation project objectives qualified through test and demonstration in the production system environment
9	MOF capabilities integration is production innovation project objectives achieved through successful new production system operations

Table 3. Production (Manufacturing) competence maturity levels

Maturity levels	Product innovation ramp-up stages	Production innovation focus per stage
1	Initial	Manufacturing competence implemented
2	Repeatable	Manufacturing competence effectiveness at comprehensive level
3	Defined	Manufacturing competence effectiveness achieved according to standards
4	Managed	Manufacturing competence managed in accordance with firm's metrics
5	Optimizing	Manufacturing competence optimized and improved

Figure 2 introduces the *production innovation cube* as a strategic planning framework for the identification and integration of the proper MOF capabilities (at their appropriate readiness level), to enable a new or develop an existing manufacturing competence, as well as for the maturity (mastering) of such new or improved manufacturing competence. Also, it depicts the development of *manufacturing competence* as the integration of production (manufacturing) technology capability, organisational (workforce) - learning - capability and financial - investment - capability to later mature (master) such new acquired competence.

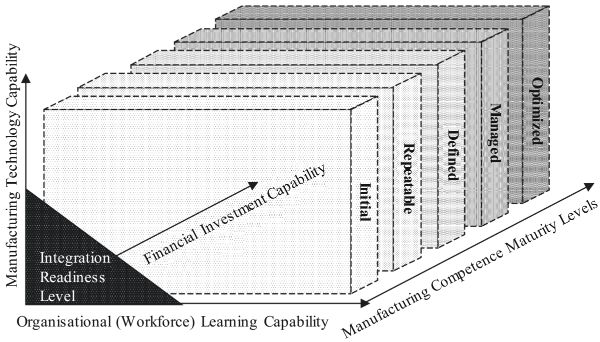

Fig. 2. Production innovation cube - a strategic planning framework

4 A Production Innovation Guide

The *production innovation guide* proposed in this paper is composed by three main phases, named: Strategy Analysis (step 1 to 5), Strategy Formulation (step 6 to 7) and Strategy Implementation (step 8 to 9). Each phase is divided in several steps to be followed by the production manager or production engineer in order to design and justify a production innovation project.

SA/Step 1. Define what drives the necessity for a production innovation project, e.g.:

- *Endogenous drivers* – A request from other organisational department:
  - Management department request for a 'production innovation' to develop a (new) competitive advantage (e.g. cyber-physical production system).
  - Human Resources department request for updating/renewing the workforce skills and knowledge in the use of new production equipment (e.g. metal 3D-printing) or working method (e.g. digital lean manufacturing).
  - Technology Development department request for updating and/or renewing production equipment (including software) to develop new manufacturing capabilities (e.g. smart manufacturing system).
  - Procurement department request for adopting a new production standard in order to facilitate interoperability of production systems and the integration of these production systems across their value chain (e.g. computer integrated manufacturing/integrated value chain).
  - Operations department request for obtaining a new production certification in order to obtain an independent third-party validation and recognition that certifies that its (cyber-physical) production system has passed certain performance, quality and (cyber-)security tests, and meets the qualification criteria stipulated in contracts, regulations, specifications or standards (e.g. Six Sigma, ISO standards).
  - Sales department request for production cost reduction to maintain a competitive product price in the market without scarifying quality (e.g. less waste (*Muda*) - lean manufacturing).

- Marketing department request for production flexibility to offer mass-customization with high quality, low cost and short-delivery time (e.g. flexible manufacturing).
- Logistics and Distribution department request for production speed to deliver product orders on time and in the required volume, especially in high-demand seasons (e.g. agile manufacturing).
- Customer Service department request for enabling servitization opportunities (e.g. product-service system, internet of things).

- *Exogenous drivers* – Enforced by competition or legislation:
  - Competition enforcing new competitive price, quality and/or delivery time.
  - Environmental regulations requesting higher levels of eco-efficiency (e.g. resources consumption and emissions).

SA/Step 2. Describe current production (manufacturing) organisational (workforce) and financial investment capabilities (*AS-IS* model):

- A *production (manufacturing) capability* can be described in terms of the ability to perform a manufacturing process within certain production performance parameters, expressed as a manufacturing process capability index (C_{pk} or C_{pm}) and/or performance index (P_{pk} or P_{pm}), in order to meet certain output specifications (e.g. customer requirements, specifications, or engineering tolerances).
- An *organisational (workforce) capability* can be described in terms of the skills and knowledge possessed by an operator or team of operators to perform a task or series of tasks within certain human performance parameters, expressed as his/her/their physical, sensorial and cognitive abilities - based on classifiers, in order to meet certain output specifications (e.g. rate of errors, speed of work).
- A *financial investment capability* can be described in terms of the willingness to invest and the financial instruments (resources) available in a manufacturing firm to invest in a project, expressed as financial investment ratios, in order to finance such (production innovation) project (e.g. ROI, IRR and MARR).

SA/Step 3. Describe necessary new production (manufacturing) and organisational (workforce) capabilities to support the production innovation's project objectives (*TO-BE* model):

- *New expected production (manufacturing) capability* expressed as improved customer experience and responsiveness (on-time delivery, manufacturing cycle time, time to make changeovers), improved quality (yield, customer rejects), improving efficiency (throughput, capacity utilisation, equipment effectiveness, schedule or production attainment), reduced inventory (WIP inventory/turns), ensured compliance (reportable health, safety and environmental incidents, number of non-compliance events/year), reduced maintenance (% planned vs. emergency maintenance work orders, operation downtime), increased flexibility (rate of new product introduction, engineering change order cycle time), reduced costs and increased productivity (total manufacturing cost per unit excl. materials, manufacturing cost as a % of revenue, net operating profit, productivity in revenue per employee, average unit contribution margin, return on assets, energy cost per unit, cash cycle time, EBITBA, customer fill rate/on-time delivery/perfect order %) [5].

- *New expected organisational (workforce) capability* expressed as operators' improved physical abilities (ability to lift, walk, manipulate and assemble) together with its non-functional properties (speed, strength, precision and dexterity), improved sensorial abilities (vision, smell, sound, touch, vibration), and improved cognitive abilities (perception, memory, reasoning, decision, motor response).
- *Expected financial investment capability* expressed as an equal to or greater than X hurdle rate (cost of capital, expected returns).

SA/Step 4. Identify the gaps between the production system *AS-IS* and *TO-BE* models for the successes of the production innovation project:

- MOF capabilities should be compared using clear assessment parameters between the manufacturing firm's *AS-IS* and *TO-BE* models.
- Manufacturing firm targeted new MOF capabilities can also be benchmarked in order to validate that the production innovation project will actually deliver a competitive advantage in the market.

SA/Step 5. Start the scouting of new production technologies (e.g. production equipment and working methods) evaluating their readiness level, and assessing their integration to the production environment (shop-floor):

- For this purpose, morphological matrixes can be used as a method and tool to select the best solutions available to realise the necessary MOF capabilities for the production innovation project (see Table 4).

SF/Step 6. Define the production equipment to be acquired (based on a make/buy study) and the training plan for the workforce as well as its financing schema (as a project):

- Activities to be conducted include assessing production feasibility, estimating manufacturing costs, defining manufacturing processes and their tooling, and beginning the training of the workforce.

SF/Step 7. Conduct the installation and set-up of the new production equipment as well as start training the workforce:

- Activities to be conducted include evaluating early production output and beginning operation of the new production system.

SI/Step 8. Ramp-up the new production equipment (the production system):

- Activities to be conducted include the gradual and continuous transition from the production ramp-up to ongoing production, working out any remaining human and/or machine problem in the production process.

Table 4. MOF capabilities needed vs. capabilities enablers - morphological matrixes

Manufacturing capability vs. Manufacturing technology morphological matrix			
Production capability needed	Manufacturing technology 1	Manufacturing technology 2	Manufacturing technology #
Capability 1	**MTRL 9**	MTRL 4	MTRL 6
Capability 2	MTRL 5	**MTRL 8**	MTRL 7
Capability #	MTRL 3	MTRL 1	**MTRL 10**
Organisational capability vs. Working method morphological matrix			
Organisational capability needed	Working method 1	Working method 2	Working method #
Capability 1	WMRL 5	WMRL 4	**WMRL 9**
Capability 2	WMRL 4	**WMRL 8**	WMRL 6
Capability #	**WMRL 10**	WMRL 3	WMRL 4
Financial Investment capability vs. Financial plan morphological matrix			
Financial Investment capability needed	Financial plan 1	Financial plan 2	Financial plan #
Capability 1	FIRL 4	**FIRL 10**	FIRL 7
Capability 2	**FIRL 9**	FIRL 7	FIRL 3
Capability #	FIRL 6	FIRL 5	**FIRL 9**

[a]Production Capability refers to the ability to produce a manufactured good.
[b]Manufacturing Technology refers to the processes and tools (e.g. machinery) to enable the production of manufactured goods.

SI/Step 9. Mature production operations until achieving regular production capability and capacity aimed.

- Activities to be conducted include the gradual and continuous improvement of the production performance and process(es) standardisation in order to increase efficiency.

5 Conclusions

In this paper, it is argued that *production innovation* is a 'socio-technical endeavour' that requires alignment of readiness levels of manufacturing technology, organisational (workforce) learning and financial investment capabilities to enable new manufacturing competence in a firm. Moreover, 'enabling' new manufacturing competences does not imply an instant competitive advantage for the firm, since newly acquired competence will need to mature and to be mastered, in order to transform it into 'true' competitive advantage. The presented research work has contributed with a proposal for strategizing for production innovation, based on a framework of readiness and maturity levels. This proposal include a step-by-step guide for production managers and/or engineers to implement a strategy for production innovation.

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A Maturity Model for Assessing the Digital Readiness of Manufacturing Companies

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Abstract. "*The most profound technologies are those that disappear… They weave themselves into the fabric of everyday life until they are indistinguishable from it*" wrote computer scientist and visionary Mark Weiser nearly 25 years ago in his essay "The Computer for the 21st Century." It turns out he was right: in the age of "Industry 4.0", digital technologies are the core driver for the manufacturing transformation. In fact, the introduction of such technologies allows companies to find solutions capable to turn increasing complexity into opportunities for ensuring sustainable competitiveness and profitable growth. Nonetheless, the effective implementation in manufacturing still depends on the state of practice: it may slow down, or even worst, may prevent from implementation. Indeed, we assume that a minimum level of capabilities is required before implementing the digital technologies in a company. Based on this concern, our research question is "are manufacturing companies ready to go digital?". This paper wants to illustrate a "tool" to answer this question by building a maturity assessment method to measure the digital readiness of manufacturing firms. Based on the inspiring principles of the CMMI (Capability Maturity Model Integration) framework, we propose a model to set the ground for the investigation of company digital maturity. Different dimensions are used to assess 5 areas in which manufacturing key processes can be grouped: (1) design and engineering, (2) production management, (3) quality management, (4) maintenance management and (5) logistics management. Thus, the maturity model provides a normative description of practices in each area and dimension, building a ranked order of practices (i.e. from low to high maturity). A scoring method for maturity assessment is subsequently defined, in order to identify the criticalities in implementing the digital transformation and to subsequently drive the improvement of the whole system. The method should be useful both to manufacturing companies and researchers interested in understanding the digital readiness level in the state of practice.

Keywords: Digital readiness · Maturity model · Digital transformation · Industry 4.0

1 Research Context and Objective

Industrial companies are digitizing essential functions within their internal operations processes, as well as with their partners along the value chain. In addition, they

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are enhancing their product portfolio with digital functionalities and introducing innovative, data-based services [1]. This is a journey they are taking towards a complete value chain transformation. At the end, successful companies will become true digital enterprises, with physical products at the core, augmented by digital interfaces and innovative services [1–3]. In a futuristic and disruptive vision, these digital enterprises will work together with customers and suppliers in industrial digital ecosystems [1]. To this aim, one of the main challenge industrial companies are now facing is to define their transformation roadmap. This is a strategic process that requires the engagement of different stakeholders (i.e. C-level managers, consultancy partners, etc.) in order to consistently obtain repeatable results. In order to build a valid roadmap-definition process, in literature it is possible to find many approaches. Among them, [4] identifies five main steps for addressing the strategic planning process: status quo analysis, strategic options generation, options assessment and evaluation, articulation of a strategic roadmap, and development of strategy. More specifically for digitalization, as stated in [5], manufacturing companies should undertake a comprehensive digital maturity assessment in order to have a transparent view on their current level of digital readiness. Indeed, a deep understanding of the current status of digitalization is a first step for a successful transformation. Once organizations have a clear perspective on their digital maturity, they should explore the corporate environment for opportunities triggered by digital technologies. Based on the identified opportunities, companies should develop a digital transformation roadmap, which has to be shared and accepted by all senior executives. Only at this time, companies would start investing to proceed in its digital transformation.

In order to support companies start defining their digitalization transformation roadmap, a model to analyze their status quo is needed. To this aim, a maturity assessment of digital readiness in manufacturing companies based on the inspiring principles of the CMMI (Capability Maturity Model Integration) framework is proposed. In fact, three application-specific purposes can be identified in literature [6–9]:

1. *Descriptive purpose*: maturity models with this purpose, want to assess the as-is situation of the organization/process;
2. *Prescriptive purpose*: a prescriptive model focuses on the domain relationships to performance and indicates how to approach maturity improvement in order to positively affect business value;
3. *Comparative purpose*: a comparative model enables benchmarking across companies; in particular, a model of this nature would be able to compare similar practices across organizations in order to benchmark maturity within different industries.

Even though these three types of maturity models can be seen as distinct, they are the evolutionary phases of a model's lifecycle. As a matter of fact, a model is descriptive in its first phase, so that a deeper understanding of the current domain situation is achieved. A model can then be evolved into being prescriptive as it is only through a sound understanding of the current situation that substantial and repeatable improvements can be made. Finally, a model, with comparative purposes, must be applied in a wide range of organizations in order to attain sufficient data to enable valid comparison

[6]. In this regard, some authors [10–14] aim at using their created maturity models within frameworks, which allow the companies to have an integrative plan that assures the alignment of their processes with the desired maturity level. In particular, companies should use these maturity models to assess their maturity levels and to benchmark them with the ones of their competitors. In this way, it will be possible for them, firstly, to identify what desired level they have to reach and, secondly, to select some items, which have to be improved. In this way, a roadmap can be defined.

Some on-line tools exist, allowing companies to self-assess their readiness for the digital transformation. Nevertheless, even if these tools allow companies to assess maturity indexes indicating their level of digitalization (i.e. models are driven by descriptive purpose), they do not provide them a structured "guide" on how to encounter the digital transformation process basing on their current situation (i.e. according to a prescriptive purpose). After having performed some research, it is possible to state that, to the best of the knowledge reached, either on-line or in literature, a model able to "guide" manufacturing companies towards the digitalization has not been found.

2 Building a Maturity Model

As far as the methodological view of developing maturity models is concerned, most of the maturity models published lacked in a sound theoretical basis and methodology. Indeed, there is a little documentation on how to develop a maturity model that is theoretically robust, tested and widely accepted [9]. Only in recent years, some authors suggested methods for the development of maturity models [6, 8, 15–19]. Even though they created their own development framework with different characteristics, the same guidelines, which have to be followed for the construction of a maturity model, can be recognized among them. Indeed, comparing these frameworks, five common activities are identified: inception, elaboration, construction, deployment and maintenance [9].

During the inception phase, the main activities to perform are problems and participants identification, as well as planning and scoping goals. Successively, in the elaboration phase, the design strategy and the architecture of the model have to be determined. In the construction phase, the tool to measure the maturity of the object of interest is built and the procedures for its deployment and management are defined. In the last stage, the deployment phase, the maturity model and assessment tool are validated. If the model is accepted, it enters in a maintenance phase, were changes are managed and, if it is necessary, the model is updated [9].

3 The Digital Readiness Assessment Maturity Model

In this section, the focus is on the activities carried out to develop the DREAMY (i.e. short name of Digital REadiness Assessment MaturitY model) and the related questionnaire. The model development of [6] was used as the framework for building the model. The phases "Design and Populate" of the overall framework are only analysed in the remainder of this paper.

3.1 Designing the Maturity Model

Architecture

To define the model architecture, it was fundamental to identify the manufacturing relevant processes, within which these activities are performed, and that are strategic for the digital transformation. When structuring the manufacturing relevant processes, the first considerations done were about how they highly depend on the company's production strategy (i.e. Engineer-To-Order – ETO-, Make-To-Stock – MTS-, etc.). ETO companies, for example, can build their competitive advantage thanks to a perfect management of quotation and customer requirement comprehension phases, while MTS companies have to be very well organized in forecasting demand and in stock management processes. As the objective is not to focus on a single manufacturing company's strategy, a modular and scalable architecture was built, enabling to adapt to the needs, and thus assessment, of companies using different production strategies.

In order to make the architecture as general as possible, manufacturing company's processes were grouped in areas, which are strategic for the digital transformation. At the end, five main areas were identified: (1) Design and Engineering; (2) Production Management; (3) Quality Management; (4) Maintenance Management; (5) Logistics Management. Each process area can be considered as a self-contained module and therefore it is possible to add or remove one or more areas in case of they are not meaningful in certain industrial situations with no impact on the macro-structure foundation. Horizontally to these process areas, it interposes the *Digital Backbone*, within which all the information exchange processes inter-areas are covered.

Maturity Levels

Once the architecture is given, maturity levels are still undefined; they are however relevant issues in maturity assessment. Indeed, for the objective of this work, the digital readiness of a manufacturing company is defined through a scale of maturity levels. These levels describe a proper set of company capabilities, to provide a snapshot of their current (digital) abilities. The levels have been based on the inspiring principles of the CMMI framework [20, 21]. The main reason of this choice is that the CMMI provides a defined structure of maturity levels, specifying what are the capabilities a company has at each level. In this way, as the five-scale CMMI maturity levels provided a generic model to start from, they have been re-adapted in order to gather the definitions, and so the semantic, of the digital readiness maturity levels (see Table 1).

Along the maturity levels, it is worth remarking the relevance of integration, either vertical or horizontal one, as well as intra- or inter-companies, and of interoperability: they are two primary levers to enable digital-orientation. Integration is a commonly known concept: it is the first systemic paradigm used to organise humans and machines at different levels [22], field, management and corporate level, to produce an integrated enterprise system. It has been recognized since long in its importance for the manufacturing chain within the networked enterprise, in order "to control and to manage the customised manufacturing of both goods and services as desired by the Internet society" [23]. Interoperability (Enterprise interoperability) is the "ability of enterprises and entities within those enterprises to communicate and interact effectively" [24]. This is an enabler of business collaboration (intra- or inter-companies), and it is not just a technology problem. Indeed, interoperability requires solutions to overcome barriers of different nature, i.e. conceptual, technological and organizational ones [24]. Nowadays, interoperability is clearly a relevant requirement that comes out along the journey towards the digital transformation.

Table 1. Maturity levels' definition

Maturity level	Description
ML1 INITIAL	The process is poorly controlled or not controlled at all, process management is reactive and does not have the proper organizational and technological "tools" for building an infrastructure that will allow repeatability /usability /extensibility of the utilized solutions
ML2 MANAGED	The process is partially planned and implemented. Process management is weak due to lacks in the organization and/or enabling technologies. The choices are driven by specific objectives of single projects of integration and/or by the experience of the planner, which demonstrates a partial maturity in managing the infrastructure development
ML3 DEFINED	The process is defined thanks to the planning and the implementation of good practices and management procedures. The management of the process is limited by some constraints on the organizational responsibilities and /or on the enabling technologies. Therefore, the planning and the implementation of the process highlights some gaps/ lacks of integration and interoperability in the applications and in the information exchange
ML4 INTEGRATED AND INTEROPERABLE	Being the process built on the integration and on the interoperability of some applications and on the information exchange, it is fully planned and implemented. The integration and the interoperability are based on common and shared standards within the company, borrowed from intra- and/or cross-industry de facto standard, with respect to the best practices in industry in both the spheres of the organization and enabling technologies
ML5 DIGITAL-ORIENTED	The process is digital oriented and is based on a solid technology infrastructure and on a high potential growth organization, which supports – through high level of integration and interoperability – speed, robustness and security in information exchange, in collaboration among the company functions and in the decision making

Analysis Dimensions

From what already defined in the maturity levels, it is clear that, when evaluating the digital capabilities of a company, not only the technologies used to support the processes have to be considered. Indeed, without structured processes and defined organization structures, a company will not be able to exploit the opportunities these technologies offer. From these considerations, from the evidences presented in the literature and considering the objective of the maturity model itself, it was decided to evaluate the digital readiness of manufacturing companies through four analysis dimensions: *Process*, *Monitoring and Control*, *Technology* and *Organization*. The decision of considering these analysis dimensions was made mainly taking into account the units of analysis of the DREAMY, which are manufacturing relevant processes. To this aim, it was decided to assess: (1) the way in which these processes are carried out (*Process* dimension); (2) the way in which these processes are monitored and controlled through the evaluation of feedbacks received from their execution (*Monitoring and Control* dimension); (3) the technologies that support these processes (*Technology* dimension); (4) the organizational structures behind these processes (*Organization* dimension).

The Maturity Model and its Use for the Status Quo Analysis
The maturity model is synthesized in Fig. 2. The model is usable, as a first function, for descriptive purposes: the maturity indexes are relevant elements for describing the as-is situation of a manufacturing company according to the different dimensions and areas considered.

3.2 Populating the Maturity Model

The findings from design – i.e. architecture, maturity levels and analysis dimensions – were validated with academia and company experts. The output of this phase was the first realise of the Digital Readiness Questionnaire. Within the questionnaire, for each question a standard normative of answers was developed. These standard answers were structured according to an increasing level of maturity, following the five-scale digital readiness maturity levels previously described. To define the answers, considerations from company experts were blended with the ones of academia experts and literature findings. This allowed exploiting the maturity model as theoretical framework in order to inform the questionnaire construction. In particular, such a construction was done by synthesizing the specific knowledge from experts and literature in different fields (i.e. design and engineering, production management, etc. according to the architecture of Fig. 1), collected and organized according to the different maturity levels and analysis dimensions. An example of the question related to Quality Management area is provided below:

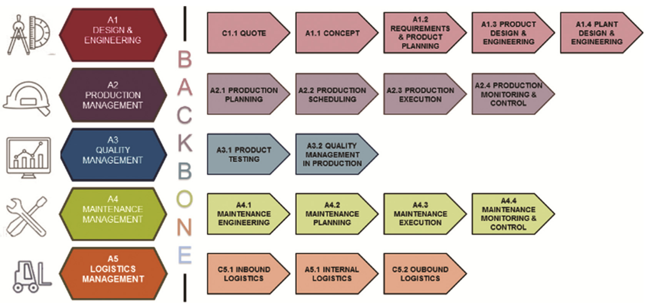

Fig. 1. DREAMY process structure

Does the organisation perform regular reviews regarding problems related to product tests and quality?

- No, no review is performed *ML1*
- Yes, reviews are performed but not by experts in the field *ML2*
- Yes, reviews are performed by experts in the field, but still not systematically *ML3*
- Yes, reviews are performed by experts in the field, from involved company departments /functions *ML4*
- Yes, reviews are performed by experts in the field, from involved company departments /functions, also including suppliers and OEMs where necessary *ML5*

Thanks to the information gathered through the execution of the questionnaire, it is possible to assess the company's digital readiness with the series of maturity indexes already presented in Fig. 2.

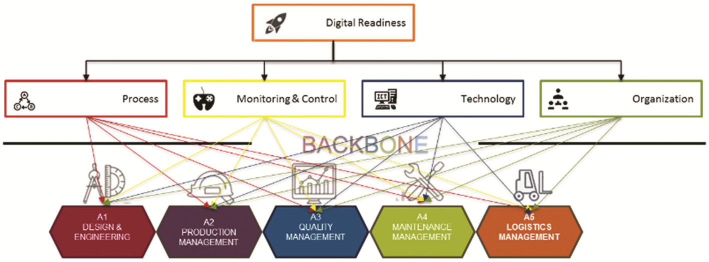

Fig. 2. Representation of the maturity indexes calculation

4 Conclusions

It is now important to discuss how the DREAMY can be used for road-mapping. Indeed, it is important to underline that although the model's objective is to help manufacturing companies to assess their processes so to figure out how they are ready for the digital transformation, it also helps in developing their transformation roadmap. Therefore, maturity assessment has to be considered just the first step of an overall approach. The next development steps regard a concrete overview on what are the suggested actions to undertake in order to improve processes' maturity. The expected output will be a list of opportunities enabled by the digitalisation that the analysed company can take advantage of to overcome the identified needs.

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Improvement Strategies for Manufacturers Using the MESA MOM Capability Maturity Model

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Abstract. Recently, the concept of smart manufacturing has emerged as a new paradigm, with which manufacturers can enhance their competitiveness in the market. Smart manufacturing paradigm can be viewed as the convergence of Information & Communication Technologies with human capabilities and manufacturing technologies. The new paradigm is expected to bring a new wave of performance improvements to manufacturing industries. However, manufacturing enterprises need to expend significant effort when preparing to adopt new technologies and realize their full benefits. MESA (Manufacturing Enterprise Systems Association) created the Manufacturing Operations Management/Capability Maturity Model (MOM/CMM) to help evaluate the maturity and readiness of manufacturing enterprises from the factory operations perspective. However, the model, in its raw form, can be time- and resource-consuming. It also lacks improvement strategies that use results of evaluation. The objective of this work is to restructure the questionnaire to reduce its completion time and to outline strategies through which a manufacturing enterprise can derive its improvement plans.

Keywords: Smart manufacturing · Manufacturing operations management · Maturity model · Readiness assessment · Improvement strategies

1 Introduction

As the global competition in the manufacturing industry becomes more intense, a large number of new technologies, both hardware and software solutions, are being developed and applied in the industry. As a result, the concept of smart manufacturing has emerged

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as a new paradigm that is expected to lead to innovations across many industries. To implement the new paradigm across various manufacturing industries, research efforts are being carried out throughout the world under governmental projects such as NNMI (National Network for Manufacturing Innovation, USA), Industrie 4.0 (Germany), Horizon 2020: Factories of Future (EU), etc., aimed at bringing innovations to manufacturing processes, productivity, and quality [1].

However, often times, manufacturing enterprises cannot fully benefit from these technologies unless they have achieved a certain level of maturity in their manufacturing operations [2]. For example, if there is no procedure established for production tracking, manufacturers are not able to select and locate necessary sensors in their manufacturing systems. A method is needed for evaluating foundational capabilities that support repeatable daily manufacturing operations and continuous performance improvements along with a guideline to help manufacturers increase their readiness for adopting the emerging smart manufacturing technologies.

In our previous work, we developed the Smart Manufacturing System Readiness Assessment (SMSRA) method that measures the maturities of the information connectivity, organization, performance management, and IT system, all of which are important components for deploying new Information & Communication Technologies (ICTs) in a manufacturing system from the shop floor level to the enterprise level [3]. Manufacturing Enterprise Systems Association (MESA) Manufacturing Operation Management Capability Maturity Model (MOM/CMM), on the other hand, provides a method for evaluating the foundational capabilities that should be in place before or while adopting ICTs, particularly at the shop floor level [4]. The model is based on the activity models that are defined in the ISA-95 Part 3 [5]. Although some overlaps exist, MOM/CMM can be viewed as a precursor to the SMSRA. In other words, a factory should already be at level 4 or level 5 of the MOM/CMM before applying the SMSRA.

NIST is working with MESA to pilot the MOM/CMM with manufacturers; however, feedback from an initial discussion with potential pilot participants provides the following conclusions: (1) providing answers to all 832 questions of the complete MOM/CMM questionnaire (or even a subset of the questionnaire for a single operational area) to evaluate the maturity is too time-consuming; and (2) there is no clear direction to how a manufacturing organization can derive improvement plans based on the evaluation result.

In this paper, we present the result of our work to reduce the effort needed to complete the questionnaire and provide an initial guideline for manufacturers to derive an improvement strategy based on the evaluation result.

2 Overview of MESA MOM/CMM

Part 1 of ISA-95 defines five hierarchical levels (0 to 4) for processes and systems that make up a manufacturing enterprise system [6, 7]. The MESA MOM/CMM is defined based on level 3 processes – the manufacturing operations management (MOM) processes. Four operational areas are defined at level 3: production operations management, quality operations management, inventory operations management and maintenance operations management. Each operational area consists of a set of activities related to detailed scheduling, dispatching, execution management, resource management, definition management, data collection, tracking and performance analysis [5].

The maturity level is measured by answering "yes/no" to the questionnaire that is organized per activity [5]. Each activity can have the maturity level 0 to 5. See Table 1 for example questions at each maturity level (within the actual questionnaire, each maturity level may have up to 9 questions). The maturity levels are defined as follows:

Level 0: There has been no evaluation performed.
Level 1: The processes are at initial stage and not documented or formally managed.
Level 2: Some of the processes are repeatable with possibly consistent results and documented.
Level 3: The processes are defined with documented standards for all activities.
Level 4: The processes are defined and documented across all organizational groups.
Level 5: The processes focus on continuous improvement and optimization.

Table 1. Example of repeated questions

Level	Question
1	There are no defined procedures for Detailed Production Scheduling and the processes are not repeatable during times of stress
2	Detailed Production Scheduling processes vary across organizational groups, with different processes and procedures used in different groups
3	Detailed Production Scheduling processes are defined across all organizational groups, and the organization follows written and controlled policies
4	(All Level 3 processes are in place)
5	(All Level 4 processes are in place)

Beside evaluating the maturity from the activity viewpoint, the questions can also be organized and evaluated with respect to 7 aspects namely roles and responsibility, succession plans and backups, policies and procedures, technology and tools, training, information integration and KPI. This will be addressed in our future work.

3 Related Works

Numerous frameworks or models for maturity assessment and/or evaluation of business or processes exist in various industries. A maturity model serves as a means for assessing and providing an improvement framework. The Capability Maturity Model (CMM) is a software engineering process improvement model developed by Software Engineering Institute (SEI) at Carnegie Melon University, which triggered surge of development of maturity models in diverse fields [8].

One of the first maturity models developed is the Quality Management Maturity Grid (QMMG) by Philip B. Crosby in 1979 [9]. It evaluates the maturity of the organization's service and product quality management processes and how organizational cultures are affected by those processes.

In the field of supply chain management, SCRL-Model (Supply Chain Readiness Level) is a well-defined maturity evaluation model. The model is designed to evaluate supply chain maturity by answering assessment questions in various sections such as inventory, supplier consolidation, supplier/customer relationships, commodity price adaptability, visibility etc. By doing so, a SCRL number is assigned to each section and it yields a level that indicates the maturity of the supply chain and how well it has been prepared. The goal of the model is to increase operational efficiency by identifying and mitigating operational risks in the supply chain [10].

While the SCRL-Model serves as an assessment tool for the supply chain management field, the Manufacturing Readiness Level has been developed by the US Department of Defense (DoD) for the manufacturing field. According to [11], the MRL defines the current level of manufacturing maturity along with elements such as cost and risks that affect the manufacturing processes.

The models introduced thus far (i.e., QMMG, SCRL-Model, MRL) assess the processes or practices in one dimension with associated questions for each level. However, MESA MOM/CMM consists of multi-dimensional questions to evaluate the maturity levels of activities in manufacturing operations and from varied aspects at the same time. Hence, the MESA approach to assessment is different from the aforementioned models.

Putting the number of dimensions covered by MESA MOM/CMM aside, an investigation on design of questionnaire is a primary concern since MESA MOM/CMM consists of series of 832 questions. According to [12], the number of questions in a questionnaire affects the quality of answers to the questionnaires. Specifically, the rate of response to the questionnaire could be increased by reducing the number of questions. Also, to reduce cognitive load on respondents, it is recommended to have a maximum of 20 words per sentence. However, one question can consist of more than one sentence [12]. Also, questions that are worded in negative tones tend to have greater cognitive load on respondents due to longer time required for their processing. It is recommended to have questions worded in positive tones as often as possible [13]. In the next section, we discuss our work to improve MESA MOM/CMM questionnaire due to these research findings and the initial feedback described in Sect. 1.

4 Restructure of MESA MOM/CMM

Currently, MESA MOM/CMM consists of 832 yes/no questions across 4 operational areas, each of which has 8 activities to evaluate maturity, effectiveness, robustness and repeatability of the manufacturing operations and practices. The MESA MOM/CMM can be treated as a benchmark for comparison between different operational areas and activities. However, parsing through and answering all 832 questions can be a daunting task.

One strategy to address this issue is to select a subset of operational areas and activities to focus on beforehand so that only a relevant subset of 832 questions is answered at one point in time. However, this approach does not save time and effort as manufacturers may not be able to decide how to prioritize operational areas or subsets. Furthermore, having a complete picture of the entire operation would allow a better investment decision to be made.

Alternatively, restructuring the questionnaire to reduce the number of questions and words while retaining the original intent of the questionnaire is pursued. The following techniques are used in the restructuring process:

(1) Questions that are composite are decomposed into multiple questions. Composite questions are ambiguous to the interviewee when only one part of the question is true. This improves the clarity and answerability of the question.
(2) Questions at all levels under a single activity are first grouped according to overlapping keywords and then converted into multiple choice questions. This reduces the number of questions and words the interviewee must parse.

Table 1 shows example questions for the 'detailed production scheduling' activity within the 'production operations management' operational area. In the table, the keyword "procedure" for detailed production scheduling appears repetitively at level 1 to 3. Similar repetitions exist throughout the questionnaire. These questions can be grouped together based on those repeated keywords and be restructured into a multiple-choice question.

Table 2 shows an example of the restructured questionnaire. Notice that the question is no longer structured per maturity level, it rather aggregates across levels. A programmatic mapping has been developed such that the answer to the new representation of the question is automatically mapped to the original question and the maturity level can be automatically calculated.

Table 2. Example of grouped questions

Choice	Question
	Procedures for Detailed Production Scheduling
A	Not defined
B	Defined, but vary across organizational groups
C	Defined across all organizational groups

We have restructured questions in 2 activities under 1 operational area. The result is promising, the number of questions was reduced to 14 from 29, and the number of words was reduced approximately by 47% (from 473 words to 248 words) in each activity.

5 Improvement Strategies

Since the evaluation work is time-consuming and labor-intensive, there should be a strategic and efficient approach to evaluations. Once an enterprise decides to evaluate its current status of maturity, it can choose an improvement strategy between the three different types as shown in Table 3: vertical improvement, horizontal improvement and hybrid improvement.

Table 3. Improvement strategies and their tradeoffs

Improvement strategies	Focus	Initial time needed	Initial capital investment	Positive effect
Vertical	High priority operational area	Low	Low	High initial ROI
Horizontal	Activity	Low	High	Balanced factory-wide improvement
Hybrid	Weakest activities	High	Depends	More balanced factory-wide improvement

Vertical improvement strategy focuses on achieving high maturity levels across activities that are high priority, one operational area at a time. This strategy can work well with manufacturers that know the particular operational area on which they would like to focus their improvement. If such a decision can be made early, the manufacturers can also address the maturity assessment one operation at a time as well. Another advantage of this strategy is that it can result in high initial ROI (Return of Investment) compared to other strategies because the resources and investments are more focused (Fig. 1).

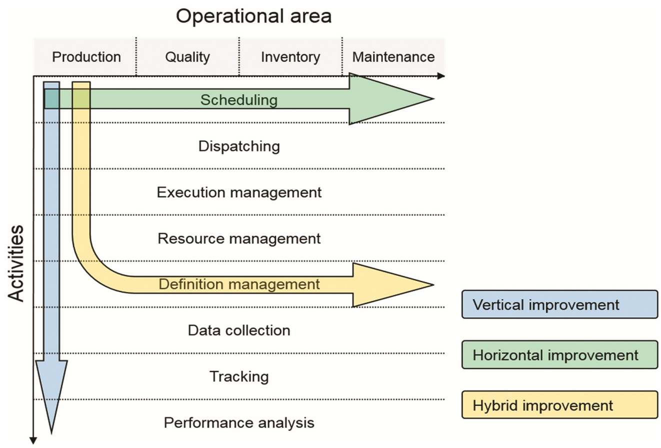

Fig. 1. Different types of improvement strategies

Horizontal improvement strategy focuses on improving maturity levels of a specific activity across operational areas. With this improvement strategy, an enterprise can achieve balanced activity maturity across operational areas so that the enterprise can seek a way to have continuous and simultaneous improvement in all these different operational areas. This strategy takes less time to complete initial maturity evaluation for selected activities. It may, however, require more capital investments as technologies tend to be modularized for each operational area such as scheduling system vs. inventory management system. The advantage can be that the strategy can lead to more even improvements for the entire organization.

Hybrid improvement strategy focuses on achieving balanced maturity levels for the entire matrix of activities and operational areas by prioritizing the improvement based on the weakest activity. With this improvement strategy, the enterprise can achieve factory-wide balanced maturity. However, if there are equally weak activities across operational areas or once the maturities across activities are leveled out, the horizontal or vertical strategy must be applied. The drawback is that to use this improvement strategy, a sizable initial effort, larger than those required in the previous two strategies, is needed to evaluate maturity levels of all activities across all operational areas. The capital investment will depend on the variation of the maturities across the matrix.

With evaluation and utilization of different types of strategies, an enterprise can pursue robust and mature manufacturing operations and processes which can yield continuous improvements and effective production. To achieve the goal of optimized manufacturing operations, an enterprise should have evaluated their practices. Figure 2 shows example evaluation results of a current and an improved status of their practices in their manufacturing operations. As shown in the charts, in current practices, performance analysis (which is denoted as POM/PA) is the weakest activity among 8 activities under the production operations management. The rest of activities are evaluated no higher than level 3. If an enterprise in this example decides to take the vertical improvement strategy, which is to promote maturity levels of all activities under one operational area, the evaluation result would look like the chart noted "After" in Fig. 2. Since level 3 in MESA MOM/CMM is a threshold that all organizations should aim to achieve initially, one would like to pursue a way to promote maturity level of activities evaluated as inferior until they match level 3 requirements before improving other activities already at level 3.

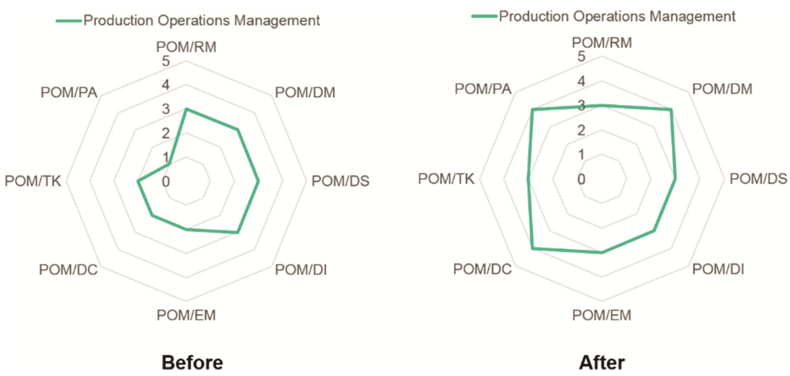

Fig. 2. Example evaluation results of current and improved status

6 Conclusion and Discussion

In this research, restructuring of MESA MOM/CMM and manufacturing operations improvement strategies were introduced. By grouping questions and converting them into multiple-choice questions, the number of words and questions included in the original model is reduced considerably. The preservation of the original intent is verified by a successful programmatic translation of answers in the new structure to the original structure. Our future work lies in the validation that the new structure saves time to answer all questions.

Three types of improvement strategies, each of which serve as a guideline for evaluating and improving the manufacturing operations practices, were proposed. With the improvement strategies and new questionnaire structure, a manufacturing enterprise can enhance its planning to complete the evaluation and track and improve its manufacturing operation management maturity, which is foundational to deploying smart manufacturing technologies.

The MESA MOM/CMM is still in its infancy stage, and we are actively working toward piloting the model with real factories. We are also considering further improving the questionnaire – to make it more respondent-friendly. To this end, we will be exploring gamification techniques. Our hypothesis is that gamifying the questionnaire would capture evaluators' interests to complete the questionnaire and reduce the rate of evaluators' drop-off before the completion of the questionnaire.

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Auto-configurable Event-Driven Architecture for Smart Manufacturing

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Abstract. In order to meet the ever-changing customer demands, smart manufacturing needs to intelligently integrate and coordinate the entire manufacturing supply chain. Event-driven architecture has been considered as a promising enabler for smart manufacturing. However, in the primitive event-driven architecture all components work in parallel, and there are few frameworks or standards that deal with organizing and managing the components. This paper proposes an ontology based holonic event-driven architecture for smart manufacturing systems. Powered by the developed ontology model and Semantic Web technology, the ontology based architecture enables the distributed components in a smart manufacturing system to be configured autonomously and collaborate with each other even when they don't know much about their counterpart.

Keywords: Event-driven architecture · Smart manufacturing system · Ontology

1 Introduction

Shorter product lifecycle, higher dynamic market, and massive customized requirements drive today's manufacturing systems to be smart. In the United States, a coalition of companies, universities, manufacturing consortia and consultants called the Smart Manufacturing Leadership Coalition (SMLC) was built to develop a shared infrastructure that enables the implementation of smart manufacturing [1]. In the meantime, starting from 2011 the German government initiated a project to promote smart factory in Germany, so called Industry 4.0. The smart manufacturing systems (SMS) have the ability to adapt to new situations by manufacturing intelligence with real-time data [2], and they need to be autonomous, self-aware, and self-correcting [3].

Over the last three decades, multiple architectures and approaches have been developed to meet the evolving requirements of manufacturing systems. Holonic Manufacturing Systems were expected to be appropriate for the next generation manufacturing systems as they provide a high and predictable performance with a high robustness against disturbances and unforeseen changes [4], and agent-based approach was considered as the most popular technology for implementation Holonic Manufacturing Systems. However, in spite of all the enthusiastic academic researches on agent-based manufacturing systems, only few industrial applications were reported owing to the conceptual and technology difficulties. With the emerging of the service oriented

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architecture, Service Oriented Multi-Agent System (SoMAS) is proposed for creating more complex, flexible, and adaptive systems by integrating the highly interoperable Web services and autonomous software agents [5–7].

With the recent development of IOT technology, SMS are able to capture more and more real-time data. These data are usually in high volume, high variety while not exactly accurate, which bring big challenges to the current manufacturing systems. In order to meet the ever-changing customer demands, smart manufacturing also needs to intelligently integrate and coordinate the entire manufacturing supply chain [8]. Backboned by complex event processing technology, event-driven architecture (EDA) can reduce the amount of information communicated in the system [9], and is known to be strong at processing high-volume complex event streams [10]. Furthermore, owing to its extremely loose coupled and highly distributable nature, EDA has advantages of integrating and coordinating the various organizations and their manufacturing resource and information resource throughout the supply chain. These features make EDA a promising enabler for smart manufacturing. Several EDA based manufacturing systems have been proposed in literature, e.g. [9, 11, 12].

However, in the primitive EDA all the event producers and consumers work in parallel, and we haven't found any frameworks or standards that deal with organizing and managing event service components in an EDA. In this case, when integrating a large variety of objects in different levels of different organizations using the primitive EDA, management, interoperability, security and privacy issues may arise. In this paper we propose an ontology based holonic EDA (Oh-EDA) to solve the management difficulties in the primitive EDA. With the ontology model, distributed event service components can be automatically configured and integrated to an Oh-EDA system like plug and play, and the service components can collaborate with each other even when they don't know much about their counterpart. The access to the event messages is distributed controlled based on the ontology based access control rules. The basic building blocks, ontology model and access control rules of Oh-EDA are introduced in the next section, which is followed by an illustrative case presented in Sect. 3; while Sect. 4 concludes the paper with the discussion of future works.

2 Auto-configurable EDA

An EDA is a software architecture that detects and responds to events [13]. An EDA usually consists of components that detect events, listen events, process reaction to events, and transmit events or message among its components [14]. In event-driven systems, actions are triggered by occurrences of events.

In Oh-EDA, the event service components are organized as holons. Each event service component is embedded with an ontology-based service description file which clarifies the feature of the service as well as its input and output events. An ontology reasoner is employed to infer the proper configuration of the components and thus enables the components to be autonomously configured and deployed into the system.

2.1 Building Blocks

The main building blocks in Oh-EDA include event services, event service managers, event message brokers, and event service assemblies (ESAs), as illustrated in Fig. 1. ESAs are the basic units that compose an Oh-EDA system. An ESA assembles a set of event services working collaboratively to achieve some common objectives. In Oh-EDA, an ESA is a holon, which can work independently and also can be a part of another ESA. In a SMS, an ESA can represent any organization in the smart manufacturing value chain, e.g. an assembly line, a plant, a supplier, or the whole supply chain. The key components in an ESA are explained below.

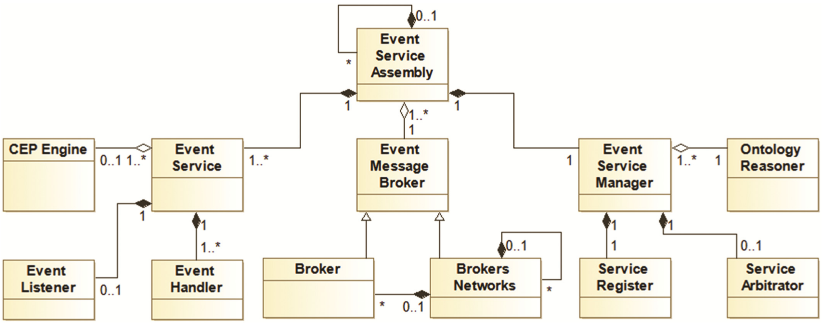

Fig. 1. Building blocks in Oh-EDA

Event service: An event service can be an event producer, an event processor, an event consumer, or their combination. The event service listens the events it subscribed via an *event listener*, and reacts to the events via *event handlers*. The events may need to be processed by a *CEP engine*. The CEP engine can be part of the service or be shared among various event services. The event handlers and the CEP engine may generate new events and publish them to the system via an *event message broker*.

Event message broker: The event message broker is the backbone of the event driven system. It enables event publishing, subscribing, and transmitting among the services. The message broker can be a single message *broker* or a distributed *network of brokers*.

Event service manager: The event service manager is responsible for the coordination, mediation, and management of the event services in an event service assembly. Event services have to be registered into the event service assembly via a *service register* before they can subscribe or publish events. In the registration, the service's access to different categories of events is granted or restricted according to the access rights that are deduced by an *ontology reasoner* based on predefined ontology-based access control rules. The *service arbitrators* are employed to solve possible conflicts among event services.

2.2 Ontology

An ontology is a formal, explicit specification of a shared conceptualization [15]. In this study, we propose an ontology model for event driven systems (EDO) that models the main entities, their relationships and related rules in an event-based SMS. We use OWL DL with Semantic Web Rules Language (SWRL) to represent EDO. OWL DL is a sublanguage of Web Ontology Language (OWL), and it permits efficient reasoning support [16]. SWRL is a rule extension of OWL DL, enabling Horn-like rules to be combined with an OWL knowledge base [17].

The top-level concepts in EDO include *Organization*, *Resource*, *Service*, and *Event*. Each of the concepts is a member of OWL class *owl*:*Thing*. The top-level concepts and their relationships are illustrated in Fig. 2. The *Organization* concept represents any organizations in the smart manufacturing value chain. The *Service* concept models the event-based services provided in the organizations, e.g. production scheduling, quality control, performance measurement, and cost accounting. The *Event* concept depicts any event message generated, published or subscribed by the services, while the *Resource* concepts represent all kinds of resources involved in the services.

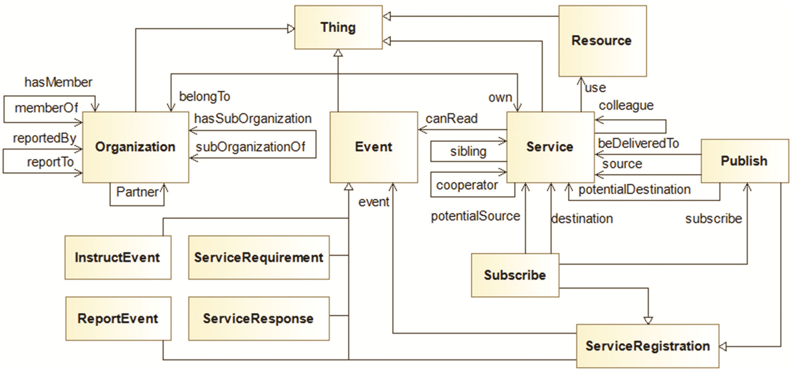

Fig. 2. Top-level concepts and their relations in EDO

EDO supports a variety of organizational structures. Generally, an organization can be a *member* of another organizations, e.g. a manufacturer in a supply chain. The *reportTo*/*reportedBy* relationship depicts the chain of command either in a hierarchy, departmental, or matrix organization. Furthermore, an organization can be a *partner* of another organization, if they collaborate with each other but they are not in a same chain of command. The other relationships between the organization entities and the service entities are defined formally via SWRL rules A1 to A7 (represented with the SWRLAPI SWRL Syntax[1] used in the Protégé project) as displayed in Fig. 3. Among the object properties, *hasSubOrganization*, *memberOf* and *reportTo* are transitive properties.

[1] Please refer to https://github.com/protegeproject/swrlapi/wiki/SWRLAPISWRLSyntax.

Name	Rule
A1	reportTo(?y, ?x) ^ hasMember(?x, ?y) -> hasSubOrganization(?x, ?y)
A2	hasSubOrganization(?x, ?y) -> reportTo(?y, ?x) ^ hasMember(?x, ?y)
A3	hasSubOrganization(?x, ?z) ^ partner(?x, ?y) -> partner(?z, ?y)
A4	own(?x, ?t) ^ own(?x, ?s) ^ differentFrom(?s, ?t) -> sibling(?s, ?t)
A5	own(?x, ?s) ^ own(?y, ?t) ^ hasSubOrganization(?z, ?y) ^ hasSubOrganization(?z, ?x) -> colleague(?s, ?t)
A6	own(?x, ?s) ^ own(?y, ?t) ^ hasSubOrganization(?x, ?y) -> colleague(?s, ?t)
A7	own(?x, ?s) ^ own(?y, ?t) ^ partner(?x, ?y) -> cooperator(?s, ?t)
B1	source(?p, ?s) ^ potentialDestinationRange(?p, "sibling") ^ sibling(?s, ?t) -> potentialDestination(?p, ?t)
B2	source(?p, ?s) ^ colleague(?s, ?t) ^ potentialDestinationRange(?p, "colleague") -> potentialDestination(?p, ?t)
B3	source(?p, ?s) ^ cooperator(?s, ?t) ^ potentialDestinationRange(?p, "cooperator") -> potentialDestination(?p, ?t)
B4	destination(?q, ?t) ^ potentialSourceRange(?q, "sibling") ^ sibling(?s, ?t) -> potentialSource(?q, ?s)
B5	destination(?q, ?t) ^ potentialSourceRange(?q, "colleague") ^ colleague(?s, ?t) -> potentialSource(?q, ?s)
B6	destination(?q, ?t) ^ cooperator(?s, ?t) ^ potentialSourceRange(?q, "cooperator") -> potentialSource(?q, ?s)
C1	source(?p, ?s) ^ event(?p, ?e) ^ sibling(?s, ?t) -> canRead(?t, ?p)
C2	InstructEvent(?e) ^ event(?p, ?e) ^ source(?p, ?s) ^ own(?x, ?s) ^ own(?y, ?t) ^ reportedBy(?x, ?y) -> canRead(?t, ?p)
C3	ReportEvent(?e) ^ event(?p, ?e) ^ source(?p, ?s) ^ own(?x, ?s) ^ own(?y, ?t) ^ reportTo(?x, ?y) -> canRead(?t, ?p)
C4	ServiceRequire(?e) ^ source(?p, ?s) ^ event(?p, ?e) ^ colleague(?s, ?t) -> canRead(?t, ?p)
C5	ServiceRequire(?e) ^ source(?p, ?s) ^ event(?p, ?e) ^ cooperator(?s, ?t) -> canRead(?t, ?p)
D1	destination(?q, ?t) ^ canRead(?t, ?p) ^ source(?p, ?s) ^ event(?q, ?e) ^ event(?p, ?e) ^ potentialSource(?q, ?s) ^ potentialDestination(?p, ?t) -> beDeliveredTo(?p, ?t)
D2	destination(?q, ?t) ^ beDeliveredTo(?p, ?t) ^ event(?q, ?e) ^ event(?p, ?e) -> subscribe(?q, ?p)

Fig. 3. SWRL rules in EDO

2.3 Access Control Rules

In Oh-EDA, the access to the event messages is controlled via the distributed service registers based on the message subscribing and publishing mechanism. The event service components take the primary responsibility for the access control. When a service is registered into the system, it sends a set of *Publish* events and *Subscribe* events to the corresponding service register, stating the type of the event messages which the service is willing to publish and subscribe. The *Publish* events also suggest the accepted destinations of the event messages, while the *Subscribe* events suggest the potential event sources. In EDO, data properties *potentialDestinationRange* and *potentialSourceRange* have been defined for the *Publish* events and the *Subscribe* events respectively. The *potentialDestinationRange*/*potentialSourceRange* can be set as “sibling”, “colleague” or “cooperator” to define the scope of the potential destination/source services instead of designating a specific service. Rules B1 to B6 shown in Fig. 3 are used to interfere the corresponding potential event destinations and sources for the publishing and subscribing.

The publishing and subscribing are then reviewed based on the related event types and the organizations’ policy. In EDO, the *Event* entities are subclassified as *InstructEvent*, *ReportEvent*, *ServiceRequirement*, *ServiceResponse*, and *ServiceRegistration*. The *ReportEvent* and *InstructEvent* depict the event messages disseminated up and down the chain of command respectively. The *ServiceRequirement*/*ServiceResponse* event represents the event messages that requires a service or response to a service requirement. The *ServiceRegistration* events are further specialized to the *Publish* events and the *Subscribe* events as stated before, modeling the publishing or subscribing of a type of events by a service. Rules C1 to C5 in Fig. 3 demonstrate some examples to define the organizational access control policy. Rule C1 states that an event message created by a service can be accessed by the siblings of the service. Rule C2 allows the *InstructEvent* entities to be delivered down the chain of commands, while rule C3 allows the *ReportEvent* entities to be delivered up the chain of commands. Rule C4 and C5 let the *ServiceRequirement* messages to be disseminated to all services in the service’s organization and its partner organizations. Of course, these rules can be tailored by the organization based on its own security and privacy policies.

If a subscribing event and a publishing event are matched with each other and the organizational access control policies are followed, the subscribing and publishing will be registered to the system, as stated in rules D1 and D2 displayed in Fig. 3.

3 An Illustrative Case in Smart Manufacturing

Service components in Oh-EDA can be seen as agents in the agent-based architecture. Therefore Oh-EDA has all advantages that an agent-based architecture has. Besides, Oh-EDA has more desired capabilities and meets the requirements of SMS in many aspects, e.g. autonomous configuration, plug-and-play deployment, highly interoperable, easy to adapt, highly scalable and robust.

In this section we present a tiny show case to demonstrate the use of Oh-EDA in a SMS as shown in Fig. 4. The case involves a toy manufacturer named *LeToy* and a third party logistics provider *XExpress*. LeToy has a manufacturing plant *LeFactory* and a warehouse *LeWare*. RFID technology is employed in the factory to monitor the movement of WIPs and the *rfidReader* service is responsible for translating the RFID data into the WIPs' movement events. LeFactory owns a scheduling service *scheduler* which receives customized orders and determines the production schedule. The production schedule is then disseminated to the *wipManager* service, which dispatches the real-time production tasks to each workstations and controls the production processes based on the WIPs' movement events. For an instance, if a WIP leaves its final workstation and enters the dispatch zone, the *wipManager* would conclude that the production has been done. Therefore it would publish an order-status-change event and require a transportation of the final product to the warehouse. The *wareTrans* service owned by LeWare provides such transportation service. Once the final product is delivered to the shipment area, the *shipment* service will publish a transportation requirement to its third party logistics partner. Besides, LeToy measures its performance via the *lePM* service, which uses the information provided by the other services, e.g. order-status-change, to calculate the performance measures. Table 1 shows a part of OWL code in Turtle syntax for representing the knowledge about the SMS. In Table 1, namespace *edo* refers to the

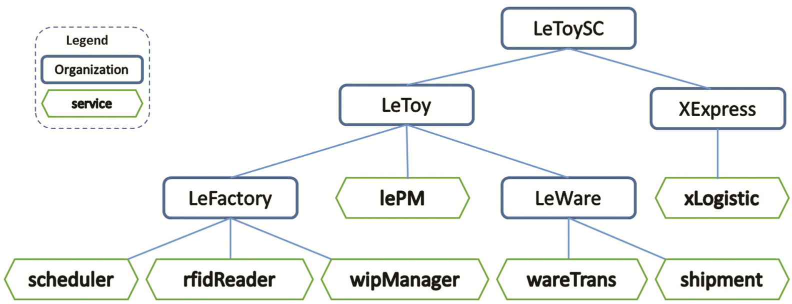

Fig. 4. The demonstration case

general EDO concepts and relations, and namespace *edsms* presents the concepts in the manufacturing domain. Figure 5 shows the inferred knowledge (the properties with the yellow background) for the wareTrans service and the wareTransSubscribe event using Protégé reasoner tool. It shows that the transportation requirements from the wipManager service will be delivered to the wareTrans service.

Table 1. Sample OWL code in Oh-EDA system

```
:LeToy rdf:type owl:NamedIndividual , edo:Organization ;
        edo:memberOf letoysc:LeToySupplyChain ;
        edo:partner xexpress:XExpress .
:LeWare rdf:type owl:NamedIndividual , edo:Organization ;
        edo:subOrganizationOf :LeToy .
:wareTrans rdf:type owl:NamedIndividual , edsms:TransportService ;
        edo:belongTo :LeWare ;
        edo:generate edsms:eExternalTransRequire .
:wareTransPublish rdf:type owl:NamedIndividual , edo:Publish ;
        edo:event edsms:eExternalTransRequire ;
        edo:source :wareTrans ;
        edo:potentialDestinationRange "cooperator"^^xsd:string .
:wareTransSubscribe rdf:type owl:NamedIndividual , edo:Subscribe ;
        edo:destination :wareTrans ;
        edo:event edsms:eInternalTransRequire ;
        edo:potentialSourceRange "colleague"^^xsd:string .
```

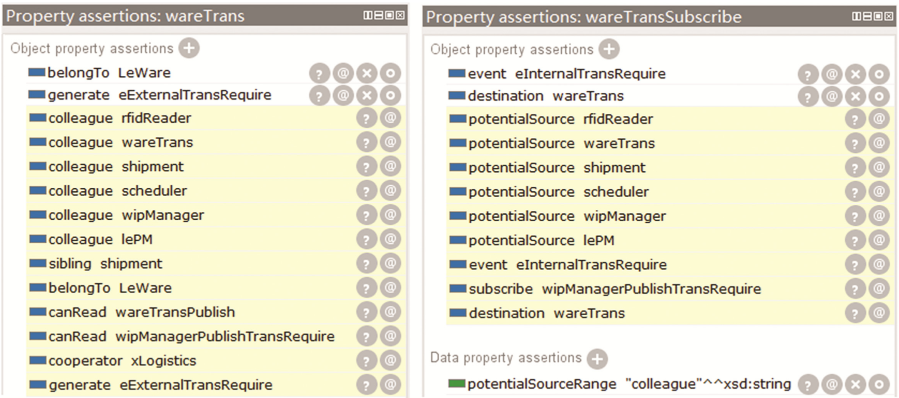

Fig. 5. Inferred properties for *wareTrans* and *wareTransSubscribe* (color figure online)

4 Conclusion and Further Work

This paper reports an ongoing work towards the auto-configurable SMS based on Semantic Web technology and event-driven architecture. The basic building blocks of the architecture and the top level ontology concepts, relations and access control rules have been developed. While the manufacturing domain specific ontologies and access control rules need to be further elaborated, and an industrial scale manufacturing system is under development for verifying and evaluating our proposed architecture.

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Industry 4.0: Evolution of the Research at the APMS Conference

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Abstract. The research on Industry 4.0 is increasing in importance over the years due to the expectation that it represents a new industrial paradigm, increasing competitiveness to the industries that can adopt it. The objective of this paper is to study the main points of research on Industry 4.0, featured universities and research centers. Using methodology based on bibliographic review, we analyzed a total of 546 papers, which composed the proceedings of the International Conference Advances in Production Management Systems (APMS), in 2014 held in Ajaccio (France), 2015 in Tokyo (Japan) and 2016 in Iguassu Falls (Brazil) and selected 39 papers to make this research. The results revealed that Industry 4.0 is increasing in importance, broadening the field of research; some suggestions for future research are presented.

Keywords: Industry 4.0 · Competitiveness · Productivity · Evolution

1 Introduction

A new industrial paradigm established on interconnectivity is already affecting industries, but in the near future, production will be able to exchange data directly with customers, supply chain, and other valuable stakeholders [1–3], in an integration never seen before. Based on high technology for automation, information and communication systems, machines and humans will be able to exchange data [4], opening new opportunities for the industries. This digital integration of resources was called Industry 4.0, an initiative of the German Government that launched the project at the Hannover Fair in 2011, when a public-private group was formed, with Henning Kagermann (Acatech – National Academy of Science and Engineering) and Siegfried Dais

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(Robert Bosch GmbH) chairing a working group [5]. The objective was to create value, developing new business models, products and services, improving operational effectiveness and solving problems by the connection of the internal environment of the factory with the outside world [1, 4–6]. The initiative was followed by other countries that launched similar projects under other names, such as *Produktion2013* in Sweden [7], *Industrial Internet Consortium* (IIC) initiative in USA [8, 9], *Fimecc* in Finland [7, 10], *MADE* in Denmark [7, 11], *Smart Industry* from the Netherlands [7, 12], *Made in China 2025* in China [2, 13] and *Japan's Robot Strategy* in Japan [2, 14].

The objective of this paper is to study the main points of research on Industry 4.0, featured universities and research centers. To make this research we analyzed the proceedings of the International Conference Advances in Production Management Systems (APMS), which gather leading experts from industry and academia, from all over the world, in a period of 3 years (2014 to 2016).

2 Literature Review

2.1 Industry 4.0 Project

The concept that gave support to the Industry 4.0 project is the use of automated production system and robotics interconnected by information and communication system to exchange data with customers, suppliers, other members of the supply chain and valued stakeholders, so that machines, human beings and resources can interact with each other, making possible cooperation in real time, in order to support mass customization, increase competitiveness and reduce waste [2–7, 11, 15, 16].

Industry 4.0 is based on three pillars: *Cyber-physical systems*, *Internet of Things* and *Internet of Services* [4]. *Smart factory* is considered a key feature of Industry 4.0 [4, 15], or the Industry 4.0 itself, also known as smart/cloud manufacturing [2, 6].

2.2 Cyber-Physical System

Cyber-physical systems (CPS) are embedded systems that using software controlled sensors and actuators, controllers and smart objects, supported by information and communication technology, make possible data exchange between mechanical/physical production systems and human beings, allowing the interconnection between machine-to-machine (M2M) as well as human-to-machine (H2M) [3, 17].

2.3 Internet of Things

The Internet of Things (IoT) is the integration through the Internet of physical objects that have computational, sensing and actuation capabilities, making possible for them to be accessed globally and even controlled from anywhere in the world [4, 8, 18].

2.4 Internet of Services

Internet of Services (IoS) refers to new ways of relating to stakeholders, as well as to things, offering new services that can be discovered, hired, used and remunerated online, changing business models.

To Xin and Lai [19] Internet of Services (IoS) consists of services that are provided by the enterprise under the demand of the user, providing the capability of collaboration and interaction in personalized way. Accordingly to Buxmann and Ruggaber [20], it consist of sellers, consumers, users and an infrastructure for services that offer services, under a business model, using the Internet, that can be accessed by the participants via many different channels world-wide.

3 Methodology

We used bibliographic review to study the evolution of the research on Industry 4.0, choosing the proceedings of the International Conference Advances in Production Management Systems (APMS).

The importance of APMS is due to the fact that it is the official conference on production management of the IFIP Working Group 5.7 on Advances in Production Management Systems, which gathers leading experts of industry and academia from all over the world [21]. The study was based on the proceedings of 2014 held in Ajaccio (France), 2015 in Tokyo (Japan), and 2016 held in Iguassu Falls (Brazil). The papers presented in the Doctoral Workshop were not considered in this research. For this research we read the abstracts of all these three publications and selected the ones that made reference to: Industry, 4.0, smart factories, IoT, IoS, smart factory, smart/cloud manufacturing and other terms that could characterize any research on Industry 4.0, not limiting to analyze the papers submitted to the sessions with this specific subject. Table 1 illustrates the quantity of papers analyzed and selected to support this research.

Table 1. Papers analyzed.

APMS Intl. Conf.	Papers analyzed	Papers selected
France (Ajaccio, 2014)	230	4
Japan (Tokyo, 2015)	163	20
Brazil (Iguassu Falls, 2016)	153	15
TOTAL	546	39

4 Findings and Discussion

We identified the countries and university/research center/company that were contributing more to the research on Industry 4.0 at the APMS, based on the first author of each paper, shown in Table 2.

Table 2. Quantity of papers per country per universities/research center/company, based on the first author of each paper.

APMS	Qty. (papers)	Country	University/Research Center/Company
France (2014)	2	Germany	University of Bremen
	2	USA	National Institute of Standards and Technology (NIST)
Japan (2015)	3	New Zealand	The University of Auckland
	2	Germany	RWTH Aachen University
	1	China	Guangdong University of Technology
	1	China	Zhejiang University
	1	China	Wuhan University of Technology
	1	China	Northwestern Polytechnical University
	1	Germany	University of Bremen
	1	S. Korea	Sungkyunkwan University
	1	S. Korea	Pohang Univ. of Science and Technology
	1	Sweden	Teknikföretagen - Assoc. of Mfg. Industries
	1	Sweden	KTH Royal Institute of Technology
	1	USA	Texas State University
	1	USA	Georgia Institute of Technology
	1	Japan	Kobe University
	1	Mexico	Tecnológico de Monterrey
	1	Slovak Rep.	FEI TU of Košice
	1	UK	Cranfield University
Brazil (2016)	3	Norway	NTNU-Norwegian University of Science and Technology
	2	USA	National Institute of Standards and Technology (NIST)
	1	USA	Morgan State University
	1	USA	Penn State University
	1	USA	West Virginia University
	1	USA	IGI, LLC
	1	Germany	University of Bremen
	1	Italy	Politecnico di Milano
	1	Mexico	Tecnológico de Monterrey
	1	Slovak Rep.	FEI TU of Košice
	1	S. Korea	Korea Institute of Industrial Technology
	1	Netherlands	University of Groningen

The research showed that academia uses different terms to refer to Industry 4.0, according to the different countries, as presented in Table 3.

Table 3. Terms used in reference to Industry 4.0 per country.

Term used	Country
Cloud manufacturing	China/Chinese authors, UK
Smart manufacturing	USA, South Korea, Italy
Industry 4.0	Germany, Japan, Slovak Republic, Mexico, Norway
Smart industry	Netherlands
Produktion2030	Sweden
Cloud-based manufacturing	USA[(a)]

[a] We found this term in only one paper from the USA.

We analyzed these 39 papers to find their main areas of study, as shown in Table 4.

Table 4. Subject of study and areas of research on Industry 4.0.

Qty.	Subject of study	Areas of research
9	Architectures	Data flow, industrial gateway, systems
6	Information and communication systems	Implantation, architecture
4	Model/platform	
3	Cyber-physical system	Platform, production control
2	Requirements Engineering (RE)	
2	Software	Components, reconfigurability
2	Human-automation symbiosis	
1	Process modelling	Knowledge share/ways to share it
1	Big Data	Management systems control
1	Digital/virtual manufacturing	
1	Reference-model	
1	System model	
1	Innovation, research and education	
1	Critical issues	
1	Networks of cooperation, manufacturing components	
1	RFID	
1	Industry 4.0 and lean	
1	Automation Technology selection	

4.1 Discussion

We could note the growing interest of academia in Industry 4.0; in 2014 (France) only 2% of the papers dealt with it, in 2015 (Japan) this percentage increased to 12% and maintained in 10% in 2016 (Brazil).

Although we have understood that the evaluation of a leading country or a leading research center is not statistically significant due to the reduced number of the sample chosen, it is useful for presenting a general idea.

The USA was the country with the biggest quantity of papers, 10 in these three Conferences, followed by Germany with 6 in total, China with 4 and 3 papers from New Zealand. The University of Bremen (Germany) and the National Institute of Standards and Technology, NIST (USA) were distinguished with 4 papers each one in the three Conferences, followed by The University of Auckland (New Zealand) and NTNU-Norwegian University of Science and Technology (Norway), with 3 papers each.

The many different terms that academia used as references to Industry 4.0, identified in these 39 papers, confound and difficult new researchers in this field, with each country trying to differentiate a unique concept.

Another point of divergence was about the key components of Industry 4.0. In our research Cyber-physical systems (CPS) and Internet of Things (IoT) were key components accepted by all these authors. No paper dealing specifically with Internet of Service (IoS) was found in the proceedings, considered by some authors as key components [15, 16], although many authors made comments about IoS. Some understood big data and cloud computing as data service, but not an independent Industry 4.0 component [4]; others included them as key components. Smart factories were considered by some as key components [15, 16], while others saw smart factories not as component, but as Industry 4.0 itself.

Enterprise architecture with emphasis on data flow, systems and industrial gateway were the main subject areas of research, followed by information and communication systems, model/platform and cyber-physical system.

The difficult in promoting the integration among the many different physical components and/or the integration of their software were the most common related problems, which may be the reason of the main subject of these papers be related to enterprise architecture, information and communication system and model/platform. Cyber-physical systems were another important topic on Industry 4.0.

One paper addressed critical issues on Industry 4.0 [22]. We would like to propose for a possible "research agenda" of future APMS Conferences on Industry 4.0: the technical and financial implementation analysis of this new manufacturing paradigm, Internet security problems, IoS research, unemployment and training of new technical specialties, as this study did not identify much research in these areas. It would also be interesting to stimulate academia to publish critical papers on Industry 4.0, so that Governments, leaders, researchers and entrepreneurs, could analyze better the pros and cons and evaluate the risks and opportunities of the investments needed to adopt Industry 4.0.

5 Conclusions

The objective of this paper was to study the main points of research on Industry 4.0, featured universities and research centers. For this purpose we analyzed 546 papers that composed the proceedings of the International Conference Advances in Production Management Systems (APMS), in 2014 held in Ajaccio (France), 2015 in Tokyo (Japan) and 2016 in Iguassu Falls (Brazil).

APMS, the official conference of the IFIP Working Group 5.7 on Advances in Production Management Systems, was chosen for being considered one of the most important international conferences worldwide on production management.

The research showed that there was increasing interest of academia on Industry 4.0; the percentage of papers presented at the APMS increased from 2% in 2014 (France) to 12% in 2015 (Japan), maintaining 10% in 2016 (Brazil). USA, Germany, China and New Zealand were the leading countries to present papers on this subject. The University of Bremen (Germany) and the National Institute of Standards and Technology, NIST (USA), presented the major quantity of papers on the three congresses, followed by The University of Auckland (New Zealand) and NTNU-Norwegian University of Science and Technology (Norway).

This study also identified that enterprise architecture with emphasis on data flow, systems and industrial gateway were the main subject areas of research, followed by information and communication systems, model/platform and cyber-physical systems. The research showed that in these 39 papers authors from each country used different terms as references to Industry 4.0, confounding and making difficult initial studies on Industry 4.0.

The limitation of this research was that only APMS Conference papers were analyzed, therefore, for future studies we suggest repeating this research to analyze other international journals/proceedings and if possible study industrial case studies and compare with academic publications, in order to analyze differences in focus areas of academia and industry.

We would like to suggest also that critical papers on Industry 4.0 could be stimulated, so that entrepreneurs, leaders, Governments and researchers could better analyze the pros and cons and evaluate better the risks, benefits and opportunities to adopt Industry 4.0. We hope that the results of this research can be useful for decisions of IFIP WG 5.7 and for the organization of future APMS Conferences, such as topics in call for papers.

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Production Internet - Functional Perspective

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Abstract. Production Internet as an eco-systemic Web-based infrastructure goes beyond the traditional setups of industrial cooperation, as well as existing peer-to-peer services for economic exchange, like e-tailing, e-sharing or crowd-funding. This paper investigates the feasibly functional arrangements of Production Internet. Throughout reflection on the state-of-art, supplemented by a foresight research, the needs, requirements and benefits are identified then composed into functional setting, which was validated using a prototype implementation. The discussed conceptualization is expected to improve operational effectiveness, efficiency of resources, and reduce transaction costs.

Keywords: Production internet · Collaborative networks · Cloud manufacturing · Production ecosystems · Supply chains · Smart manufacturing · Web-services

1 Introduction

The industries are growingly exposed to openness and networking. The major drivers of this megatrend are globalization and ICT developments. The first eco-systems built upon Internet capabilities like Alibaba or Facebook, exhibit strong and global impacts in their domain of operation. The key Web-based eco-systemic developments are coined together as the Seven Internets [12]. Some of them, like the Logistics (Physical) Internet [7] and Production Internet [12] are still rather concepts, than a reality. The latter one, which is expected to provide a new economic and organizational momentum to the globally networked industries, is investigated in this paper.

Production Internet goes beyond the peer-to-peer based Web-services for economic exchange: e-tailing, crowd-funding, e-sharing, etc. The breaking innovation is by support of structured workflows of products/services, and also by automated matching of demands and resources. The rise of Production Internet is conditioned by particular technologies. The most vital are Web services and semantic technologies [2]. The other important are: multi-agent systems, smart technologies and CPS, cloud computing, and Service Oriented Architectures (SOA). By alignment of capacities and demands of collaborating parties, Production Internet departs from the existing forms of buyer-supplier relationships, like markets, supply chains or partnerships.

The focus of this paper is on functional development of Production Internet, while technology aspect is treated secondarily. The core functions of Production Internet are

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built around qualitative and quantitative fits of products and services with resources, along demand flows.

The paper is organized as follows. The next section reviews the state-of-art: drivers of industrial networking, developments of ICT, and Internet solutions which herald the Production Internet. Section 3 introduces the foresight research and presents key findings. Section 4 discusses the most promising uses and users, and the expected benefits. Section 5 projects functional specification for the beginning and prototype developments. Section 6 reports the prototype implementation, which was primarily intended to validate the concept, and enable future experimental research. Section 7 summarizes the paper and reflects on further research and development.

2 State-of-Art

This section reflects on existing theories of industrial networking, and available ICT aids. This way the starting point for Production Internet development can be learned.

The strategic importance of ICT to support industrial networking is determined by possible benefits, mostly in terms of competitive advantage and economic performance. The industrial networking follows a variety of archetypes, ranging from traditional market supply to novel forms of virtual collaboration. With this regard the theoretical basis for adoption of ICT support can be viewed by the lenses of the five established theories. The resource based view centers on the offering of capacities and capabilities as the source of competitive advantage [1]. In this view ICT is expected to support performance of resources. The transaction costs theory focuses on governance structures of economic exchange [14]. Herein ICT can be viewed as a mean to reduce transaction costs of searching contractors, bidding, etc. The relational view seeks competitive advantage in inter-organizational relationships [3]. Therefore the strategic role of ICT can be seen as facilitator to relationships management. The dynamic view focuses on organizational capabilities to rapidly and smoothly adapt, reconfigure, integrate and extend resources and abilities, in response to changing requirements and needs [13]. Similarly, ICT can be viewed as enabler and facilitator to dynamic capabilities. The resource dependence theory considers uncertainty due to utilization of resources of other firms [8]. Accordingly the role of ICT is to aid ability of an organization to control or limit the dependence on others resources. The concept of Production Internet apparently responds to all established theories of industrial networking.

The existing ICT solutions and technologies that can support industrial networking, which typically take the user-company perspective, are represented by variety of systems and technologies [4, 5, 9, 11]: ERP1, ERP2, EAI, ERP adapters, SCM, DRP, CRM, WMS, TMS, ECR, CPFR, EDI and I-EDI, mobile & tracking technologies (M-CRM, RFID, PDA et al.), Web services, Semantic Web, grid computing, cloud manufacturing, cloud-ERP, knowledge-based systems, ontologies, intelligent agents. If the existing systemic solutions offer any capacity to consider structures of products or services, it is by proprietary systems used within a rigid setting of cooperation. Centrally maintained data structures are used in such cases to represent products or services [10]. Otherwise the coordination is operated on transaction basis: B2B, B2C, O2O etc. The existing systems typically use classic triggering mechanisms to coordinate inter-organizational operations, like replenishment or pull flows. The offerings of products, services and resources to external parties are typically given as specified items (catalogues). Qualitative characterization with this regard is not yet exploited. Although the recent concept of cloud manufacturing hypothetically provides a significant potential to support the development of Production Internet, it still remains rather a research topic discussed at high level, and mostly from architectural and technology point of view [4]. However some Web services emerging in China and USA clearly anticipate the rise of Production Internet and can be viewed as its heralds. All of them represent the megatrend coined as sharing or access economy, which concerns such economic arrangements, in which the participants open and mutualize the access to resources, products and services, rather than exploit advantages of ownership. The representative examples are: Alibaba/Taobao as ecosystem for clients, manufactures, sellers and forwarders; CreditEase as platform for peer-to-peer lending and microfinance; Groupon as demand bulking service; Covisint as auctioning platform to purchase standard products; Zuora as demand subscription service; NetSuite OneWorld as cloud service for multi-company management of resources; Kickstarter crowdfunding platform as demand, supplies and funds amalgamation service; Cybernauts as platform to support start-ups, alliances, joint ventures, and similar, to integrate the entrepreneurs and venture micro-capital. Although the listed solutions exhibit a reach variety of networking services, they do not go beyond the limits of peer economy, and follow the integration patterns of online market places, or proprietary platforms. Nevertheless, they clearly indicate the probable directions of functional development.

3 Foresight Research

This section reviews the foresight research of Production Internet. The key aim is to identify the most probably functional developments, considering the needs and requirements of potential users. The expert panel involved: Web-services providers (Taobao, Cybernauts, Haozhuanye, Alo7), technology providers (Huawei, SAP), ICT venture capital (KnowledgeHub), consultancy (Accenture), and professional societies (Crowdfunding World Championship Council). The semi-structured interviewing and brainstorming was run in a face-to-face mode, mostly virtually. A set of questions was provided in advance then used to lead interviews, supplemented by other direct, indirect, and ad hoc questions. Following topics have been centered on: (i) new forms of inter-organizational collaboration in terms of: services/processes; structures; coordination principles; patterns of demand, service, and resource offerings; (ii) heterarchical, distributed and herd control of operations; (iii) new functionalities; (iv) knowledge and cognitive supports, semantic networking, knowledge management; (v) trust and credibility management; (vi) most promising patterns of deployment; (vii) benefits. All interviews were documented, and in most cases recorded. The suggestions of panelists were just plainly compiled, while opinions were not weighted.

The leading findings from the research can be condensed as follows:

1. Production Internet should firstly focus on manufacturing, stock keeping, forwarding and selling activities, as well as related coordination. These should be gradually supplemented by a variety of support services: (1) trust, reliability, and credibility management; (2) bidding; searching, discovery, and matching of various offerings and demands, both in qualitative and quantitative way, and considering spatiotemporal aspects; (3) tracking demand, work and material flows, payments; (5) management of legal responsibility; (6) confidentiality management; (7) funding;
2. Final clients, manufacturers, and forwarders are recognized as the key actors along the beginning developments of Production Internet;
3. The bills of materials/processes based coordination, and using relational databases is assessed as ineffective in large scale environments by most experts; novel forms of demand should be considered, especially by going beyond the 'due date-due quantity' concept, and avoiding schedules based coordination;
4. Distributed and heterarchical modes of coordination should be further explored;
5. Robotized decision making, using cognitive abilities, should be investigated to overcome the shortcomings of human decision making (e.g. due to the asymmetric perception of risk, herd behavior, learning and forgetting asymmetries); other supports, like business intelligence, Big Data, could be also considered in the future;
6. Recognizing regional and overall characteristics of ecosystems, like states or phase transitions (e.g. in reference to changing loads or variability characteristics), to facilitate and modify the ongoing coordination of flows, should be investigated;
7. Interacting with the existing legacy/local systems should be considered.

The suggestions of experts can be also synthesized into an evolutionary pattern indicating the main directions for functional development of Production Internet (Fig. 1).

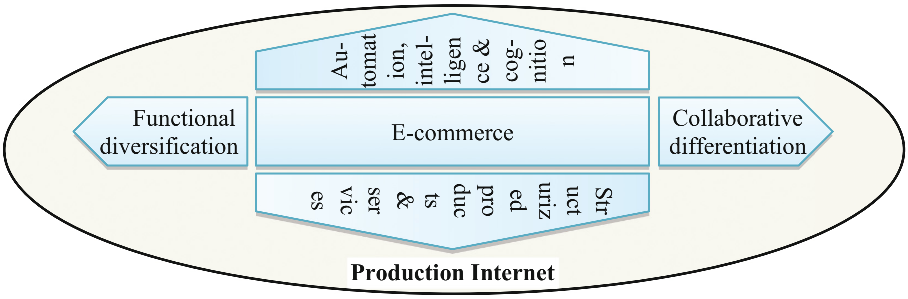

Fig. 1. Evolution towards Production Internet – main directions

Experts suggest E-commerce ecosystems (Alibaba/Aliexpress) as a starting basis to develop the Production Internet. The prior breaking innovation should be consideration of products and services as structurized items. This grounding development shall be followed in a twofold way by functional diversification, i.e. by adding consecutive functions (as listed before), and collaborative differentiation, i.e. by adding new actors and forms of networking. The crowning of Production Internet will be throughout progressive enrichment with automation and artificial intelligence, including the autonomous cognition. Some experts suggest that bio- or eco-mimicking intelligence to maintain homeostasis of production ecosystems could be innovated with this regard.

Other results of this research are also referred and exploited in the further sections.

4 Dissemination and Benefits

The research introduced in the preceding section has also identified a range of success factors for the extensive dissemination of Production Internet. It was done by projecting the most probable uses and users, in terms of their characteristics, needs, requirements, and expected benefits. The factors for successful dissemination of Production Internet, as suggested by experts, are listed in Table 1. Although some of them are not strictly independent, they were weighted separately by 1 ÷ 10 scale (lowest to highest).

Table 1. Key factors for successful dissemination of Production Internet

No.	Factor	Av.weight
1	User is a small party (SME)	10
2	Very low to medium repetitiveness & volume of flows	9,5
3	Low investment to enter transaction or collaboration (equipment, etc.)	9
4	High variability of flows	9
5	Sourcing effort high to medium	9
6	Many sourcing options	8,5
7	Customized products (assembly- to engineer-to order)	7,5
8	No requirements for certifications	7,5
9	Low or moderate complexity of flows	7,5
10	In-house or outsourced design	6,5

From the above view we can conclude about the most probably uses and users of Production Internet. It should be primarily attractive to such SMEs, who offer customized products (ATO to ETO) at low volumes, rather in a non-repetitive mode, and for whom the sourcing effort and transaction costs are important. Other factors of susceptibility are variability, low or moderate complexity flows, no requirements for certifications, and no need for shared design.

The research panel has also identified the most important and distinctive advantages, which can result from using the Production Internet:

- Increased visibility of offerings; hence improved efficiency of owned resources;
- Improved operational performance (lead times, inventory turnover, productivity, flexibility); increased capital turnover; overcame economy of scale;
- Easy and fast matching of offerings; hence, reduced transaction costs;
- Reduced and optimized dependence on resources of other firms;
- More synergies due to exploitation of complementary and distinctive resources;
- Improved changeability and reduced need for changeability.

Apart of the benefits to users, which interestingly correspond with all theories of industrial networking discussed in Sect. 2, the overall impacts on economy, society and environment, were also appreciated by the panel, like e.g.: improved efficiency of the whole economy; increased capital turnover; less wasteful economy; tamed powers of spatial concentration of economic activities due to improved opportunities for localized and distributed economic activities; increased welfare; more inclusive and sustainable economy; improved eco-friendliness (reduced emissions, pollution, etc.).

The above reviewed findings made by the research panel provide a sound argument in favor of dissemination of Production Internet, and suggest the most prospective uses and users. As the technological barrier in terms of ICT does not actually exist, it is only a matter of time before arise of the first Production Internet platform.

5 Functional Specification for Prototyping

This section lists the functionalities that are most likely offered by first implementations of Production Internet, to be included in the prototype development. They were directly concluded or detailed from the before reported results of foresight, as well as from the functional analysis of only existing eco-systemic platform for E-commerce, i.e. Aliexpress. They are:

1. Offering and processing of structured demand (products/services);
2. Offering of resources (processing, warehousing, forwarding);
3. Credibility assessment and conditioning (including reliability and trust);
4. Qualitative, quantitative and spatiotemporal matching of demands and provisions;
5. Demand (orders, subscriptions, schedules) and orders processing; orders tracking;
6. Operational coordination of material, work and information flows (based firstly on ordering and pull flow principles, VMI, and to limited extend on pull flows);
7. Product and process information management;
8. Discounting, bidding, auctioning;
9. Claims and returns management;
10. Payments management.

It was presumed, following the opinions of research panel, that the first users will be final clients and the bidders of products, resources or manufacturing services.

6 Prototype Development

This section reports a prototype development of Production Internet. It is mainly aimed to enable experimental research and educational use. Another purpose is to validate the concept of Production Internet.

The development is based on multi-agent systems [6] and ontology engineering [11]. The multi-agent environment provides capacity for mimicking Web services and Web-based interactions [6]. Additionally it provides a setting for the Service-Oriented Architectures and cloud-based infrastructures [6]. It was also considered as the initial mean to automate coordination activities. The prototype implementation was made using the GAIA based conceptualization, and JADE, WADE and WOLF toolkits.

For the prototyping purposes distributed ontologies were assumed as the only mean to process data and knowledge [11]. The ontology for discussed development was elaborated by adaption of the TRANSFORMERS ontology for manufacturing and logistics, which was elaborated before at Warsaw University of Technology [11]. All interacting agents (robots) are equipped with own operational ontologies.

A layered architecture was assumed for the prototype development. The main function of the bottom layer, i.e. 'transaction layer', is to process offerings. Two types of robots are employed herein: (i) 'propositioning robots' handle the offerings; (ii) 'transaction supervisory robots' manage all services related to the use of resources, fulfillment of internal orders, receiving, and forwarding. This layer interfaces users, resources, as well as real processes.

The upper layer, i.e. the 'brokerage & coordination layer' incorporates the whole collectivity of robots that align demands and offerings. Their key roles consist in spatiotemporal matching of products, resources, services and demands. The robots compose structures of products, and then processes to enable planning and operation of indispensable services. The transformational approach is applied to explode and aggregate demands, then processes, following the approach of transformational paradigm [6]. This way the whole spatiotemporal mereotopology of demands, processes, and resources can be operated in a coherent and homogenous manner. The 'brokering robots' match demands, resources and services, while the cohort of 'balancing robots' leverage the traffic of flows, considering utilization and synchronization aspects.

As yet only two above layers have been implemented. The 'homeostasis layer' takes an aggregate view of operations, and focuses on the overall balance of loads and flows, i.e. as viewed within the whole ecosystem. It concerns blockings and jams that can be brought about by temporal overloads of manufacturing or forwarding capacities, or alternatively by delimited material and resource supplies. The products and resources are roughly cut into qualitative and spatial categories to anticipate the temporal overloads and jams. Alternative streaming of flows can be then advised by 'streaming robots' to the balancing robots. The role of this layer analogizes the aggregate planning, and also follows the idea of adaptive control.

The top layer, i.e. the 'layer of evolution' considers the self-adoption of Production Internet following the concept of autonomous cognition. New behavioral patterns can be self-learned with regard to the observed changes, e.g. in terms of variability, mix of services, and similar. The change can be implemented by embedding new behavioral rules into the knowledge of robots operating in the lower layers. Although at the first glance this kind of capabilities may be viewed as futuristic, actually the available cognitive technologies enable its implementations, at least in some interesting areas, like e.g. the widespreading of newly learned rules of allocating demands and services into the knowledge bases (ontologies) of balancing and streaming robots.

As yet the initial prototype development employs a limited scope of functionalities, namely the first seven of listed in Sect. 6. It does not pay attention to the scalability. This kind of approach can be justified by the focus of the first development on functional aspects, and with this regard – on discovery of particular issues that can be faced in the future along the further development of the Production Internet.

7 Summary and Future Work

This paper investigates the possible functional settings of Production Internet. Throughout reflection on the state-of-art, supplemented by a foresight research, the needs and benefits were identified then composed into functional conceptualization, which was validated using a prototype development. The eco-systemic solutions of Production Internet should significantly limit the shortcomings of existing economical institutions, especially by improved operational efficiency, increased sharing and better utilization of resources, improved transaction costs economics, and finally by improved economic performance of economic exchange.

The future research should explore full scope of functionalities and networking. The deployment of cognitive abilities could be another important extension. Other aspects, like scalability, interoperability, also provide challenges to the further work.

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Repair Crew Scheduling Considering Variable Disaster Aspects

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Abstract. Human beings have suffered from disasters continuously, therefore, the post-disaster efforts to reduce additional damages have been widely conducted. In this study, we focused on the repair crew scheduling to set a plan for repairing destroyed roads. Rural areas were considered because of limited link members of supply chain networks, and rural isolation caused by road destruction is the main concern of this study. To reflect the intrinsic nature of a disaster in the short-term, additional damages and variable damage rates were considered. The repair crew scheduling problem considering variable disaster aspects was proposed to minimize total damages caused by isolation. A small-scale experiment was conducted and the result showed that our model can be used to effectively reduce further damages compared to previous research.

Keywords: Repair crew · Humanitarian logistics · Relief scheduling · Mixed integer program

1 Introduction

Human beings have long suffered from catastrophes such as natural or man-made disasters. During the post-disaster period, disaster damages prevent rapid relief activities and it is generally complicated to recover damages [1]. Among disaster damages, especially in rural areas to which accessible routes are limited, road destruction is significantly fatal because roads are not only social support routes but also the supply routes for relief goods [2, 3]. Yan and Shih [2] focused on network repair and distribution of relief goods simultaneously. In the follow-up paper [4], they developed an ant colony system (ACS) algorithm to compensate for the limitations of previous studies. Duque et al. [5] developed the network repair crew scheduling and routing problem (NRCSRP) to minimize the weighted sum of total times for relief in isolated disaster areas.

However, previous research about repair planning has mainly focused on reducing the time to supply relief goods or initial relief without considering variable characteristic of the short-term situation. In the short period in post-disaster, damage conditions vary depending on types of disaster and recovery situations. For example, earthquakes cause not only immediate damages but also additional damages that develop over time [2, 6]. Damages also differ by type of disaster and the conditions where it occurs. Particularly

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in cases of casualties, appropriate action is required within a specific timeframe to prevent further damages. For these reasons, we developed a repair crew scheduling problem by extending the work of NRCSRP [5]. We propose the repair crew scheduling problem considering variable disaster aspects (RCSPVDA). We assumed that the damage patterns in different isolated areas follow different damage functions, and that a single supply hub and a single repair crew are assigned to all sites in the area. This model minimizes the sum of total damages caused by isolation conditions.

This paper is organized as follows: Sect. 2 introduces the repair crew scheduling problem and Sect. 3 illustrates the mathematical formulation. Section 4 presents the example of a small size problem. We provide a conclusion on this study in Sect. 5.

2 Model Description

The model follows the definition similar to that provided by Duque et al. [5], and the mathematical formulation is based on that introduced by Duque et al. [7]. The road network is defined as an undirected network, $G(V, E)$. V is defined as a node set that includes damaged node set, V_r, and isolated node set, V_d. We assume that damaged nodes should be repaired by the repair crew. Passing through damaged nodes is impossible without repair. For damaged node $i \in V_r$, it take s_i unit times to repair. After repair, the node functions as a normal node. Without loss of generality, the definition of damaged nodes includes both destroyed roads and damaged areas. Before isolation conditions are resolved, victims in inaccessible areas are afflicted with lack of necessaries. Two main factors were considered to analyze total damages of isolated areas: (1) disaster damages from the initial and following disasters, (2) isolation damages caused by lack of accessibility preventing relief activities.

To consider the variable aspects of disasters in node $i \in V_d$, which is the main contribution of our study, we considered the golden time, g_i. The golden time is a given time bound within which an appropriate responsive management should be conducted. For instance, the golden time includes the last time to avoid additional disasters or to save lives from critical injuries. It is assumed that the golden time of each node is known. In addition, one-to-one correspondence between the golden time and an isolated node is assumed. If an appropriate action is not conducted to an isolated node until the golden time, extra disasters deteriorate the isolated node. Direct physical damages from disasters are denoted as p_i, such as earthquake or tsunami. As time goes by without being treated, we assume the damage increases linearly, but the rates of increment are different before and after the golden time. We assume that the damage rate before the golden time, w_i^1, is less than or equal to the damage rate after the golden time, w_i^2. Figure 1 illustrates cumulative damages before and after the golden time. Focusing on the discontinuity of the first graph, we can see that it implies the occurrence of the additional disaster after the golden time. The second graph shows the change of the damage rate after the golden time.

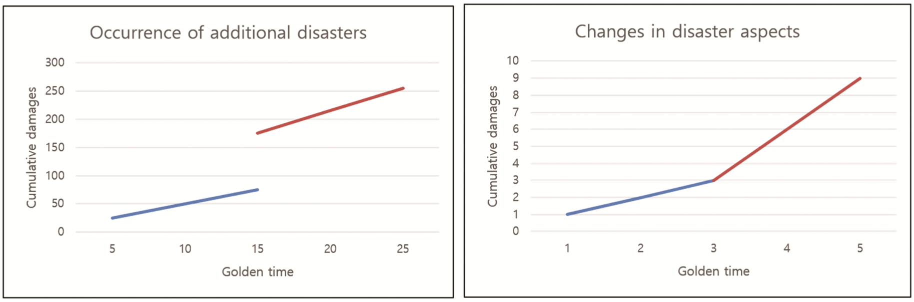

Fig. 1. Examples of cumulative damages with varying disaster aspects.

A supply hub denoted by *ss* is an origin node in which a repair crew begins his or her activities. Destination Node *sd* is a dummy node which indicates the repair crew has completed tasks; if the repair crew reaches the destination node, it implies that all the plan of the repair crew has been done. Figure 2 represents an instance of a network with damaged nodes. It takes t_{ij} unit times for the repair crew to move from node i to node j, depicted between nodes in Fig. 2. The apparent structures of the original and model networks are not the same because damaged arcs in the original network were converted into damaged nodes in the model network. For example, Nodes 5 and 7 in the model network are identical to the damaged arcs in the original network. Depending on the conditions of nodes around, the undamaged nodes can be either accessible from the supply node or not. When all links of a node are damaged, the node is in isolation.

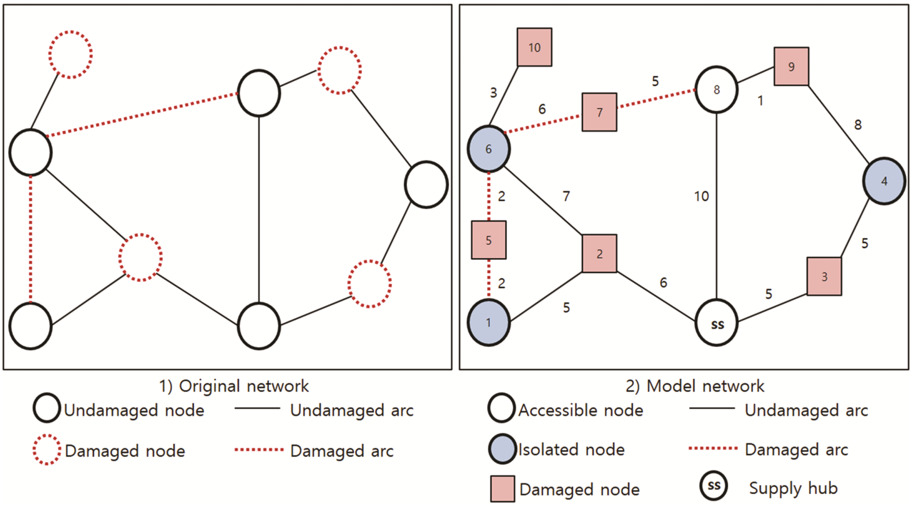

Fig. 2. Example of a damaged road network.

3 Mathematical Formulation

Additional definition of sets, parameters, and decision variables are as follows:

Sets

A Set of damaged node pairs (i,j); logically possible sequences of repairing nodes; $\forall i \in V_r + ss, \forall j \in V_r + sd, (i,j) \neq (ss, sd)$

Parameters

s_i Repair time for damaged node $i, \forall i \in V_r$

F_i Parameters for calculation; cumulative damage differences before and after g_i in node $i, \forall i \in V_d$; $F_i = p_i + g_i \cdot \left(w_i^1 - w_i^2\right)$

Decision variables

x_{ij} 1, if a repair crew repair moves to node j after repairing node $i, \forall (i,j) \in A$
0, otherwise

r_{kl}^{ij} 1, if a repair crew moves from node k to node l when a repair crew moves to node j after finishing repairs at node $i, \forall (i,j) \in A, \forall k, l \in V$
0, otherwise

a_k^{ij} 1, if a repair crew passes node k when a repair crew moves to node j after finishing repairs at node $i, \forall (i,j) \in A, \forall k \in V_k, k \neq i \neq j$
0, otherwise

y_{kl}^j 1, if isolated node j, is linked to a supply chain with road from node k to node l, $\forall j \in V_d, \forall k, l \in V$
0, otherwise

b_k^j 1, if isolated node j, is linked to a supply chain with passing node $k, \forall j \in V_d, \forall k \in V$
0, otherwise

c_i 1, if additional disasters occur in node $i, \forall i \in V_d$
0, otherwise

z_i Time when node i is repaired, $\forall i \in V$

u_i Time when isolated node i is linked to the supply chain, $\forall i \in V_d$

v_i Time when a repair crew arrives at damaged node i before it is repaired, $\forall i \in V$

d_i Total damages in node $i, \forall i \in V_d$

We include a part of our formulation, and the formulation was based on the previous research [7]. The mathematical formulation is as follows:

$$\begin{aligned} &Minimize \sum\nolimits_{i \in V_d} d_i \\ &Subject\ to \end{aligned} \tag{1}$$

$$\sum_{i \in V} x_{ssj} = 1 \qquad (ss, j) \in A \tag{2}$$

$$\sum_{i \in V} x_{isd} = 1 \qquad (i, sd) \in A \tag{3}$$

$$\sum_{i \in V,(i,j) \in A} x_{ij} = \sum_{k \in V,(j,k) \in A} x_{jk} \qquad \forall j \in V_r \tag{4}$$

$$\sum_{i,j \in V,(i,j) \in A} x_{ij} = |V_r| + 1 \tag{5}$$

$$\sum_{k \in V} r_{kj}^{ij} = x_{ij} \qquad \forall i, j \in V, (i,j) \in A \tag{6}$$

$$\sum_{k \in V} r_{kj}^{ij} = x_{ij} \qquad \forall i, j \in V, (i,j) \in A \tag{7}$$

$$\sum_{k \in V} r_{kl}^{ij} + \sum_{m \in V} r_{lm}^{ij} = 2 \cdot a_l^{ij} \qquad \forall i, j, l \in V, (i,j) \in A,\ l \neq i \neq j \neq sd \tag{8}$$

$$z_i + \sum_{k,l \in V} t_{kl} \cdot r_{kl}^{ij} + M \cdot \left(x_{ij} - 1\right) \le v_j \qquad \forall (i,j) \in V, (i,j) \in A \tag{9}$$

$$v_i + s_i = z_i \qquad \forall i \in V_r \tag{10}$$

$$z_k + M \cdot \left(b_k^i - 1\right) \le u_i \quad \forall i \in V_d, \forall k \in V_r \tag{11}$$

$$z_k + M \cdot \left(a_k^{ij} - 1\right) \le z_j \qquad \forall i, j \in V, \forall k \in V_r, (i,j) \in A \tag{12}$$

$$u_i - g_i \le M \cdot c_i \le M + u_i - g_i \qquad \forall i \in V_d \tag{13}$$

$$w_i^1 \cdot u_i \le d_i \qquad \forall i \in V_d \tag{14}$$

$$w_i^2 \cdot u_i + F_i + M \cdot \left(c_i - 1\right) \le d_i \qquad \forall i \in V_d \tag{15}$$

The objective function (1) minimizes the sum of total damages in isolation. Constraints (2) to (5) define the flow of the repair crew. Constraints (6) to (8) denote the routes of the repair crew. Note that flow constraints related to isolated nodes are excluded because they are similar to those of the repair crew. The detailed information can be referred to [7]. Constraint (9) restricts the arrival time of the repair crew to the next damaged node and Constraint (10) denotes the time to finish repairing a damaged node. Constraint (11) ensures the time to link an isolated node i to other nodes. Constraint (12) enforces the time sequence to repair a damaged node. Constraint (13) ensures the case which an isolation time of node i is greater than the golden time. Constraints (14) and (15) denote total damages when an isolated time of node i is less or greater than the golden time, respectively.

4 Small-Scale Example

A small-scale example and solution is presented to help explain the proposed model. We used the same network shown in Fig. 2. Ten nodes are in the network; however, we need to add a dummy node, *sd*. For this reason, the network node set is $V = \{0, \ldots, 11\}$. Nodes 2, 3, 5, 7, 9, and 10 are damaged nodes, therefore, $V_r = \{2, 3, 5, 7, 9, 10\}$. In addition, Nodes 1, 4, and 6 are isolated nodes; $V_d = \{1, 4, 6\}$. We set the repair times for damaged nodes as 6, 5, 3, 2, 7, and 4, respectively. Likewise, we also set parameters related to isolated nodes as follows: $w_i^1 = \{5, 3, 2\}, w_i^2 = \{6, 5, 3\}, p_i = \{0, 100, 0\}$, and $g_i = \{20, 25, 15\}$. To explain the difference between the NRCSRP and the RCSPVDA, experiments were conducted under the same conditions. However, the NRCSRP did not take into account w_i^2, p_i, and g_i. Therefore, the solution for the NRCSRP may not be competitive if disaster rates are different before and after the golden time. The damaged nodes directly related to isolation damage are 2 and 3. Therefore, the problem is the same as if we were prioritizing the two nodes. After repairing these two nodes, which means that the isolated nodes are linked to the supply chain, the way to repair the remaining damaged nodes is arbitrarily chosen because the choice of order does not cause additional damages.

The optimal routes of the NRCSRP was 0-2-0-3 and that of the RCSPVDA was 0-3-0-2. The detailed results of the experiment in terms of damages caused by isolation are presented in Fig. 3. Under static damage conditions, the solution of the NRCSRP is logical because repairing damaged Node 2 links isolated Nodes 1 and 6 to the supply chain, and the sum of their damage rates is 7, which is larger than the damage rate of isolated Node 4. The repair crew arrived to Node 2 at time 6, and it took 6 unit times to repair the node. Therefore, both isolated Nodes 1 and 6 were linked to the supply chain at time 12, and the cumulated damages were 120 ((5 + 3 + 2) × 12). The operation of the repair crew was ended after linking Node 5 to the supply chain at time 28 with the total damages 168 (120 + 16 × 3). On the other hand, under the routes 0-3-0-2, Node 5 was linked first at time 10, and then, Nodes 1 and 6 were linked at time 27. The total damages of the routes 0-2-0-3 (168) were much lower than that of the routes 0-3-0-2 (219). In contrast, under variable disaster conditions, the situation can be the opposite as those of the static situation. Although the damage rate in the isolated Node 4 was lower than the sum of damage rates of the others, the isolated node has the highest priority because additional detrimental events were predicted that would be unavoidable unless the node was treated first. It can be seen that cumulative damages dramatically increased at time 25 under the routes 0-2-0-3, and direct disaster damages could be avoided under the routes 0-3-0-2 with relatively high isolation damages; the isolation damage rate of Nodes 6 and 1 increased at times 15 and 20, respectively. Therefore, the routes of the repair crew schedule in the RCSPVDA was 0-3-0-2. As a result, the total damages of the NRCSRP is 274 and those of the RCSPVDA is 238, showing that consideration of variable disaster aspects can help reduce further damages.

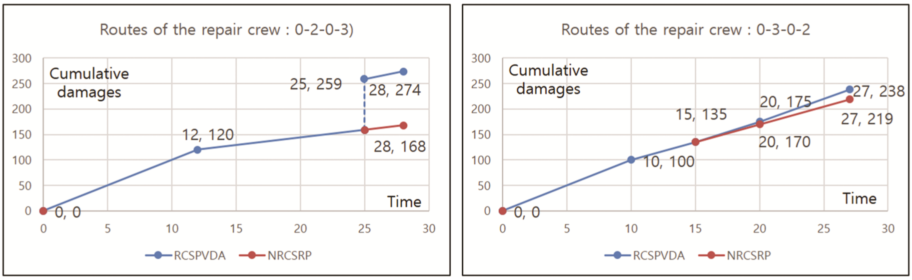

Fig. 3. Cumulative damages with respect to operation time in different routes.

5 Conclusion

We introduced a repair crew scheduling problem considering variable aspects of disasters. We assumed that disaster aspects in each isolated area can be changed after a certain time, and this point is the main contribution of our study. A repair crew who leaves at a supply node was delegated to minimize further damages in the post-disaster period. The small-scale example showed that the RCSPVDA can be effectively used to reduce disastrous damages. However, the mathematical model is limited to solve small-scale problems because of the complexity problem. Therefore, developing efficient heuristic algorithms are interesting research topics.

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Product and Asset Life Cycle Management in Smart Factories of Industry 4.0

An Approach to Development of System Architecture in Large Collaborative Projects

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Abstract. Innovation projects in manufacturing domain often include several end users with different use cases that require a special approach for converging to one architecture solution, which addresses the needs of all end users. The communication between end users and developers in different research and software development projects should be supported correspondingly. This paper describes an approach to development of software intensive system architecture in large collaborative projects that extends traditional approaches with different architecture viewpoints and additional iterative steps aiming to design a main platform integrating project solutions. The approach is applied and validated in a large collaborative EU-funded H2020 research project entitled Z-Factor, i.e. Zero-defect manufacturing strategies towards on-line production management for European factories. Based on the standard ISO/IEC/IEEE 42010 that implies a process based on a set of relevant architecture viewpoints and following the architecture development approach introduced in this study, Z-Factor platform is defined by the following viewpoints: conceptual, functional, information, and deployment.

Keywords: Software engineering · System architecture · Collaborative projects · Manufacturing

1 Introduction

In today's complex world of IT, business and manufacturing, innovation may often emerge thanks to the involvement in research and development projects of heterogeneous and interdisciplinary teams whose members are coming from different backgrounds and expertise [1]. Such projects should accommodate both the diverse user needs as well as the various interests and goals of the team development members. The communication between end users and developers in different research and software development projects should be supported correspondingly [2]. This paper describes an

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approach to development of software intensive system architecture in large collaborative projects that extends traditional approaches with different architecture viewpoints and additional iterative steps aiming to design a main platform integrating project solutions. The approach is applied and validated in a large collaborative EU-funded H2020 research project entitled Z-Factor [3]. Based on the standard ISO/IEC/IEEE 42010 that implies a process based on a set of relevant architecture viewpoints and following the architecture development approach introduced in this study, Z-Factor platform is defined by the following viewpoints: conceptual, functional, information, and deployment.

2 Approach to Development of System Architecture

Figure 1 shows the architecture development approach.

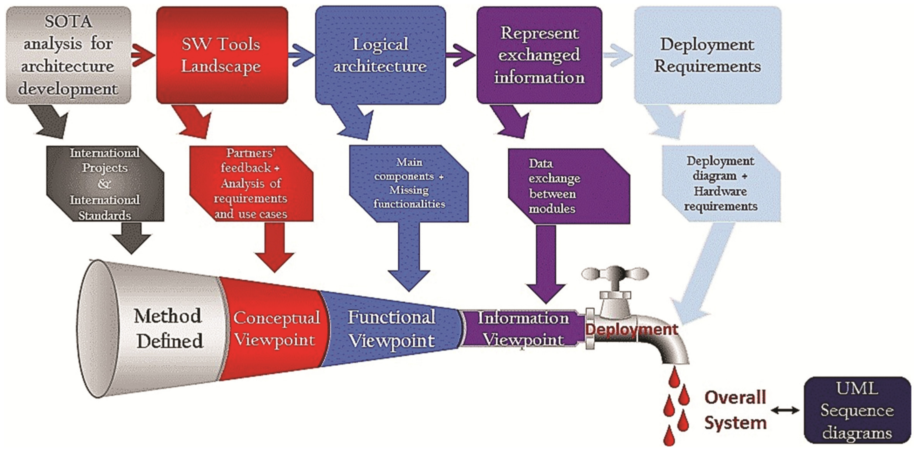

Fig. 1. Architecture development approach

In the State of the art (SOTA) analysis step, relevant large collaborative projects and international standards are analyzed from a system and architecture perspective in order to (i) define the architecture development method, and (ii) identify critical aspects for the system architecture that should be taken into account.

The design of the main system architecture is carried out based on the knowledge and insights from relevant international projects, and the documentation of the architecture is based on the standard ISO/IEC/IEEE 42010 (2011) "Systems and software engineering — Architecture description" [4]. This standard establishes a methodology for the architectural description of software intensive systems. The standard implies a process based on a set of relevant architecture viewpoints, and in this study we consider four viewpoints, i.e. conceptual view, functional view, information view, and deployment view.

The System Architecture of the main platform is described starting from the high-level architecture and tools' description down to the definition of data flow and tools' inner structure. The architectural description includes aspects related to the identification of the major system components, how they should interact and how their external interfaces should be defined.

The first high-level description that leads to the definition of System Architecture consists in identifying and classifying all the tools presented in what can be called the software tools' landscape, i.e. the conceptual view. The conceptual architecture provides an overview of the tools along with their dependencies and affiliation to the responsible leading partners. In this step, project documents, partners' feedback and the input from the analysis of the project requirements and use cases play an important role.

In the functional view the components, their functionality, and their interactions are described. Functional viewpoint contains all the functions that the system performs and the responsibilities as well as interfaces of the functional elements with respect to the relationship between them. These functions are described using UML diagrams. In this step, a first version of the functional architecture is defined by (i) identifying the technologies and software modules to be provided by the project partners, and (ii) thinking of and identifying the missing modules and functionalities which are required for the implementation of the main platform and that will be developed and integrated along the project. Following this description of the main functional view, all technology partners provide a detailed description of the expected inputs, generated outputs and main functionalities as well as the component diagrams for each tool.

In the next step, a schema is provided to represent the exchanged information between the envisioned components. The information view describes the application domain models and the data flow as well as the distribution. Finally, the deployment requirements are collected from the partners and deployment diagram is designed accordingly. The deployment view describes how and where the system will be deployed, which physical components are needed, as well as the dependencies, hardware requirements and physical constraints. Finally, UML sequence diagrams designed for each use case should clarify how the platform will work and which components are relevant to achieve different tasks. The final system architecture thus represents a key cornerstone in setting the basis for the successful deployment of future project results by providing the means for their harmonization in a coherent infrastructure.

3 Implementation of the Approach in Z-Factor

The EU H2020 Factory of the Future (FoF) project Z-Factor focuses on Zero-defect manufacturing strategies towards on-line production management for European factories. The Z-Factor Platform and solution introduce five multi-stage production-based strategies targeting (i) early detection of the defect (Z-DETECT), (ii) prediction of the defect generation (Z-PREDICT), (iii) prevention of defect generation by recalibrating the production line (multi-stage), as well as defect propagation in later stages of the production (Z-PREVENT), and (iv) reworking/remanufacturing of the product, if this is possible, using additive and subtractive manufacturing techniques (Z-REPAIR), and finally (v) management of the aforementioned strategies through event modelling, KPI (key performance indicators) monitoring and real-time decision support (Z-MANAGE). Accordingly, Z-Factor architecture will encompass the design and development of a diverse set of technologies with different specifications and requirements aligned with these 5 main Z-Factor strategies. Consequently, the Z-Factor Platform will be demonstrated in three different pilots belonging to the three end users (i.e., Microsemi, Interseals, and Durit), where each one targets at different aspect of the operation and activities.

Following the logic of the Z-Factor platform design and development, in the following subsections we develop the Z-Factor system architecture which comprise four different architecture viewpoints (i.e. conceptual, functional, information, deployment).

3.1 Conceptual Viewpoint

The first high-level description that led to the definition of the System Architecture consisted in identifying and classifying all the software tools to be developed in Z-Factor. In this step of the architecture development, we collect and categorize the technologies and software components that the individual partners of the Z-Factor project brought in with them. In addition, the partners' expertise has been quickly identified and used as best as possible in this first process. This has also helped us to identify gaps in the architecture

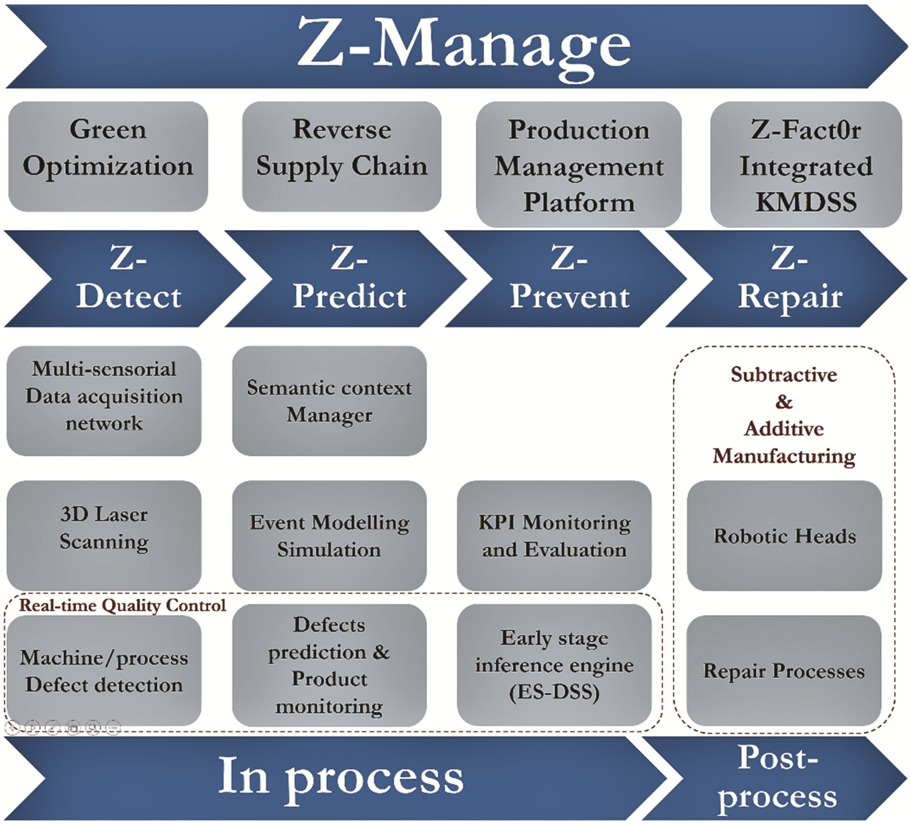

Fig. 2. Z-Factor conceptual architecture viewpoint

that needed to be filled in order to achieve the platform envisioned by the Z-Factor project. Figure 2 presents this landscape by proposing a compact representation of the involved tools.

3.2 Functional Viewpoint

Beginning from the conceptual architecture defined in the previous section, we have started putting the components into an initial architecture, identifying services and dependencies within the platform. We have also added new components in order to cover all the required Z-Factor functionalities. The result of this process is presented in this section, which includes the defined overall Z-Factor functional architecture. As it can be observed in Fig. 3, Z-Factor overall architecture has been subdivided in different layers, as specified initially, where components are of different nature and offer different functionalities.

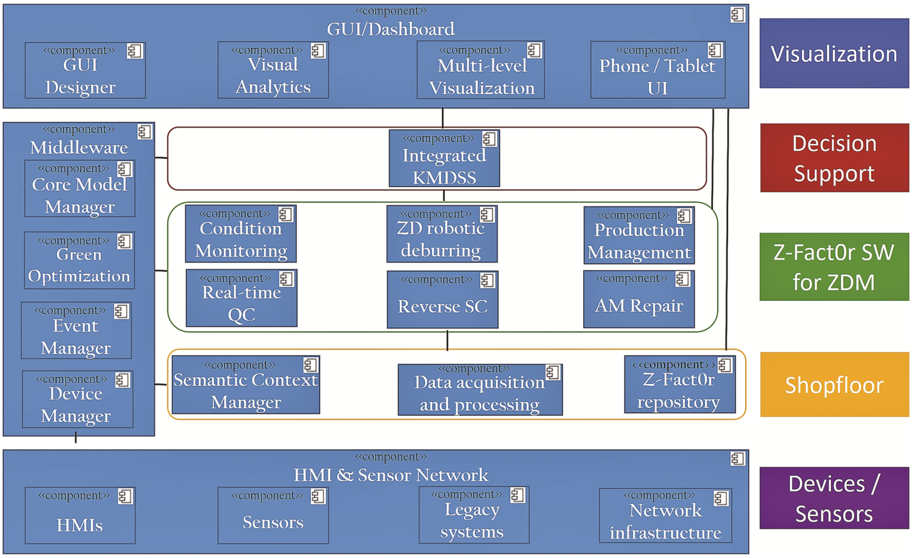

Fig. 3. Z-Factor functional architecture viewpoint

In order to define the System Architecture in such a way that it represents a usable schema for the implementation, a UML Component diagram has been created (shown in Fig. 3), where each tool has been represented as a component. Component diagrams are particularly useful when applied to distributed development. In fact, the initial architectural modelling efforts during cycle 0 focuses on identifying the landscape of the system and UML component diagrams which enable the modeling of the high-level software components, and more importantly the interfaces to those components. Once the interfaces are defined and agreed to teams, it is much easier organizing the development effort between sub-teams.

Z-Factor functional viewpoint thus contains all the functions that the system should perform as well as the responsibilities and interfaces of the functional elements and the relationship between them. These functions are described using UML diagrams. Figure 3 shows the component diagram view of the overall Z-Factor architecture.

To sum up, the main components, their functionality, and their interactions are described in the functional view. Accordingly, the main components for Z-Factor architecture are:

- HMI & Sensor Network, which includes sensors, actuators, HMIs for humans to provide input to machines and thus the overall system, cameras, network infrastructure, legacy systems, etc.
- Shop-floor components which comprise semantic context manager, data acquisition and processing including 3D laser scanning, and Z-Factor repository.
- Middleware including device manager, event manager, green optimizer, and core model manager.
- Z-Factor software modules for zero-defect management in manufacturing, which builds the service layer and includes Z-Factor specific tools such as real-time quality control, production management, reverse supply chain, zero-defect robotic deburring, and additive/subtractive manufacturing repair.
- Decision Support System (DSS) component, which will supervise and provide feedback for all the processes executed in the production line, evaluating performance parameters and responding to defects, keeping historical data.
- Finally, a visualization layer has been foreseen, which includes GUI/Dashboard designer, Visual Analytics Module, multi-level visualization component, and phone/tablet UI, etc.

Having identified the main functional view, we have then clarified the role of each layer and components. As first step of this phase, a template has been defined in order to collect a short description of all components brought by the partners. In particular, this template has aimed to collect the following component information: description of the main functionalities, related services, dependencies, inputs needed and outputs provided. This detailed description is introduced by a short description of the tool, pointing out the associated task and the principal user(s) of the tool. Then, the functional requirements are pointed out, meaning that for each tool a list of the main inputs, the main outputs and the main functionalities are listed and explained. After this analysis, the software structure of the tool architecture is given by the use of an UML Component Diagram allowing a first, deeper analysis on how the tool will be implemented. Eventually, a complete description of the modules included in the detailed view is provided in order to point out the responsibilities of each module and their interactions with the overall System Architecture.

3.3 Information Viewpoint

The information viewpoint describes the way that the architecture stores, manipulates, manages, and distributes information. The ultimate purpose of virtually any computer system is to manipulate information in some form, and this viewpoint develops a complete but high-level view of static data structure and information flow. Accordingly, this section illustrates a schema to represent the exchanged information between the envisioned components of the Z-Factor platform. Figure 4 highlights this information viewpoint diagram.

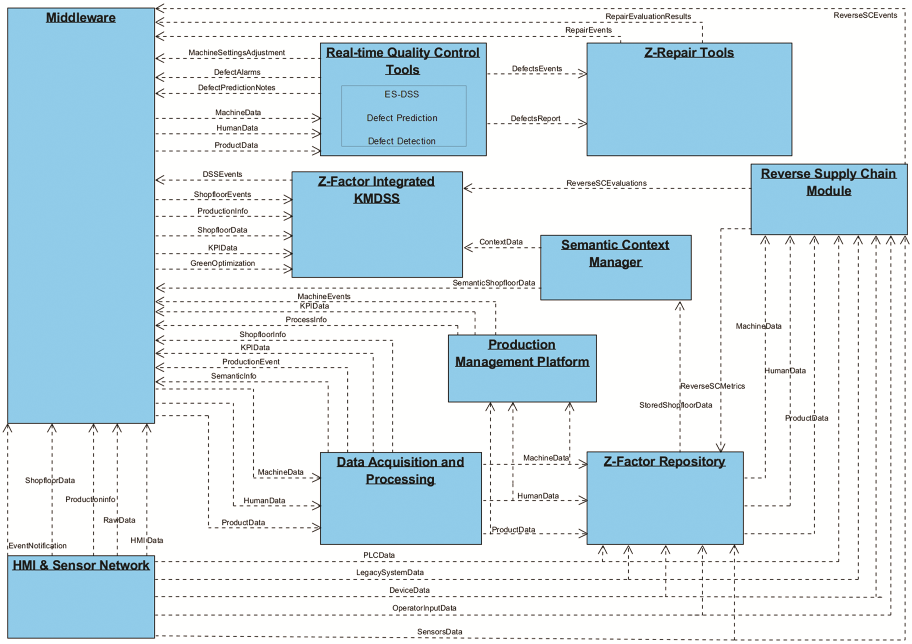

Fig. 4. Z-Factor information architecture viewpoint

3.4 Deployment Viewpoint

The deployment view needs to document the required deployment environment of the Z-Factor platform, which depends on the pilot areas and their topology. In this section, a first component diagram indicating the deployment view of the Z-Factor components is depicted in Fig. 5.

The HMI & Sensor network is comprised by a variety of heterogeneous sensors including the preinstalled factory automation system, which provides information about the production activities and the status of the factory infrastructure. Furthermore, it is comprised by the other sensors which will be used within the Z-Factor project. All these sensors/devices will be connected to the Middleware Device Manager through corresponding gateways, which will forward the information from the shop floor to the Middleware. The Device Manager, running in a dedicated PC named IoT Gateway, is equipped with all the necessary drivers, so as to understand and interpret the multi-sensorial information. The Device Manager is interconnected with the Middleware Event Manager, which could be located on the same PC (i.e. IoT Gateway) or even on another workstation as it is depicted in Fig. 5. The integrated Knowledge Management

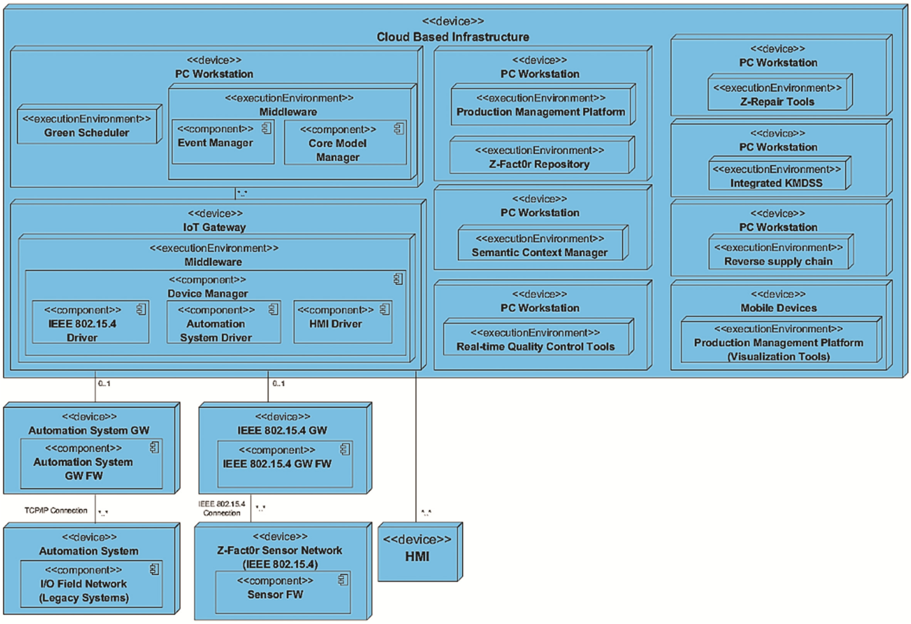

Fig. 5. Z-Factor deployment viewpoint

and Decision Support System (KMDSS) is interconnected with the Middleware Device Manager in order to acquire data stemming from the sensor network. This information is subsequently processed, generating recommendations which are then provided to users or other subsystems in the form of Events through the Event Manager.

All Z-Factor components, which will be connected among each other with the Middleware Event Manager, could be installed either on the same PC workstation or distributed to a number of PCs. Figure 5 illustrates the case where the Z-Factor components are distributed to various PC workstations. All the Z-Factor components compose the cloud-based Z-Factor infrastructure and will be interconnected among each other with a dedicated intranet, which could be either wired, wireless or even a combination of wired and wireless.

4 Conclusion

The introduced approach has proven its applicability on the realistic example of a large collaborative research project, demonstrating its ability to support the users and developers on their way from project requirements and software tools' description to the unified system architecture. Mutual analysis of the architecture by end users and software developers with different competences inspired all sides and supported the definition of new solutions. The resulting Z-Factor platform satisfies the identified business requirements of the industrial end-users and will act as main driver for the interpretation and explanation of the activities related to the design and management of a zero-defect manufacturing system at large. The application of this method in large innovative projects would facilitate their success.

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Improved Life Cycle Management by Product Communication

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Abstract. Many manufacturing companies have limited insight into the complete life cycle of their products. Insight that is necessary to manage the environmental impacts associated with the company's operation. One possible solution to this challenge is to apply emerging sensor technology for communicating with products. Despite the current trend of digitalization and use of sensors in the manufacturing industry, there is little attention given to how product communication may improve environmental sustainability.

We propose a framework on how product communication can facilitate improved life cycle management, by contributing with needed information for improved value chain insight, design for environment and end-of-life management.

Keywords: Sensor application · End-of-life management · Design for environment · Value chain insight

1 Introduction

Environmental awareness is growing throughout the society and the pressure on manufacturing companies to operate in an environmental sustainable way is increasing. In order to address the environmental impacts associated with a product, a life cycle perspective is required. Both to ensure that all impacts are addressed, and to prevent problem shifting of environmental issues. Life cycle management (LCM) is one framework for assuring that the life cycle perspective is kept throughout all company activities.

Having control of, and insight into, the entire value chain is becoming an important part of running a business. However, for many manufacturing companies that are not distributing their products themselves, knowledge of the complete life cycle of the products is limited. In particular, insights into users and end-of-life stages are particularly restricted. On the other hand, technologies that enable information tracking or product communication throughout the product life cycle are increasing. Digitalization, sensors and internet of things (IoT) are overall trends in manufacturing. They are anticipated to result in better products, zero defect manufacturing processes, more integrated

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value chains etc. However, less attention is given to how these trends may improve environmental sustainability for the manufacturing industry. Based on the challenge of lack of necessary information from the product life cycle to manage the environmental sustainability issues, and the possibilities with new emerging sensor technology, a conceptual framework is developed. By communicating with products (through integrated sensor technology) manufacturers upstream in the value chain can gain valuable information from the use-phase as well as end-of-life of their products that can be useful for improving environmental sustainability.

This paper presents theoretical background and considerations on how LCM can be improved by increased knowledge on the products life cycle, enabled by sensor technology. By exploring LCM of reusable or reconfigurable products, this paper addresses the potential of applying sensors to improve the environmental performance of the companies and provide basis for improved LCM. This paper first discusses relevant literature, before introducing potential applications. Thereafter we propose and discuss three areas of LCM where product communication can contribute with valuable information.

2 Literature Review

2.1 Life Cycle Management

During the past decades, international agreements and initiatives have been calling for a broader more holistic perspective on sustainability than that of a factory's or an organization's physical boundaries. Moving towards more sustainable manufacturing there is a need of framework that integrates life cycle thinking and the different instruments available to address the environmental consequences of an organization's operation. LCM is not a specific tool, but an extensive framework with a toolbox for governing environmental aspects. LCM is aiming to widen the traditional management scope beyond the organization's boundaries by managing the impacts associated with the entire life cycle of a product or product portfolio [1]. Therefore, LCM requires contributions from across the entire organization and external stakeholders. The different departments in an organization contribute to LCM in performing their operations by using sustainability tools and frameworks. Product development can contribute by performing design for sustainability, production and distribution, sales and marketing and purchasing by performing their tasks with a clear sustainable objective, and additionally an environmental department contributes by coordination and capacity building [1]. Balkau and Sonnemann [2] identifies a broad range of instruments for practicing LCM in an organization. They all require insight into the life cycles of the products and processes, value chain analyses, environmental management systems (EMS) as a framework for LCM, product stewardship or extended producer liability and design for environment in particular. In this paper we will, inspired by Balkau and Sonnemann [2], focus on the parts of LCM that is assumed to have a potential for improving LCM through the utilization of data from product communication: value chain insight, design for environment and end-of-life management.

2.2 Environmental Improvement by Product Communication

Sensors are currently used for many purposes, in particular in logistics and transportation for tracking and tracing products. A sensor detects a value or a change in a value, like pressure, temperature, vibration and converts it into a signal [3]. There is a wide range of functionality of sensors, and they come in a wide range of sizes, with or without an external power source, from simple RFID to advanced internet of things (IoT) solutions. For this paper, the broad range of sensors and communication technology available for producers or users to communication one-way or two-way with products is labeled *product communication*.

The amount of literature available on the use of sensors for improvement of environmental sustainability impacts appears to be limited. Most of the studies that are published focus on the use of RFID for improving environmental performance. Sensors and RFID may give access to information that can be used to achieve more efficient energy use, reduction of CO_2 emissions, improved waste control and improved recycling rates [4], reduced transport due to improved inventory management [5] and reduced traffic congestion due to faster and automated driver security inspection [6]. Integrated sensors may be used for monitoring, detection and prediction of product failures, as well as estimating the remaining life of product components [7]. This may provide a basis for improving environmental sustainability by changing existing end-of-life processes. For WEEE (Waste of Electrical and Electronic Equipment) recycling effectivity may be raised by improved product information and product identification from RFID technology [8]. Finally RFID tags can be used for improving recycling, including recycling of the RFID tag itself [9]. Digitalization and integration of manufacturing, referred to as Industry 4.0 also provides opportunities for improving resource efficiency and continuous energy management [10], holistic resource efficiency, facilitation of cradle-to-cradle thinking and sustainable process design [11].

3 Industrial Application of Framework

The objective of the overall research project is to guide manufacturing companies towards improved sustainability performance by applying LCM. The framework is developed with complex, high-tech reusable or reconfigurable products for either business or consumer markets in mind. Products with a medium to long lifetime, consisting of multi-materials and that must fulfill high quality and safety demands. The companies operate on worldwide markets, adding complexity to the products' life cycles because of the different types of markets, users groups and end-of-life options available.

4 Framework and Discussions

We propose a framework on how sensors can be used to facilitate LCM for such manufacturing companies. Figure 1 shows the data that is potentially available from sensor technology, both data collected from the life cycle of the products (straight lines), and information sent from the producer to other actors in the life cycle (dotted lines). From a manufacturer's perspective, interesting data can be collected from communicating with the products throughout its lifetime. A producer can collect data from the end user on user patterns, from the distributor on maintenance, repair and reuse intervals, from the end-of-life handler on why and how the product reaches end-of-life, and challenges with end-of-life handling. Finally, the producer can potentially gain information from products that are subjected to unregulated disposal.

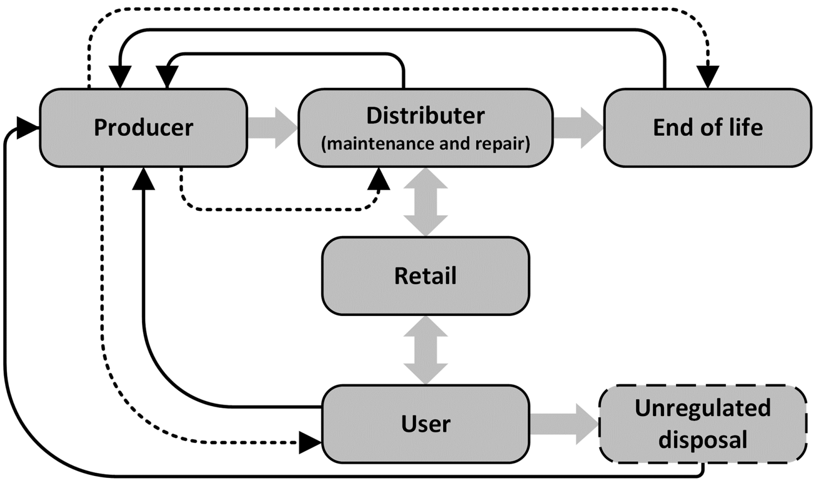

Fig. 1. Data collection from the products life cycle by product communication.

A producer can also communicate with the product and/or the users throughout the lifetime by sending information to end user on safe use and safe disposal, to the distributor on safe maintenance and repair and information on reuse of parts and to end-of-life handlers on information on the content of the product and recommendations for disposal. This information gathering and exchange influences environmental sustainability of the product by providing value chain insights, basis for design for environment and proper end-of-life management, which are all central part of LCM.

4.1 Value Chain Insight

The focus on environmental issues is increasing and the manufacturing companies are experiencing pressure for managing these issues. It might be requested by governments through laws and regulations or more indirectly by stakeholders such as customers or NGOs. Some companies choose to manage their environmental impact through following a standardized environmental management system (such as ISO14001 or EMAS). Addressing environmental issues is a complex task, and the reporting associated with the EMS may be work-intensive and challenging. Many companies are experiencing a lack of insight and knowledge to carry out the reporting in a responsible way.

Life Cycle Assessment (LCA) is one of many tools used for reporting and environmental sustainability planning by companies. However, it is a complex tool and challenges with data availability and data quality often occur [12]. Improving data availability and quality, by utilizing sensor data, may simplify and lighten the work efforts put into this type of analysis and reporting.

Lack of data with sufficient quality for use and end-of-life of products is often a problem in LCA, and affects the applicability of the obtained results [13, 14]. Improved data will not only make LCA more robust, but also improve its role as a decision making tool integrated in a LCM system. By tracking products and gaining insight into user patterns, service and maintenance patterns and part replacement history, data improvement may be feasible, and provide more robust LCA results.

Besides environmental reporting that is required by regulation, manufacturers frequently receive inquiries from customers to document environmental footprint of the products. Increased knowledge on environmental issues for their products is therefore necessary. There may also be strategical benefits in increased environmental knowledge on the products, as more and more consumers are concerned with environmental issues. It will be a competitive advantage if they can promote their products as the greener choice.

4.2 Design for Environment

In general, up to 80% of environmental and social cost factors of a product are determined in design and product development phases [15, 16]. For reusable and reconfigurable products with long lifetimes; design of new versions as well as replacement parts, and maintenance services of products in use are crucial for minimizing the environmental footprint. Point of departure for design is often an overview of the product's entire value chain and insights into the various users' needs, user patterns and situation.

For manufacturers of products distributed through and serviced by other business actors, information exchange in the value chain is often limited. The value chains can be complex and include a large number of actors. A medium to long lifetime of the products add to the complexity and might further reduce access to information. The manufacturers typically receive information through inquiries from distributors on reoccurring problems with the product. Nevertheless, manufacturers often have limited insight into the cause of failures, declining product quality, accidents or misuse. Sensor data might provide insights into user patterns and situations that cause product failure, rather than a customer's narratives of what happens.

The manufacturers might have limited information on successful and safe user situations. In particular, restricted insight into how various users are handling the products in ways that affects safety issues and might prolong or shorten the products' lifetimes. For example, information on how roughly or careful the products are handled during transport and maintenance can provide a more accurate specification of impact loads. Product communication and co-creation with customers and distributors can result in products that are easier to maintain, new replacement parts and services, and solutions for reconfiguration, in all prolonging the lifetime of the products.

One important point of departure for design for environment is the end user. Understanding of the users are often achieved through interviews, observations or co-designing [17]; thus qualitative methods involving a limited number of users. Sensors might provide relevant information from a larger number of users and when direct contact with users is difficult. In particular for products distributed to wide geographical markets and when there are large cultural differences between various user groups.

To develop more disruptive sustainable solutions, insights into user practices and behavior are necessary [18]. In design research, the aim of design for sustainable behaviour is to create products in such a manner that they are supporting greener choices and greener user behaviour related to products. A simple example is water kettles where the user can choose to stop the heating at 80, 90 or 100 ℃. Analysis of sensor aggregated data can potentially provide useful information on user habits and use-patterns that are more or less environmental efficient, supplementing understanding achieved through qualitative approaches. Finally, if a two-way product communication is developed, such a smart product might allow for instant feedback to the users on unsafe use of the product and support more sustainable user patterns and nudge the right end-of-life handling.

4.3 End-of-Life Management

A part of moving towards an environmental sustainable society is reducing the emissions of greenhouse gases. A large share of the emissions is caused by production of goods and services. An escalation in the depletion of virgin resources is seen due to increased customer demands for new products. This is a threat to the environment for several reasons. Mining and extraction of virgin materials are often associated with several environmental consequences, increased CO_2 emissions, toxicity for humans, ecosystems on land and water and other emissions to air to name some. Besides the problems already mentioned, a decrease in availability for several virgin metals leads to a need for an improvement of take-back systems for products after service life. It is crucial to reduce the draw of primary resources, and keeping materials and resources in the loop, i.e. a shift towards a circular economy. Information on what happens with each product after its main purpose is fulfilled is essential for achieving this.

What kind of end of life treatment a product should be subjected to depends on the original design of product, but also several factors influenced by its use, maintenance frequency, replacements and other external conditions. Sensor technology may fulfil the mentioned needs for information. One important issue is deciding when a product reaches its end-of-life; either a distributor or a user find that the product is not functioning in a satisfying way, visual appearances is unsatisfactory, or after a certain amount of time, according to regional specific regulations. In addition, some users might dispose their products outside the regulated recycling plan.

The increase in the use of multi-materials in products also provides challenges for recycling and end-of-life. One way to simplify and improve end-of-life systems is to make decisions based on acquired product information from monitoring devices (sensors) embedded in the products. Tracking of products may give information on products that can enable correct waste handling, ensure proper handling of products with safety issues, simplify and facilitate sorting and recycling. This may provide basis for a larger degree of take back of materials and easier sorting, which is a huge step towards closing the material loops.

For the manufacturing companies information provided by attaching sensors may be used for designing a framework for regional specific end-of-life recommendations that may be communicated to the distributor and end-of-life handlers. Today, an increased complexity of products is often seen, with more and new materials and material combinations. Tracking gives the possibility for integrating this type of information in the product, and making it available for the end-of-life handlers. Information provided may simplify decisions on whether a product should be repaired or disposed. This information may prevent fully functioning products from being discarded due to strict regional regulations, owed to safety issues.

Finally, other environmental sustainable relevant information is how many products that reach end-of-life or is lost in the use stage due to unregulated disposal.

4.4 Potential Disadvantages with Sensors

The attachment of sensor technology to a product leads to more material, energy and resource use. The increased use of raw materials for producing the sensor, and a possible energy need for operating it, add to the overall environmental footprint of the product. The addition of a sensor can potentially complicate the final disposal of the product, by introducing more materials, complex structures and possibly detachment issues. For this reason, the addition of a sensor to improve environmental performance should be weighed against the material challenges the recycling of the product (and sensor) introduces [9].

Communicating with a product after factory gate is complicated due to data retention, security and customer privacy. Therefore, the ethical dimension of product surveillance must be carefully considered before implementing sensor technology.

5 Concluding Remark

The main contribution from this work is the link between LCM and product communication. We have shown that there are several environmental benefits associated with communication with products throughout the use and end-of-life. The areas where data collection can contribute to improve LCM are value chain insight, design for environment and end-of-life management. By communicating with the product throughout its lifetime, data that is collected can be used for improved reporting and simplified use of assessment tools such as LCA, design of products, parts and services based on actual user patterns, more robust decision making for environmental sustainable design and product development, and finally, a more responsible end-of-life management.

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Cross-Correlation Method for Orchestration of Preventive Maintenance Interventions

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Abstract. The paper has the objective of investigating the effect of the arrangement of the maintenance interventions along the planning horizon on the reliability of a mechanical system. In fact, the specific arrangement of the maintenance interventions during a specified time horizon influences the system reliability, and this is an aspect that has not received much attention in the literature. The aim of this paper is to propose an orchestration model that finds the best arrangement of maintenance interventions based on a deep analysis of the system reliability using the cross-correlation mathematical operator. The research demonstrates that, by means of a proper arrangement of the preventive maintenance interventions, higher minimum system reliability can be achieved.

Keywords: Reliability · Failure mode · Preventive maintenance · Cross-correlation

1 Introduction

Reliability, together with Availability and Maintainability, is a performance indicator and it allows the quantification of how long an item can operate without failure (Nakagawa 2005, Furlanetto et al. 2006). Reliability is defined as the probability that the item will perform a required function under stated conditions for a stated period of time (Macchi et al. 2012a). This parameter must be kept at high level when failure cost is high (e.g. spare parts replacement cost, damages cost, etc.) and when failures have dramatic consequences in terms of safety (e.g. in the case of airplanes, nuclear and chemical plants) (Furlanetto et al. 2006). In this case, maintenance costs have to be minimized while keeping the risks within strict limits and meeting satisfactory requirement.

The system reliability R_{sys} depends on many factors, the main ones are discussed hereafter. R_{sys} depends on the reliabilities of the various failure modes R_i. The reliability of a generic failure mode i depends on the parameters used to describe its failure behaviour. If the Weibull distribution describes the failure behaviour, three parameters have to be considered: the typical life α, the shape factor β and the time scale factor γ (Macchi et al. 2012a). The number of interventions that are planned in the reference time horizon influences the system reliability. An elevated number of maintenance interventions allows reaching high system reliability (Furlanetto et al. 2006). The system reliability is affected by the so-called human factor. Sometimes, the operators do not perform the maintenance intervention perfectly and, as a consequence, a partial

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(or even null) improvement of the reliability follows. According to this view, the concept of imperfect maintenance can be introduced and can be applied to both corrective and preventive maintenance. For further information about the topic, look at (Andrew K.S. Jardine 2005, Doostparast et al. 2014, Lie and Chun 1986, Tsai et al. 2001). Eventually, the system reliability is affected by the arrangement of the maintenance interventions in the planning horizon, i.e. the disposition of the interventions in the time window under consideration. With the same number of interventions in the planning horizon, a proper disposition of the interventions along time can lead to higher system reliability: the disposition that maximizes the reliability can be found. The search of the best disposition of the interventions to maximize the reliability is herein defined as *orchestration* (Fumagalli et al. 2017). Because of the poor attention of the scientific literature about this topic, the paper wants to contribute on the research about the impact of this novel factor on the system reliability.

The work focuses on a generic system and its failure modes that are assumed to be maintainable, independent and in a series-wise configuration (Fedele et al. 2004). A failure mode is defined maintainable if it can be improved by means of a maintenance action (Zequeira and Be 2006, Castro 2009, Lin et al. 2000). Two failure modes are independent if an intervention on the first failure mode does not affect the other failure mode and vice versa (Zequeira and Be 2006).

In Sect. 3 a method to find the arrangement of the maintenance interventions in the planning horizon that maximizes the system reliability, respecting the constraint regarding the same number of interventions, is presented. The method uses the cross-correlation, a mathematical operator that is described in Sect. 2. In Sect. 4 a numerical application of the cross-correlation method is developed. Eventually, conclusions and future developments are reported in Sect. 5.

2 Cross-Correlation in Maintenance

Auto-correlation and *cross-correlation* are mathematical operators which find many applications in various fields (Vorburger et al. 2011, Tsai and Lin 2003, Michele et al. 2003). In signal processing analysis finding a quantitative indicator that measure the *similarity* between two signals x(t) and y(t) is very important. It may happen that two signals are shifted in time: the cross-correlation is able to determine the time shift between them, looking at the time instant in which the two signals are more similar. The formula of the unbiased cross-correlation for two sampled signals x(t) and y(t) can be found looking at (Doebelin 2008).

The system reliability plot is the resulting signal of the combination of the reliability signals of the failure modes of the system. As said, the failure modes are in series-wise configuration: the reliability of the system $R_{sys}(t)$ at a generic time t is given by the product of the reliabilities of the various failure modes at that time instant (Furlanetto et al. 2006, Trapani et al. 2015). In the paper, the Weibull distribution is used, which is described by means of three parameters: the life parameter α_i, the shape factor β_i and the location parameter γ_i. It is assumed that the effect of a PM on the failure mode i is the restoration to the reliability curve $R_i(t)$ of that failure mode up to one. On the contrary, a CM on FM_i does not influence the reliability curve $R_i(t)$. In the paper both the average system reliability R_{avg} and the minimum system reliability R_{min} are taken into account. This is an innovative aspect since, generally, in literature the reliability is considered just as a constraint to be respected (e.g. the reliability of the system must be kept above a specified threshold) (Das 2007, Doostparast et al. 2014). The two indicators (R_{avg} and R_{min}) are necessary to demonstrate that the orchestration of the maintenance interventions in the planning horizon influences the reliability of the system.

A machine subject to various failure modes is considered. For each failure mode the best preventive maintenance interval T_{pi} can be calculated using one of the optimization models present in literature (the one that minimizes the maintenance costs or the one the maximize the availability are only some examples (Macchi et al. 2012b)). A first situation that may happen is the following: two scheduled interventions very close in time. The reliability of the system is very low before the first maintenance intervention and, since the two scheduled interventions are very close in time, after the second one it is almost one. This is not a good situation and it can be improved in two different ways: trying to opportunely space the two maintenance interventions or trying to aggregate them performing them at the same time. The paper focuses on the first option. Sometimes, the spreading out of the maintenance interventions is also appreciated when simultaneous downtime of components is undesirable (Anon 1997). Further, the spreading out of the maintenance interventions leads to workload distribution of the maintenance resources, that must be coherent with maintenance planning and scheduling constraints, as well as production plan (Macchi et al. 2014a, Macchi et al. 2014b).

The paper addresses the problem about how finding a proper distance between two or more maintenance interventions. The idea is to treat the curves of the reliability of the various failure modes as signals and to compare them using the *cross-correlation*. In the following section the method is described in detail. The method has been developed for a system subject to only two failure modes. The difficulty of extending the method to more than two failure modes is explained in Sect. 5. The cross-correlation method that is presented in Sect. 3 is a method that allows changing a maintenance plan that already exists; it allows arranging in an intelligent manner the already planned maintenance interventions. It is not a maintenance optimization method in the classical sense (whose output is a maintenance plan), since it is applied *after* having generated a maintenance plan. It can be seen as a further tool to improve a maintenance plan (in fact, the number of interventions that have to be performed in the planning horizon remains the same).

3 The Orchestration Model

A system affected by two failure modes (FM_1 and FM_2), each one described by its Weibull parameters (α_1, β_1, and γ_1 for FM_1 and α_2, β_2, and γ_2 for FM_2), is considered. An assumption is done: $MTTF_1 < MTTF_2$, i.e. the first failure mode is more critical than the second one (it is characterized by a lower mean-time-to-failure). Actually this is not a hypothesis, but rather a way to say that the following discussion is valid if we name “failure mode 1” the failure mode with the lowest $MTTF$, and so the one that requires more urgent action in time. A PM on the FM_1 is performed every T_{p1} weeks and on the FM_2 every T_{p2} weeks. So in the specified time horizon $T_{horizon}$ the indication about *when* and *on which* failure mode a PM has to be performed is given, i.e. the maintenance plan is already done. The reliability of FM_1 is a periodic signal with period equal to T_{p1} while the reliability of FM_2 has a period equal to T_{p2}. The *system* reliability can be plotted, considering that at every time instant t it is equal to the product of reliabilities of the two failure modes at that time.

The system reliability signal can be very irregular, due to the fact that the maintenance interventions have been optimized only considering the various failure modes separately. In other words, the irregularity is due to the fact that clock-based preventive maintenance is done for both the failure modes but with different preventive maintenance intervals: a maintenance intervention on FM_i is performed every T_{pi}, where T_{pi} is the optimum PM interval for failure mode i (according to the maintenance optimization model that has been used). Sometimes only few weeks pass between a PM on FM_1 and on FM_2 and sometimes a wider distance between the two interventions is present. In the paper a method to space in an intelligent manner the maintenance interventions is proposed and the cross-correlation operator is useful to develop it. The objective is to find the time instant T_p in which the two periodic signals (reliability of failure mode 1 $R_1(t)$ and of failure mode 2 $R_2(t)$) present the minimum similarity. The idea is to shift one reliability curve of T_p time units in order to act on one failure mode in the time instant in which the other is more different. In this way a situation that presents two advantages is reached. The first one is that the maintenance interventions are more regularly disposed in the time horizon and this leads to a workload distribution of maintenance resources. The second is that, with the optimal disposition proposed by the cross-correlation method, the minimum of the system reliability has a higher value than in the non-optimized situation.

The cross-correlation method allows spacing the maintenance interventions in an intelligent way: keeping the same number of interventions in the time horizon, higher system reliability is reached. In order to find the instant T_p in which the two signals (reliability of failure mode 1 and 2) present the minimum similarity, the two periodic signals must be cross-correlated. The cross-correlation function gives reliable results if it is calculated using a big number of points. So, in order to reach reliable results from the method, the reliability signals are stretched so that they have got no more $T_{horizon}$ points, but a bigger number of points. Since they are periodic signals, this can be done simply adding more periods to them. After that the two signals have been cross-correlated, from the cross-correlation plot, the time instant T_{min} in which the cross correlation presents a minimum is identified. T_{min} is linked to the instant T_p of interest (in principle the two values may not coincide, as it will be explained later on). Calculating the cross-correlation between $R_1(t)$ and $R_2(t)$ means to shift to the left $R_2(t)$ while keeping fixed $R_1(t)$. The cross-correlation is a periodic signal since the two input signals $R_1(t)$ and $R_2(t)$ are periodic. The period T of the cross-correlation is equal to the least common multiple (*l.c.m.*) between T_{p1} and T_{p2}. It is easy to understand, in fact, that, after a time equal to the least common multiple, the whole signal, given by the combination of $R_1(t)$ and $R_2(t)$, repeats itself. So it is sufficient to analyse one period of the cross-correlation since after the *l.c.m.* just repetitions of information are present. Thanks to the periodicity of $R_{xy}(t)$ the calculation of the cross-correlation for negative time shifts can be avoided. It can happen that the *l.c.m.* and so the period T of the cross-correlation is higher than the planning horizon $T_{horizon}$ of the maintenance problem. In this situation the cross-correlation plot is analysed only from time $t = 0$ to $t = T_{horizon}$ and in this time frame the minimum of the cross-correlation is found. Once that the time instant in correspondence of which there is the minimum cross-correlation has been identified, the necessity of finding T_p, the optimum time-shift of interest, arises. Two possible cases can occur:

- $T_{min} < T_{p2}$. This is the situation in which the time instant in correspondence of the minimum of the cross correlation is lower that the period of the moved signal ($R_2(t)$). If this condition is verified $T_p = T_{min}$, i.e. the optimal distance between the interventions is directly the time instant T_{min}.
- $T_{min} > T_{p2}$. It means that the minimum similarity between $R_1(t)$ and $R_2(t)$ is reached moving on the left $R_2(t)$ of T_{min}. Since $T_{min} > T_{p2}$, moving on the left $R_2(t)$ of T_{min} is equivalent to move $R_2(t)$ of n time units; n is the difference between T_{min} and T_{p2}.

After having identified T_p, the system reliability curve can be plotted. It is the product between the $R_1(t)$, that has remained fixed, and $R_{2new}(t)$, which is the $R_2(t)$ signal shifted on the left of T_p time units. So a new maintenance plan is generated. It contains the same number of interventions of the original plan but has two advantages. The first one is that the spacing between the interventions is more homogeneous; the second one is that the minimum system reliability has increased.

4 Numerical Application of the Model

Let assume a system subject to two failure modes with the following characteristics:

- FM_1: $\alpha_1 = 20$, $\beta_1 = 2.5$, $\gamma_1 = 0$ that corresponds to a $MTTF_1 = 17.75$ weeks.
- FM_2: $\alpha_2 = 35$, $\beta_2 = 3$, $\gamma_2 = 0$ that corresponds to a $MTTF_2 = 31.25$ weeks.

The time horizon $T_{horizon}$ is the year (52 weeks). It is supposed to perform a maintenance intervention on FM_1 every $T_{p1} = 12$ weeks and on FM_2 every $T_{p2} = 13$ weeks. The maintenance plan for the as-is situation (original maintenance plan) is represented in Fig. 2. From the analysis of the system reliability plot, the following indicators (avarage system reliability, minimum system reliability, number of interventions on the first and second failure modes) can be calculated: $R_{avarage} = 93{,}08\%$, $R_{minimum} = 72{,}68\%$, $N_{FM1} = 4$ and $N_{FM2} = 4$. Looking at the maintenance plan, it is evident that the interventions are not well spread out in the time horizon. Clearly, the situation has to be improved, trying to better space the maintenance interventions.

The cross-correlation method between $R_1(t)$ and $R_2(t)$ is applied. The cross-correlation signal is a periodic signal since the two input signals $R_1(t)$ and $R_2(t)$ are periodic. The period T of the cross-correlation is equal to the least common multiple (*l.c. m.*) between T_{p1} and T_{p2}, which in the example is equal to 156. So every T the *system* is completely restored to an AGAN condition since at the T^{th} week two perfect maintenance interventions have to be performed, the first on FM_1 and the second on FM_2.

The minimum of the cross-correlation is at $T_{min} = 22$ (Fig. 1); so the two signals present the minimum similarity at the 22^{th} week. Shifting on the left $R_2(t)$, which is a periodic signal with period T_{p2}, of T_{min} time units is equal to shift it on left of $T_p = T_{min}$-T_{p2} = 22-13 = 9 time units. So a new reliability curve $R_{2new}(t)$ can be built and it

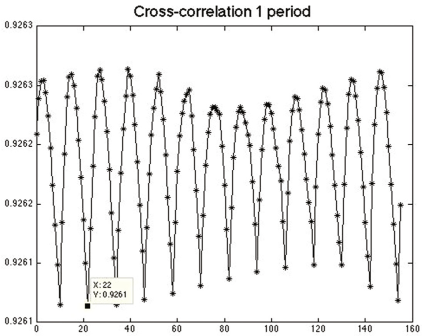

Fig. 1. Cross-correlation plot.

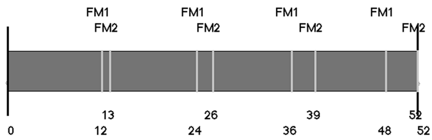

Fig. 2. Original maintenance plan.

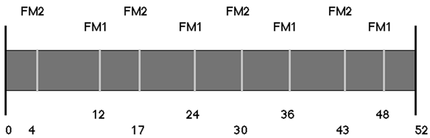

Fig. 3. New maintenance plan.

will be used to calculate the new system reliability plot. In particular, the first maintenance intervention will be performed on the FM_2, the one that has been shifted, and it will be at the week number T_{p2}-T_p = 13-9 = 4 week.

After having applied the cross-correlation method, the new maintenance plan (Fig. 3) and the new system reliability signal are analysed. From the analysis of the system reliability plot, the following indicators can be calculated: $R_{avarage}$ = 93,24%, $R_{minimum}$ = 74,77%, N_{FM1} = 4 and N_{FM2} = 4. Looking at the indicators, it is observed that the cross-correlation method proposes a better disposition of the maintenance intervention (as it can be seen in Fig. 4), leading to a higher minimum system reliability while keeping the same number of interventions. In particular, the cross-correlation method allows finding the best disposition of the interventions, i.e. the one that gives the higher minimum system reliability.

5 Conclusions

There are some limitations to the cross-correlation method proposed above. The following comments are derived based on some numerical tests that have been carried out, but are not presented in the paper.

Firstly, the cross-correlation method implies to anticipate a maintenance intervention of T_p time units in order to reach the situation in which the reliability curves of the two failure modes are less similar (less superimposed) and to reach the consequent advantages. It can happen that the anticipation of a maintenance intervention leads to the situation in which a further intervention on the shifted failure mode should be performed in the planning horizon. In this case, the hypothesis of keeping the same number of interventions of the original maintenance plan is violated.

Secondly, in another situation, there can be a maintenance plan in which the maintenance interventions are already disposed regularly and so there is no need to apply the cross-correlation method, or better if the method is used, it does not lead to satisfactory results. This happens when the two failure modes are very different in terms of *MTTF* and so a failure mode must be maintained very more frequently than the other. The last consideration implies that $T_{p1} << T_{p2}$.

A third situation happens when the time horizon is long compared to the T_{pi}. In this case, the beneficial effect is present only at the beginning of the time horizon, while at the end it fades away. The cross-correlation method allows spacing as much as possible a sequence of numbers, but sooner or later the numbers in the new spaced sequence will be near again. The method "shifts" in time the problem of having a non-regular disposition of the interventions, but if the temporal period in which the problem has been shifted is part of the planning horizon, then the method does not provide satisfactory results; it simply creates a change in the trend: a good situation at the beginning and a bad situation at the end.

Eventually, the cross-correlation method proposed in Sect. 3 considers a system subject to only two failure modes. The discussion has to be extended to more than two failure modes, since a machine/mechanical system is expected to fail with more than two failure modes. The main difficulty is that the cross-correlation function is a mathematical operator that takes into consideration only two signals at a time. In signal processing analysis there is not an *extension* of the cross-correlation to more than two signals because it is sufficient to cross-correlate pairs of signals. However, the interest for this paper is not to align the reliability curves of the various failure modes, but rather to find of how many time units the curves have to be shifted in order that they present the minimum similarity. A possible future development is finding a way to properly extend the cross-correlation method to a mechanical system subject to a generic number *n* of failure modes.

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System-Oriented Reliability-Based Methodology for Optimal Joint Maintenance and Production Planning

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Abstract. The integration among the organizational functions managing assets along its lifecycle is a crucial aspect for production companies to implement Asset Management. In this paper, an iterative four-step methodology is presented to support the joint maintenance and production planning considering the system configuration optimization as well. The objective is to overcome the limitations of most of the approaches that can be found in the literature regarding joint optimization models, by integrating it with a system-oriented and reliability-based approach. Reliability, Maintainability and Availability analysis at system level is used to support the traditional joint optimization models. The methodology is applied in an industrial case in the mining sector.

Keywords: Joint maintenance and production planning · Asset management · Lifecycle · Production system · Reliability

1 Introduction

One of the core concepts within the Asset Management discipline is the multi-disciplinary integration among functions in an organization to manage assets along its lifecycle [1, 2]. Within this perspective, the typical 'silo' behaviour which keeps maintenance and other life cycle processes separated in an organization is no longer sustainable [1, 3, 4]. In particular, when referring to production contexts, maintenance and operations are the two functions dealing directly with the assets to make it operate and that need to work in an integrated way. Nevertheless, the integration between these two functions is still a challenging issue for companies. In fact, they are related through a strict but apparently contrasting interconnection, dealing with the same resources (production assets) with different goals [5]. On one side, the Availability of a plant is connected to the effectiveness of maintenance activities that should be capable to minimize the amount of time in which the plant is in a fault state. On the other hand, the Utilization is related to the production activity: the plant is utilized to reach commercial objectives considering the resource constrains. The contrast between maintenance and production functions is related to the unreliable nature of the machines that compose a

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system. When asset performances diverge from its desired target value, the interest of maintenance is to stop the asset, in order to intervene to extend its life cycle availability, while production needs to utilize it to maximize its efficiency. For this reason, there is the need of finding proper models that enable a joint planning of maintenance and production, which are based on a reliability approach [6]. Moreover, our hypothesis is that such models should address asset systems in their entirety, taking into account that industrial assets are complex systems composed by different components interrelating among themselves. Such interactions, together with the state of each component, affect the state and performance of the system itself. Hence, the effect of any local decision has to be considered in maintenance and production joint planning [7]. “Effective life cycle management is one of the key responsibilities of production and maintenance management at the asset system level” [3]. Successfully integrating the planning of production and maintenance activities can bring several benefits in terms of efficiency of the production system. The idea is to determine a global optimum avoiding to reach a local optimum that maximize the performance of a single function affecting negatively the performance of the other.

The production system design is a critical aspect to be considered as well, since the design decisions may have a decoupling effect between maintenance and production. In fact, optimal design is capable to provide a spare capacity that can reduce the impact of the maintenance intervention over the system production and can reduce the demand for maintenance, increasing the reliability of the system with redundant resources.

The aim of this paper is to present a methodology that support reliability-based system-oriented joint optimization of maintenance and production planning, keeping into account alternative configuration scenarios as well. Section 2 is focused on the State of art on the addressed topic. The developed methodology is presented in Sect. 3. In Sect. 4 the application of the methodology in a real industrial context in the mining sector is presented and discussed. Finally, Sect. 5 concludes the paper.

2 State of Art and Problem Statement

In the scientific literature, it is possible to find several reviews about joint optimization models such as [8, 9]. Overall, by investigating the models that have been proposed so far, several existing limitations can be identified, and the main ones are the following. Firstly, many of them do not truly implement real integration among maintenance and production planning but they use sequential or hierarchical approach [10]. Secondly, few models take into account the systemic perspective and the relevance of the design configuration in the optimization process. In fact, a very common approach is the so called black box modelling, where it is assumed that the performance of single machines perfectly reflects the systemic one. In the literature, some models propose alternative solutions taking into account this aspect [11–13]. Even if those models take into account the necessity of considering the occurring interrelationship between system components, the complete systemic vision is still missing. Finally, most models are characterized by low degree of applicability, being mathematical models with high computational complexity; losing its usefulness in industrial implementation [8].

Overall, the gap in the literature targeted in this paper is the absence of a methodology that, without increasing the computational effort of the models, integrates the planning of maintenance and production, and the optimal design configuration of a system. To reach this objective, the methodology must keep: (i) systemic perspective, considering the impact of all the elements in the system; (ii) reliability-based approach, considering the uncertainty of machines behaviour; (iii) life cycle orientation, supporting decisions along the asset life cycle [14].

3 System-Oriented Reliability-Based Methodology for Joint Maintenance and Production Planning

The methodology proposed in this paper aims to integrate the joint optimization models that can be found in the literature, with a systemic perspective evaluating the optimization process at system level based on a reliability-oriented approach. The methodology is based on the premise that, since it is fundamental to keep a systemic perspective, the relationship between the design of the system and maintenance and production planning has to be considered as well.

An iterative four-step methodology is proposed that integrates a joint optimization model with Reliability and Maintenance engineering analysis at system level. It is based on the modelling of the system under analysis through the Reliability Block Diagram (RBD) technique offering an integrated and reliability-oriented view of the system with a bottom-up perspective while keeping an easy implementation approach [15]. Stochastic simulation is then used for describing the random nature of reliability-related phenomena [16]. This approach has been exploited in the defined methodology in order to effectively identify the criticalities in the system, and therefore the improvement opportunities. The Joint optimization model is integrated with it and is applied at unitary process level (defined as the group of system components used for a macro-phase of the production process) (Fig. 1).

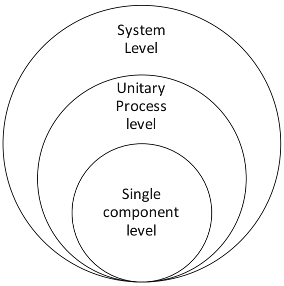

Fig. 1. System hierarchy representation

The output of the methodology consists of a joint production and maintenance planning and of the indication of the optimal design solution at system level. In particular, the methodology is composed of four steps and they are: (i) system criticality analysis, (ii) configuration alternatives definition, (iii) joint optimization model resolution, (iv) reliability-based system-level performance analysis. Each step is detailed hereafter.

STEP 1: System criticality analysis. The first step aims at implementing performance analysis at system level for detecting criticalities. The main objective is to calculate the incidence of each system component on the overall system availability, taking into account its performance and its positioning within the RBD model of the system. Monte Carlo simulation is used to run the performance analysis and the most critical unitary processes and components are identified. This step enables focusing on the criticalities.

STEP 2: Configuration alternatives definition. In the second step, a discrete set of configuration alternatives is defined. In practice, the installation of redundancies (total redundancy, stand-by etc.) to the most critical components may be considered. In doing so, both the reliability perspective and the technical feasibility must be considered. Once the set of alternatives is defined, the expected performances for each of it are evaluated by modifying the RBD model accordingly and running the simulation. In this way, the input to the next step is given by a set of configuration alternatives for each critical unitary process with the related expected performance and total cost of ownership (related CAPEX and expected OPEX). The configuration alternatives together with the as-is scenario are the input for the next optimization step.

STEP 3: Joint optimization model resolution. The third step consists in running a joint optimization model to determine the decision variables optimal values. The following outputs are generated given a reference time horizon: production planning in terms of number of batches to be produced in each time interval, maintenance planning in terms of frequency of preventive maintenance interventions and selection of optimal configuration alternative among the ones identified in step 2, for each critical unitary process under analysis.

STEP 4: Reliability-based system-level performance analysis. The last step allows going back from the unitary process level to the system level. The aim of this step is to evaluate if the optimization outputs in terms of configuration alternatives effectively improve the overall performance of the system. In order to do so, the reconfiguration options selected by the joint optimization model for the critical unitary processes are integrated in the system RBD model and the overall system performances are evaluated through simulation and can be compared with the 'as is' scenario's performances (Fig. 2).

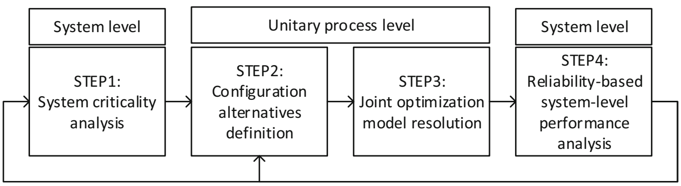

Fig. 2. The proposed methodology

A recursive approach is proposed. In fact, the reconfiguration options from the optimization model at unitary process level may not affect the system performance. In this case, it is possible to go back to step 2. Moreover, in case that a reconfiguration option is identified, new improvement opportunities can be found by running again the methodology from step 1 selecting criticalities in the new system configuration.

4 Application Case

The proposed methodology was tested in an application case in the mining industry. The analyzed plant is a top-class copper concentrate production plant located in Chile. A model capable to deal with the structure of a batch process system, characterized by the presence of various inter-operational buffers, was selected from the literature [12]. Figure 3 shows the production process under analysis, showing the unitary processes composing it. The asset under analysis is at its Middle of Life stage.

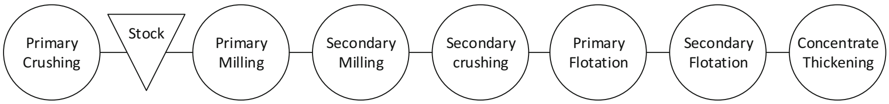

Fig. 3. Production process scheme at Unitary Process level

As supporting tools, the Reliability and Maintenance Engineering Software, R-MES Project© (developed by the CGS company http://www.cgssa.com/en/) is used in order to implement the performance analysis at steps 1, 2 and 4, supporting RBD modelling and Monte Carlo simulation. An optimization solver for determining the solutions of the joint optimization model for maintenance and production planning used at step 3.

STEP 1: System criticality analysis. By building the RBD model of the plant and running Monte Carlo simulation, it is possible to identify which of the unitary processes impact more on the system performance (availability). It resulted that primary crushing, primary milling, secondary milling and secondary crushing account for 80% of the system unavailability. The following steps are applied to these four unitary processes. Moreover, breaking down the performance analysis within each critical unitary process it was possible to identify the criticalities at component level (critical equipment).

STEP 2: Configuration alternatives definition. Considering that the mining context does not present strong constrains in terms of financial and space availability, reconfiguration alternatives were defined for each critical unitary process identified at step 1. Table 1 shows the set of reconfiguration alternatives for the primary crushing. Performance analysis was run through simulation, based on the modified RBD model of the system integrating the modification required by each alternative. The output is the expected failure rate and related CAPEX for each configuration alternative.

Table 1. Reconfiguration alternatives for the primary crushing unitary process

Reconfiguration alternatives	Expected failure rate	CAPEX [k$]	Proposed reconfiguration
'As-Is'	0,0026	0	No change in the system
'To-be 1'	0,0015	6,25	Add a redundancy over the Crusher
'To-be 2'	0,0014	7,1	Add a redundancy on Overload-Feeder line

STEP 3: Joint optimization model resolution. In this step, the optimization model [12] was applied for each unitary process considering the different configuration alternatives. The joint model's objective function is the maximization of the system effectiveness, that is given by the difference between the system expected revenues and the required investments cost and the production and maintenance costs (both hidden and tangible) in the planning horizon. The output is the optimal joint planning of maintenance and production, the expected utilization and availability (Fig. 4), the number of batches to be produced in each period and the batch size. Moreover, the reconfiguration alternatives that maximize the objective function are selected for each unitary process under analysis (by mean of a Boolean variable) (Table 2).

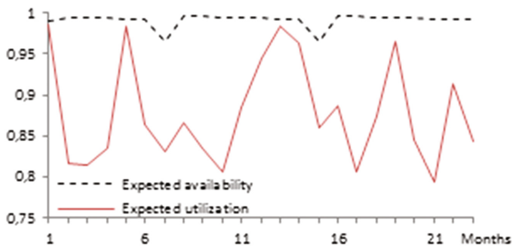

Fig. 4. Joint optimization output: expected utilization and availability of the plant

Table 2. Joint optimization output: optimal configuration alternative for each unitary process

Critical unitary processes	Configuration Alternatives		
	'As-is'	'To-be 1'	'To-be 2'
Primary crushing	0	**1**	0
Primary milling	0	0	**1**
Secondary milling	**1**	0	0
Secondary crushing	0	**1**	0

STEP 4: Reliability-based system-level performance analysis. The selected reconfiguration alternatives come from the optimization done at unitary process level in the previous step. In order to evaluate if the system performance effectively improves by introducing them, system performance analysis is run again through

simulation and adjusting the RBD model of the plant. In this case, the expected system unavailability is reduced from 18% to 10% justifying a reconfiguration investment's profitability.

4.1 Discussion

The joint framework application enlightens the potentiality of the integration between system design and maintenance and production planning. Scenario-based sensitivity analysis is useful to discuss the underlying dynamics that correlate maintenance and production planning with system design. Table 3 shows how the design reconfiguration selected through the joint optimization model changes when MTTR (Mean Time to Repair) variates. Reducing the MTTR, the sub-systems criticality decreases, due to lower expected hidden costs and therefore investments in design decrease as well (Fig. 5).

Table 3. Optimal configuration alternatives

Critical unitary processes	Scenarios				
	A (−40% MTTR)	B (−20% MTTR)	C (As-is scenario)	D (+20% MTTR)	E (+40% MTTR)
Primary crushing	As-is	To-be 1	To-be 1	To-be 1	To-be 2
Primary milling	To-be 1	To-be 2	To-be 2	To-be 2	To-be 2
Secondary milling	As-is	As-is	As-is	As-is	To-be 1
Secondary crushing	To-be 1	As-is	To-be 1	To-be 2	To-be 2

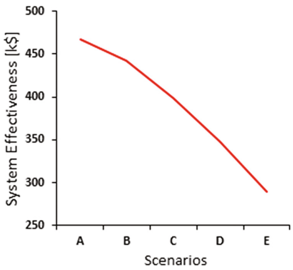

Fig. 5. Sensitivity analysis: System effectiveness vs. MTTR reduction

Another scenario-based sensitivity analysis was conducted considering the system production capacity (Table 4) (Fig. 6).

Table 4. Optimal configuration (C = system production capacity, D = Demand)

Critical unitary processes	Scenarios			
	F (C = 95% D)	G (C = 110% D)	H (C = 125% D)	I (C = 160% D)
Primary crushing	To-be 2	To-be 1	To-be 1	As-is
Primary milling	To-be 2	To-be 2	To-be 1	As-is
Secondary milling	To-be 1	As-is	As-is	As-is
Secondary crushing	To-be 2	To-be 1	To-be 1	As-is

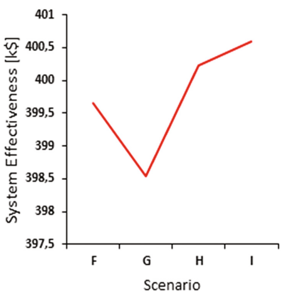

Fig. 6. Sensitivity analysis: System effectiveness vs. production capacity variation

The design configurations selected through the joint optimization model in the scenarios enlighten how required investments in new equipment are lower when the spare capacity is higher than the demand (in the extreme scenario (I) the investments result null). Moreover, in that case, the model indicates higher maintenance frequency.

5 Conclusions

The integration between maintenance and production planning and design reconfiguration is a challenging aspect for asset management. The methodology proposed in this paper introduces the possibility to integrate existing joint optimization models in the literature with a system-oriented reliability-based approach. The methodology consists in a four-step iterative process, which, through a reliability-oriented approach, enables evaluating a system's criticalities, identifying the best design reconfiguration alternative and determining the optimal maintenance and production planning. The methodology is applied in the mining industry.

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Dispositioning Strategies of Maintenance Tasks in Offshore Wind Farms

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Abstract. Operation and Maintenance (O&M) is a key value driver for offshore wind farms. Consequently, reducing O&M costs improves their profitability. This paper introduces different typologies of dispositioning maintenance tasks in offshore wind farms, in order to help design the strategies and organization of maintenance. Based on the special requirements of offshore wind farms regarding planning and controlling the O&M activities, a morphological analysis was developed. With this different disposition strategies for offshore wind farms could be generated. The consequences of choosing different characteristics are allegorized in an exemplary fashion. The work presented in the following is the foundation for designing a software-based dispositioning tool for usage in offshore wind farms, which will help to increase the effectiveness of the disposition in offshore wind farms by maximizing the number of accomplished tasks per day and minimizing the time technicians stay on the wind turbine and the ships.

Keywords: Tool asset management · Operation and Maintenance · Disposition · Offshore wind farms

1 Introduction

Improving the profitability of offshore wind farms is essential for a successful and sustainable energy turnaround. However, in relation to other energy sources offshore wind farms are still not as competitive. This becomes obvious when comparing the levelized cost of energy (LCOE), a key performance indicator for profitability of energy sources (Fig. 1. Levelized Cost of Energy [1]). The LCOE depicts the costs of power production respective to the expected operating life of a power plant. This calculation considers the total lifetime cost, such as discounted capital costs, overheads and expenses for fuel divided by the lifetime discounted electricity outcome. As it can be seen in Fig. 1 the LCOE for offshore wind farms exceed the LCOE for any other energy source.

To achieve a competitive advantage, the LCOE must be reduced. There are defined levers to do so, such as optimizing the O&M processes and organization, which consumes 28% of the [overall] lifecycle costs [2]. Consequently, O&M is a key value driver and crucial for improving the profitability of offshore wind farms. For example,

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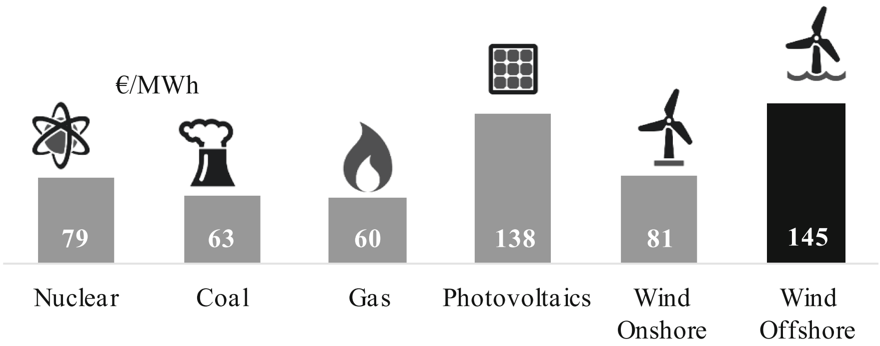

Fig. 1. LOCE [1]

a reduction of 10% O&M costs leads to an advance of 4% of earnings before interest and taxes (EBIT). An improvement of 1% of availability would lead to an increase of the EBIT by 2% [2].

Reducing O&M costs by optimizing the disposition efficiency is the overall goal of this study. Typologies of the disposition of maintenance tasks in offshore wind farms will be introduced. These typologies help to design the maintenance organization and determine the task and resource planning strategies. Effectively, it is used to design a software that plans and dispositions the tasks and resources in offshore wind farms. This software tool was developed as a prototype in the research project DispoOffshore, funded by the German Federal Ministry for Economics.

2 Maintenance in Offshore Wind Farms

The maintenance of offshore wind farms requires different standards and is more challenging than onshore maintenance. Those challenges and standards must be considered when designing disposition strategies for the maintenance operations.

Offshore wind farms are not easy to access, as they are placed several kilometers off shore and from the service hub. Therefore, vessels have to drop off the technicians by performing precise maneuvers. Additionally there is no access to the wind turbines when, due to bad sight or huge wave heights from the weather conditions, vessels cannot safely travel [3]. The efficiency of a daily working plan is therefore dependent on the ideal allocation of maintenance tasks to service technicians and vessels. This assignment determines whether the routes of the vessels are optimal and whether the appropriate technician with the required qualifications will finish all necessary tasks. If this assignment is not performed in an optimum fashion, the vessels will have insufficient routes and too few tasks for the estimated working hours each day. These considerations apply to designing the working plan of each day.

Previous work in this field suggests different approaches on planning and control of tasks and resources. In relation to this paper, methods of production economics and service management were examined. The Production Planning and Control Model (PPC-model) addresses the termination of problems and allocations of production services and resources [4]. This approach minimizes processing time needed to plan more tasks with limited resources (here: workers). To deal with the problem of combined tours and personnel planning within short time windows, Zäpfel and Bögl came up with multi-period vehicle routing and crew scheduling with outsourcing options. The strategy considers different vehicles with variable capacities and outsourcing options for tours and external staff [5]. The Product Service System (PSS) capacity planning, by Krug, schedules the performance of PSS close to optimum. One part of this concept is the prediction of future service dates and the warrant resources [6]. Irawan developed a strategy to optimize maintenance routing and scheduling for offshore wind farms. They also proposed a solution method based on a Dantzig-Wolfe decomposition of the problem, which strived to find the optimal route that minimizes maintenance costs [7]. Stålhane evolved a method for the similar purpose of optimizing the routing and scheduling of vessels to perform maintenance at offshore wind farms. On the other hand, two alternative models of optimization were assessed: an arc-flow and a path-flow [8].

None of the previously mentioned approaches meet all requirements for the dispositioning in offshore wind farms on an operational level. The research by Irawan and Stålhane are most relevant to this paper. However, they do not take into consideration the staff's qualification, organizational circumstances nor a prioritization of the tasks, as an important part of the disposition on an operational level.

3 Disposition Strategies of Maintenance Tasks and Resources in Offshore Wind Farms

Based on the special requirements of offshore wind farms, a morphological analysis of the disposition of maintenance tasks in offshore wind farms is introduced. This analysis can be used to design the maintenance processes and disposition strategies for the offshore wind farm's maintenance organization.

3.1 The Morphological Analysis

The morphological analysis (or box) was the chosen technique to identify and evaluate the imposed requirements of offshore wind farms. As there are complex restrictions for the maintenance organization of offshore wind farms, it is hard to identify a solution which meets all requirements. The morphological box depicts all the requirements while helping to determine the best disposition strategy.

The morphological analysis was first introduced by Zwicky, showing the totality of conceivable solutions for a problem. First, the problem is defined, analyzed, and generalized to partial aspects. These partial aspects are classified with independent parameters, which can apply to all possible solutions. After this, the parameters are specified with their characteristics. All parameters must be depicted in the morphological box, the dimensions of which equal the characteristics. All possible solutions have to be assessed and evaluated without prejudice before the final decision can be made [9].

The morphological analysis is suitable to describe complex structures by organizing the tokens of dispositioning. By doing so, the parameters must fulfill the following criteria: purpose significance, ability to ascertain, differentiability, integrity, ability to quantify, and independence from one another [10–12]. In the following, a morphological analysis for the dispositioning strategies in offshore wind farms is introduced.

3.2 Morphological Analysis of Wind Farm Specific Requirements

The morphological analysis was performed throughout interviews and surveys with experts in the field of dispositioning tasks for offshore wind farms. The results of these expert interviews were partitioned into 4 categories, which cover 26 parameters. These parameters can apply to a variety of feasible solutions, and each are specified with 2 to 7 characteristics.

These categories involve the "Sequence of dispositioning steps", "Prioritizing and optimizing", "Assignment team and means of transport" and "Weather", all described in the following.

The category "Sequence of dispositioning steps" contains all of the steps needed to assign tasks to the respective qualified person or resource, assemble the teams, and assign the means of transport (Fig. 2). The chronology of these steps can vary and therefore influences the outcome of the disposition strategy. The allotted number determines on which position, within the heuristic, the respective assignment step would be.

Categories	Parameters	Characteristics		
Sequence of dispositioning steps	Qualified person/resource	1	2	3
	Means of transportation	1	2	3
	Assembling the teams	1	2	3

Fig. 2. Sequence of dispositioning steps

The category "Prioritizing and optimizing" determines whether the tasks were preselected during preparation, whether the tasks were allocated manually, automatically, or semiautomatically, and whether the tasks are divided into subtasks ad recombined to task bunches (Fig. 3). Furthermore, parameters for the prioritization of tasks found in the task repository and the optimization of criterion for the algorithm are incorporated in this category. Either the due dates, locations, first-in-first-out principal or their urgency, which can be related to opportunity costs by not operating wind turbines, can prioritize tasks. This prioritization influences the order of the tasks in the repository. To receive the optimal task disposition, the algorithm needs a criterion to optimize. The criteria meet targets, such as making full use of the ships' or teams' workload, utilizing shorter routes, lowering costs, minimizing the preparation time, the shortest overall duration or maximizing the quantity of disposed tasks.

Categories	Parameters	Characteristics				
Prioritizing and optimizing	Process of task allocation	Manual	Automatic	Semiautomatic		
	Fission and recombination of task bunches	Yes	No			
	Prioritizing the tasks	Urgency	Due date	Location	First in first out	
	Optimizing algorithm	Minimizing set-up time	Vessel/team utilization	Shortest overall duration	…	Quantity of tasks

Fig. 3. Prioritizing maintenance tasks

The category "Assignment teams and means of transport" determines all aspects that are needed for the team allocation. Figure 4 shows alternative options regarding the means of transport as a part of this category. This selection can be made manually, semi- or full-automatically, but there are also different options within the means of transport themselves. Either a helicopter or a ship can be used. Although the helicopter requires less time to reach the wind farm, it is more expensive than a ship transfer. However, this is only necessary for urgent repairs during weather conditions the ships cannot handle.

<table>
<tr><th>Categories</th><th>Parameters</th><th colspan="4">Characteristics</th></tr>
<tr><td rowspan="3">Assignment teams and means of transport</td><td>Team allocation</td><td>Manual</td><td>Automatic</td><td colspan="2">Semiautomatic</td></tr>
<tr><td rowspan="2">Means of transport</td><td colspan="2">Teams not restricted to one ship</td><td rowspan="2">Teams restricted to one ship</td><td rowspan="2">Heli-copter</td></tr>
<tr><td>Shuttle between wind farm and service hub</td><td>No shuttle between wind farm and service hub</td></tr>
</table>

Fig. 4. Team assembling and means of transport

The last category, "Weather", displays if certain weather characteristics are considered in the distribution (Fig. 5). This covers the wind direction, wave height, restricted sight (due to fog or night time), and tide.

Categories	Parameters	Characteristics	
Weather	Wind direction	Yes	No
	Wave height	Yes	No
	Restricted sight	Yes	No
	Tide	Yes	No

Fig. 5. Weather

3.3 Disposition Strategy Development

A disposition strategy is an approach to make fast disposition decisions with justifiable expenditure for the purpose of the striven for targets [13]. Based on the morphological analysis, described in the previous section, different disposition strategies for offshore wind farms can be designed. This can be achieved by choosing a specific path through the morphological box.

The tasks are defined by several attributes, such as the assumed time the technicians need to accomplish the task, the due date to make sure that the guarantee does not expire, and the priority measured by urgency such as troubleshooting over regular maintenance and rectification of defects to inspections. A list of required qualifications confines the variety of teams and means of transport. In addition, lists with needed material and tools, as well as the location of the task, whether it is on a wind energy plant and the platform, are part of a task's characterization. Changes in characteristics of a parameter lead to different disposition strategies. The relevant characteristics depend on the operational procedures for maintenance of the considered wind farm.

Two examples: As there are only six food boxes available per wind turbine the maximum number of people on a turbine is set to six. These boxes contain supplies for workers in case recovery is not possible at that time. This needs to be considered when assigning tasks to the technician teams on the same wind turbine.

Additionally, altering the choice for means of transport has a significant effect on the disposition too, as displayed in Fig. 6. Using a ship offers two different opportunities of usage. A so-called "taxi service", which does not restrain the teams to the use of only one ship, allows the team to use any vessel in the wind farm on demand. Using a so-called "shuttle service" links the teams to a certain ship which has a predefined route through the wind farm. Figure 6 illustrates the alternation between a "shuttle service" to a "taxi service". These modifications have a decisive effect on the disposition software, effects on the time the teams spend on one ship and how many ships are in use.

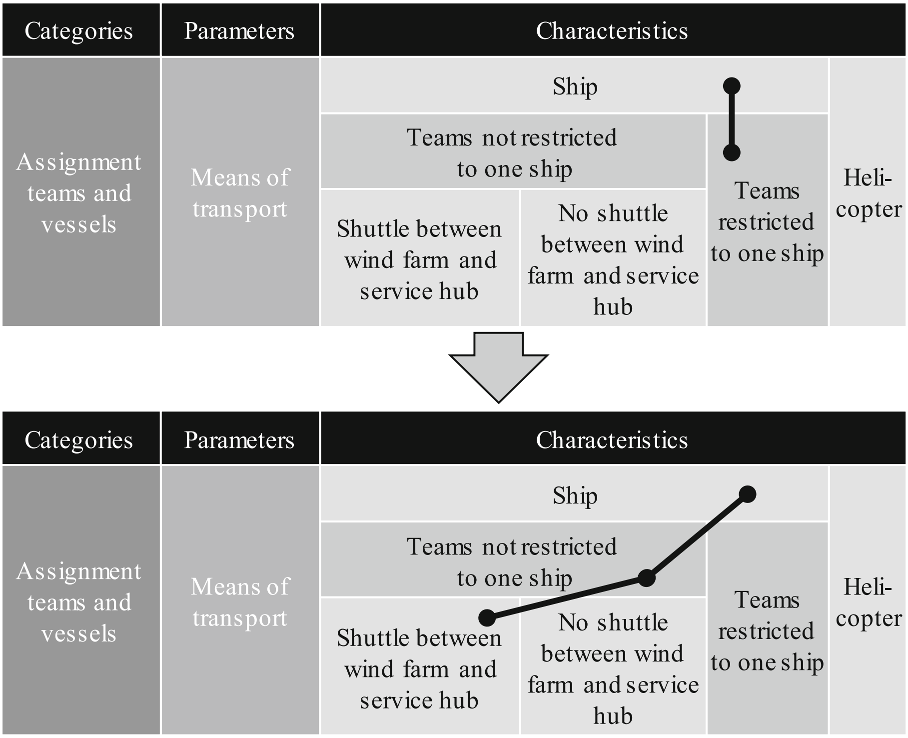

Fig. 6. Means of transport

It becomes obvious that by altering the boundary conditions and characteristics, the disposition strategy changes.

4 Conclusion

Introduced was a morphological analysis, which enables a systemic approach to design the disposition strategy of offshore wind farms. This morphological analysis was acquired by interviews and surveys with experts in the field of dispositioning tasks for offshore wind farms and based on the special requirements of offshore wind farms regarding the maintenance organization, planning, and control. The results show 4 parameter categories, which cover 26 parameters. These parameters can apply to a variety of feasible solutions and are specified with each 2 to 7 characteristics. Based on the described morphological analysis, different disposition strategies for offshore wind farms can be designed. The consequences of choosing different characteristics were shown in examples. The work presented is the basis for designing a software-based dispositioning tool for usage in offshore wind farms. This software tool will help to increase the effectiveness of the disposition in offshore wind farms by maximizing the number of finished maintenance tasks per day and minimizing the time technicians stay on the wind turbine and the ships. The next steps include the validation of this software tool, in total, during live operation in a wind farm. Further research should be conducted in regards to digitalize and connect the whole data chain, from automatic generation of maintenance tasks to automatic control and disposition of maintenance resources.

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Cyber-Physical (IIoT) Technology Deployments in Smart Manufacturing Systems

Advances in Internet of Things (IoT) in Manufacturing

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Abstract. As a promising technology with increased adoption in recent years, Internet of Things (IoT) realizes ubiquitous interconnection of physical devices through internet, opening doors for building powerful industrial applications by leveraging the advances in sensor technology and wireless networks. IoT technologies can be viewed as enablers for smart manufacturing and Industry 4.0. This review paper focuses on applications of IoT in manufacturing, which is also known as Industrial Internet of Things IIoT. To that end, technologies relevant to the application of IoT in manufacturing, such as wireless sensor networks (WSNs), smart sensors, big data analytics, and cloud computing are discussed. A service oriented architecture (SOA) based four-layer model for realizing IoT applications in manufacturing is proposed. Finally, a review of the state of art of IoT applications in manufacturing including shop floor automation, predictive maintenance, energy aware manufacturing, and smart workers is presented with relevant industry use cases.

Keywords: Industrial Internet of Things (IIoT) · Big data analytics · Wireless sensor networks (WSN) · Predictive maintenance · Energy aware manufacturing · SOA · Smart manufacturing · Industry 4.0

1 Introduction

1.1 Understanding Internet of Things

Internet of Things (IoT) can be defined as an ecosystem of interconnected, uniquely identifiable physical devices and software components having an ability to exchange data with other devices over a network with limited human intervention. The internet of things Global Standards Initiative (IoT-GSI) defines IoT as "*a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies*" [1]. One can visualize IoT as a seamless interconnection of the physical world and cyber worlds, with a pervasive presence around us [2]. IoT technologies provide means for physical objects to be monitored or controlled remotely over a network. This capability, coupled with ubiquitous interconnection of heterogeneous devices, opens doors for a new class of applications. The physical devices that can be interconnected vary from tiny electronics embedded into products to large automated buildings, vehicles, and everything in-between. An IoT application relies on a

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foundation created as a result of integration of sensors, actuators, and tracking devices such as RFID tags coupled with information and communication technologies, enabling cooperation among interconnected objects to achieve common goals.

There is an increased interest in using IoT in industries [3]. The three-year old Industrial Internet Consortium (IIC) comprises over 250 member companies [4]. Applications of IoT appear in a diverse set of industries including manufacturing, agriculture, traffic monitoring, food processing, health monitoring, and personal fitness. Additionally, there has been a sharp increase in the number of publications related to IoT. A search of Web of Science indicated that the number of publications in IoT increased from 0 to 6836 between 2006 and 2016. It is estimated that IoT will encompass 50 billion devices by 2020 [5].

This review focuses on identifying existing IoT technologies, architecture requirements, and applications specific to the manufacturing domain. In the current day global competitive environment, manufacturing companies are continuously striving to improve their competitiveness in terms of product price, time to market, efficiency of production processes, costs, etc. New technological paradigms like IoT play a crucial role in keeping companies competitive while meeting continuously changing customer needs. In fact, IoT has a great potential to transform the manufacturing sector [6] by creating novel business opportunities. IoT technologies enable integration of sensor and other electronics into various physical elements in a manufacturing plant where, with cooperative communication, entities can autonomously exchange information leading to processes that can govern themselves by taking intelligent decisions. This provides unprecedented opportunities for the manufacturing sector where resources can be monitored in real time, enabling higher safety and performance. This promising idea has led to several global initiatives such as “the Fourth Industrial Revolution” in German industry (also called “Industry 4.0”), “Factory of the Future” in the European Union, and “Made in China 2025”.

2 Enabling Technologies for IoT Applications

In this section, technologies which form the backbone of IoT applications in manufacturing are discussed.

2.1 Wireless Sensor Networks (WSN)

There are barriers to running cables on a factory floor because of potential safety hazards and associated costs. This is exacerbated as the distances between the connected points grow. WSNs can alleviate many of these barriers by offering numerous spatially distributed sensor nodes[1] that are wirelessly connected through gateways to enable remote monitoring of physical or environmental conditions [7]. Table 1 summarizes currently available wireless communication technologies suitable for WSN [8, 9].

[1] Autonomy refers to devices equipped with sensors capable of self-recovery and making localized decisions.

Table 1. Comparison of different communication technologies in IoT

Technology	Range	Frequency	Power consumption	Data rate
NFC (IEC 18000-3)	Up to 0.2 m	13.56 MHz	Low (~50 mA)	Up to 424 Kb/s
Bluetooth LE (Bluetooth 4.2 Core Spec)	Up to 100 m	2.4 GHz	Low (~12.5 mA)	1 Mbps (Smart/ BLE)
Wi-Fi (IEEE 802.11a/b/g)	Up to 100 m (can be extended)	2.4 GHZ/5 GHz	Medium/High (~116 mA)	150–200 Mbps (download); up to 20 Mbps for upload
WiMAX	Up to 30 miles	2–11 GHz	High (Depends on range of coverage ~200 W)	Up to 83 Mbps (download); up to 46 Mbps (upload)
RFID	Distance driven by operating frequency: up to 200 m for active RFID	LF:125–134 kHz HF:13.56 MHz UHF:850–960 MHz	Low (Depends on operating frequency and tag type)	Up to 640 Kbps
Cellular (4G/LTE)	35 km max for GSM, 200 km max for HSPA	1900/2100 MHz	High (~184 mA)	3–10 Mbps (LTE)
Z Wave (ITU-T G. 9959)	30 m	900 MHz	Low (~2.5 mA)	Up to 100 Kbps
ZigBee (IEEE 802.15.4)	Up to 100 m	2.4 GHz	Low (<10 mW)	250 Kbps
EnOcean (IEC 14543-3)	Up to 300 m (outdoor) and 30 m (indoor)	315 MHz, 868 MHz, 902 MHz	Low (Stand By: 100 nA)	Up to 125 Kbps

A typical autonomous WSN node consists of radio, battery, microcontroller, analog circuit, and sensor interface [7]. As seen in Table 1, high data rate capability often results in power hungry devices. The selection of communication technology for manufacturing shop floor is largely influenced by the size of the plant, the number of physical assets that need to be monitored, and their location within the plant.

2.2 Smart Sensors

Sensors have evolved over the years from bulky dedicated devices to miniature multi-variable sensing packages. Sensors are primary sources for any actionable data that can contribute to profitable business decisions. A smart sensor has localized computational capability to turn raw data into actions in real time, allowing fast responses and circumventing network latency issues. While some smart sensors have actuation capability, this function is mainly limited to dedicated hardware. A number of sensors are already being used the manufacturing domain, primarily to monitor machines and processes. A recent survey from PwC reveals that 35% of the manufacturing industry in US is already collecting and using data from smart sensors embedded in machines, to enhance operational efficiencies [10].

2.3 Big Data Analytics

Increased adoption of sensors to monitor physical assets such as machinery and end products leads to generation of massive amounts of raw data, estimated to be in the order of 1000 Exabytes (or 1 Zetabyte) annually per plant and expected to increase in coming years [11]. This massive amount of data, commonly referred to as big data, needs to be analyzed in a computationally efficient and timely manner for identifying trends and patterns among process parameters and outputs. Insights derived from such big data analytics is already changing decision-making in industry and a number of new ventures are targeting related business opportunities [10].

2.4 Cloud Computing

Cloud computing is changing the way industries do business by eliminating upfront cost for localized computing resources, and replacing this with lower-cost "pay-as-you-use" computing as a service over the Internet [12]. Moreover, cloud computing is dynamically scalable, which makes it an ideal platform for big data analytics where powerful computing resources may be used intermittently. Cloud computing's scalability, better resource utilization, and plug-and-play networks of heterogeneous devices have led to the emergence of "Cloud Manufacturing" [12]. Cloud manufacturing can be viewed as an approach where hardware and software functions are virtualized as a scalable, "elastic", virtual manufacturing enterprises that can be rapidly configured or shut-down. This can be expected to play an important role in realizing the full potential of the IoT paradigm.

3 Architecture for IoT Applications in Manufacturing

Service Oriented Architecture (SOA) consists of discrete services, which are composable to achieve a higher-level goal. SOA standards allow for a physical device's functionality to be offered as interoperable services independent of vendors, products, and technologies [13]. Since IoT is based on cooperative communication between heterogeneous devices to achieve a specific goal, SOA can be applied [14].

There has been a lot of research related to design of multi-layer SOA for IoT in general and also for specific domains like manufacturing. Gubbi et al. [15] proposed a cloud-based framework for generic IoT that includes three layers: network of things, cloud computing, and applications. Atzori et al. proposed a three-layer model for IoT consisting of an application layer, a network layer, and a sensing layer [2]. Lee et al. suggested a five-layer architecture model for cyber-physical manufacturing systems consisting of a sensing level for data acquisition; a data-to-information conversion level involving smart analytics for component health; a cyber level for cyber modelling and simulation; a cognition level for remote visualization; and a collaborative-diagnostics and configuration level which involves self-configuration and self-optimization based on learning [16]. Y. Zhang et al. proposed a real-time information capture and integration framework for IoT applications in manufacturing, comprising 3 layers: event sensing and capturing; manufacturing and data processing; and application services [17].

The architectures proposed by Gubbie et al., Atzori et al., and Zhang et al. are functional architectures and are relatively compatible where IoT applications are present only at the top layer, whereas in the architecture proposed by Lee et al., each level has increasingly sophisticated IoT applications, making it a hybrid of functional and application architecture. In this paper, we build on these to propose a 4-Layer SOA for IoT applications in manufacturing including sensing and data acquisition, network, services, and applications layers as illustrated in Fig. 1 along with the specific functionality for each layer. Note that our proposed architecture would be suitable for cloud manufacturing or non-cloud manufacturing. While no industrial implementation of the proposed architecture exists at present in its entirety, the individual elements of the architecture have been successfully realized in practice, and are presented in the next section.

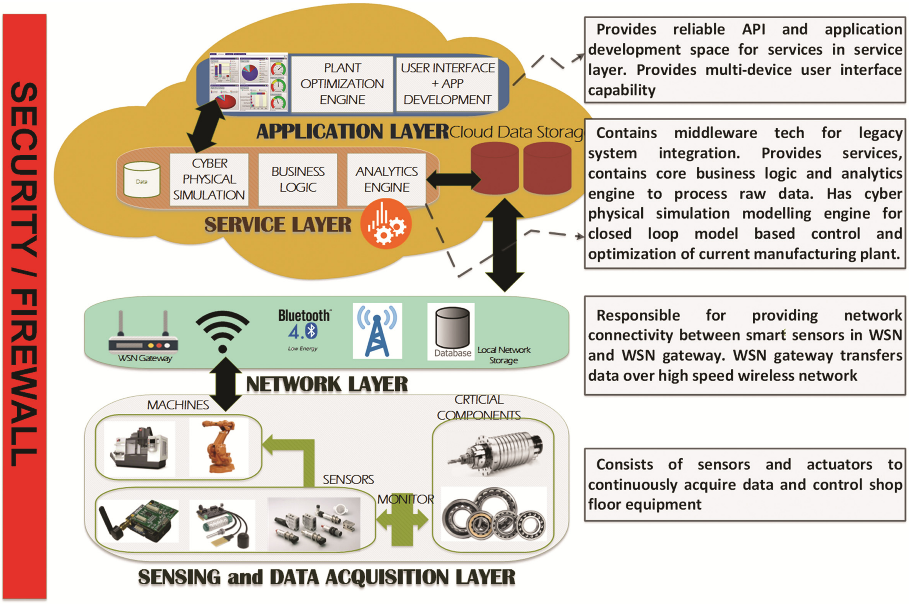

Fig. 1. Proposed SOA-based architecture for IoT applications in Manufacturing

4 IoT Applications in Manufacturing

A: Real-time data collected from the shop floor can be used for designing an optimal production systems with automated work flows. Optimal decisions on production scheduling are driven by results of raw data processed through powerful analytics. *Industry Example:* At Siemens' electronics manufacturing plant in Amberg, Germany, machines and computers handle 75% of the operations autonomously, with roughly 1,000 automation controllers in operation along the production line. Parts being produced communicate with machines by means of a product code that tells the machines their production requirements and which steps need to be taken next [18].

B: Analyzing real-time data on a machine's health in correlation with equipment process models can lead to predictive maintenance based on the remaining useful life estimation and automated condition-based maintenance strategies, leading to lower machine downtime and increased productivity. *Industry Example:* GE's digital wind-farm (a fleet of IoT-enabled wind turbines) is monitored in real time and the collected data on rotor speed and weather conditions is used to build predictive-maintenance models using GE's Predix™ cloud-based analytics software. "*Every day at GE's remote M&D Center in Atlanta, Georgia, GE collects more than 30,000 operating hours of data from a fleet of more than 1,500 assets. Insights drawn from this volume of power generation big data have translated into total customer savings estimated at $70 million in 2014*" [19].

C: The manufacturing sector typically accounts for one-third of the global energy demand [20]. An IoT application allows for continuous measurement of energy consumption of physical assets on the shop floor. This, when correlated with production plans and states of assets, can lead to dynamic, closed-loop energy regulation algorithms to intelligently regulate assets to the low-energy states, resulting in energy savings while maintaining the throughput level (despite the ramp-up time from a low-energy state to an operational state). This is not only applicable to manufacturing equipment, but also for plant HVAC and lighting systems. *Industry Example:* At BMW's Spartanburg (SC, USA) production plant, IoT-based smart energy meters constantly measure energy consumption of the facility to predict and identify sources of abnormal or high energy consumption. This led to total energy savings of over 100,000 kWh in the first year, which is estimated to correspond to total energy cost savings of about 25 million euros over next 10 years. Additionally, the system can also identify imminent breakdowns of equipment by monitoring energy usage. For example, if a piece of equipment is using more energy without any change in production parameters, it is likely a result of malfunction or wear and tear of its components [21].

D: There is a new trend in applying wearable technology to enhance productivity and workforce safety. *Industry Examples:* Thyssenkrupp, AG has more than 24,000 service technicians who use mixed-reality devices in elevator service operations. Hands-free remote holographic guidance reduces the average length of service calls by up to four times [22]. Intel and Honeywell have collaborated to develop a system of wearable sensors that monitor a worker's breathing, heart rate, posture, and toxic-gas exposure. Data from the sensors is analyzed and displayed on cloud-based dashboards, helping managers better anticipate unsafe working conditions [23].

Mapping the application B to our four-layer SOA model, smart sensors in the sensing and data-acquisition layer continuously monitor the electronic signature of components of a windmill such as rotor bearings, rotor blades, gearbox, etc. This data is transmitted in real time to the service layer through WSNs in the network layer. The service layer may be cloud-based or on-premises proprietary software having analytics capability to sift through the data and detect any anomalies or trends that are indicative of component degradation by comparing the data with inputs from analytical reliability component models. These trends, along with estimated remaining useful life of the component derived by comparison to component reliability models, are presented on user dashboards in the application layer. This can be used to automatically trigger preventive maintenance or to alert service managers to schedule maintenance of affected components, helping to avoid unexpected downtime due to breakdowns and failures. Next, application D comes into action, where service technicians use mixed-reality wearable technology devices to efficiently identify the component and service it.

5 Conclusions and Challenges

This paper reviewed the main enabling technologies for IoT: wireless sensor networks, smart sensors, big data analytics, and cloud computing. Based on prior architectures for such systems, a new SOA-based four-layer architecture was proposed. Successful IoT applications in manufacturing were reviewed and mapped to the proposed four-layer architecture. Integration of smart-sensing and actuation capabilities on equipment with cyber space offers prospects of new levels of productivity, and could become an important dimension of competition in the future. A few of the current IoT applications in manufacturing used cloud computing, but most did not. There are several research challenges limiting widespread adoption IoT applications in manufacturing: (1) Data security/privacy concerns: opening up vast number of connected devices to the cloud offers multiple points of entry for an attacker; (2) Integration of legacy equipment often needs dedicated patches and may not be always feasible; (3) Need for open standards: Standards help improve interoperability of different systems resulting in sustainable functioning of the system and increased adoption; and (4) Technological barriers: manufacturing applications that require real-time feedback control may not be able to tolerate the data transfer latency that can arise with IoT. Other challenges include the high cost of sensor instrumentation and legal issues of data ownership. Overall, emerging IoT applications in manufacturing open new research challenges that require technology standards and solutions that can harness large streams of real-time data to optimize operations across the entire manufacturing life cycle.

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The Transition Towards Industry 4.0: Business Opportunities and Expected Impacts for Suppliers and Manufacturers

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Abstract. Industry 4.0 is today one of the major opportunities for companies competing in the market. In last few years, more and more companies have started to define the path to move from their traditional production systems towards the Industry 4.0 paradigm; accordingly, different models have been proposed in literature to support the business transformation. This paper reviews the technological improvements proposed by Industry 4.0 to understand what are the main processes involved in the transformation and what are the suitable strategies to face the business and operational changes that are required. In particular, we identify and discuss two main perspectives: the suppliers and the customers. For both of them, different business opportunities are presented, and the expected performance improvements discussed.

Keywords: Industry 4.0 · Smart manufacturing · Business transformation

1 Introduction

The Industry 4.0 paradigm has opened high potentialities to implement new business and operational models. Many manufacturing companies around the world have been encouraged to invest in research and industrial projects to enable the realization of smart factories [1–3]. In this context, several technology providers have started offering products and product-service solutions (PSS) based on key enabling technologies that have achieved a stable and mature phase of their lifecycle, i.e. IoT for data acquisition and transfer, autonomous and collaborative robots, IT platforms for big data [4]. Despite this, many customers (i.e. manufacturing companies) are still restive to change their production processes to be Industry 4.0-compliant. There are several implementation barriers for smart manufacturing, not exclusively technology-related. The main issues refer to the business process transformation of manufacturers, and include, among others, organizational impacts and employees skills [5]. Further, some barriers depends on companies' business models and on their positioning in the supply chain.

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The aim of this paper is to clarify what are the potentialities of implementing Industry 4.0 solutions in different contexts, discussing the potential business opportunities and benefits, and to provide a theoretical and practical contribution to the companies that are defining their path towards a smart manufacturing model.

2 The Vision of Industry 4.0

2.1 The Key Enabling Technologies

Different technologies have been classified as pillars for Industry 4.0 [6]. For example, a report from the Boston Consulting Group [7] identified nine key technologies that can support the smart transformation of an industrial production system.

A first class of technologies refers to autonomous robots and additive manufacturing, advanced "hardware" technologies based on innovative devices and equipment that support the automation of a production process. One of the main aspects regarding automation solutions is the shift towards collaboration, adaptability, and autonomy to react to external changes [8, 9], resulting in the implementation of Cyber-Physical Systems (CPS) that provide cognitive capabilities to physical assets [10].

A second class of technologies encompasses solutions for data management, acquisition, transformation, visualization, and integration [11]. In this class, we can identify technologies such as the (Industrial) Internet of Things (IoT) (the core technology for connecting objects and devices in manufacturing systems, allowing communication and cooperation [12]), big data analytics, cloud technology (along with cybersecurity solutions) [13], simulation and augmented reality that can be used in product and process design, production control, and optimization [14] using data coming from different sources.

These two classes of technologies allow the realization of horizontal and vertical integration [15]. Horizontal integration refers to the creation of a network enabling real-time communication among suppliers, manufacturers and final customers. Vertical integration involves the IT structure inside an enterprise enabling data exchange from the sensors/actuators level to the ERP level, in order to provide real-time decision-making and corrective actions from the business to the shopfloor.

Although technology represents one of the main aspects driving the transformation of traditional manufacturing companies, the introduction of innovative solutions has to be guided by strategic considerations about business opportunities from the introduction of Industry 4.0 principles. In the next paragraphs, a discussion of these business transformation opportunities is provided.

2.2 The Design Principles of Industry 4.0

Smart factories are characterized by the following features, or design principles, conceived to develop production processes aligned with the Industry 4.0 vision [16]:

- Interoperability. Horizontal and vertical integration among different systems require the creation of specific standards and protocols. Although some attempts of

standardization have been made by the German *Plattform Industrie 4.0* with the Reference Architecture Model for Industry 4.0 [17], the definition of interoperability standards still represents an open research issue.
- Virtualization. In CPSs, each physical asset is characterized by a virtual counterpart that is used to perform simulation and optimization in a virtual environment [18].
- Decentralization. If changes occur along processes, distributed intelligence embedded in physical assets allows faster and more responsive corrective actions, facilitating decision-making processes, which can be managed at local level [19].
- Real-time capability. The IoT enables real-time information flows, with the possibility to achieve real-time optimization inside the processes [20].
- Service orientation. CPSs, together with cloud technologies, enable the implementation of service-oriented architectures (SOA), where computation capabilities can be accessed via the web, and process operations can be performed only when required by products through sensing technologies.
- Modularity. Advanced manufacturing solutions are conceived as modular, in order to be adapted to the different needs of the production. Reconfigurable Manufacturing Systems provide an example of a modular structure [21].

The abovementioned features suggest that Industry 4.0 does not influence production processes exclusively from a technological point of view. Business processes require also a change of perspective to fulfil horizontal and vertical integration. For this reason, a deeper insight about business transformation proposed by Industry 4.0 emerges as essential.

3 The Business Transformation of Industry 4.0

3.1 The New Paradigm of Collaborative Business Processes

To understand the business transformation that will involve the factories of the future, it is necessary to study in depth the changes in business processes, as proposed by the Industry 4.0 paradigm. The Industry 4.0 is a wide and global vision, involving the whole manufacturing environment, proposing new perspectives for business processes too. Thanks to the connectivity offered by IoT, a manufacturing process can be seen as one of the main elements of a more complex system (Fig. 1). Here, the factory is one of the crucial points for data generation, while data exchange is always bidirectional, making suppliers, customers, transportation systems and employees fully integrated and relevant for the optimization of the whole system. In such a context, the network of stakeholders, products and equipment, allows an end-to-end engineering integration along the value chain [22], while five value creation factors - products, processes, equipment, humans and organization - can be identified, and thus properly managed by companies to undertake the Industry 4.0 transformation.

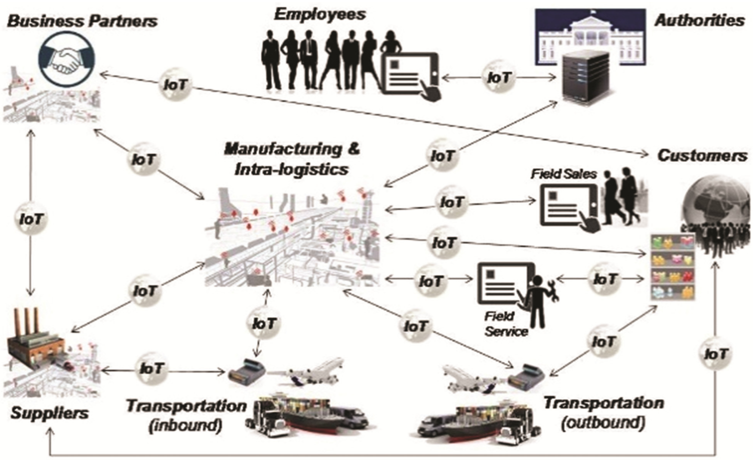

Fig. 1. Business scenario of Industry 4.0 [17]

Products become smarter, because they have embedded sensors and identification technologies [3]. They can do computations and communicate with the environment, providing their identity, state and properties [23]. To communicate with these smarter products, the equipment and the processes have to change. Indeed, the factory becomes conscious and intelligent enough to make decisions at decentralized levels and in real time about machines maintenance and production control [3]. Also the work organisation changes, moving to "human cyber-physical system", defined by [24] as a "system engineered to: (a) improve human abilities to dynamically interact with machines in the cyber- and physical- worlds by means of 'intelligent' human-machine interfaces, using human-computer interaction techniques designed to fit the operators' cognitive and physical needs, and (b) improve human physical-, sensing- and cognitive capabilities, by means of various enriched and enhanced technologies (e.g. using wearable devices)". Finally, relevant impacts at organizational level emerge. In particular, among the 68 competences identified as relevant for Industry 4.0 in [5], technological skills, mainly related to the use of data analysis and IT, as well as behavioural competences (i.e. teamwork, collaboration, negotiation), have cross relevance to succeed in an Industry 4.0 context. Further, an increasing importance is given to long-life learning and knowledge management, also regarding legislation and safety awareness.

3.2 Industry 4.0: A Model for Business Transformation

The main challenge faced by companies embarking upon an Industry 4.0 transformation refers to the alignment of their business strategy with the vision proposed by the smart manufacturing paradigm. This point, referred to as the "Envision" stage in [25], represents the first out of three steps characterising an Industry 4.0 transformation. It requires a deep understanding of the concepts at the basis of the Industry 4.0 paradigm, as well as a clear idea of the aims each company wants to achieve exploiting new technologies. For this reason, it mainly involves the management.

Also customers, suppliers and technology partners can take part in this stage due to their influence on business model configuration. This phase, which ends with an investment estimation, is followed by a second stage concerning the formulation of specific roadmaps to translate long-term strategies into practical areas of development. Readiness assessment models and maturity models [26, 27] play an important role in identifying companies' strength and weaknesses, and to understand the best development actions, according to the main organisational and business drivers characterising the Industry 4.0 environment where companies operate. Finally, during the "Enact" phase, a pilot project can be implemented in the company. Different opportunities can be envisioned, including either technological or organizational and infrastructure projects. A clear objective and a wide collaboration of all the involved stakeholders, with the composition of cross-functional teams, is needed to succeed. Only by identifying improvements and real advantages, it can be possible to extend pilot projects at large scale, transforming them into operational standards.

4 Different Perspectives on Business Transformation

The optimal path of business transformation towards Industry 4.0 is highly affected by different company's features and position in the supply chain. Suppliers, technology providers, and machines/equipment manufacturers (suppliers for short) can be characterised by sophisticated PSS business models, where the product offering is bundled with services, support, and knowledge [28]. Customers and users, instead, are usually manufacturing organisations using the technologies in their processes. Thus, suppliers embed the technology in their products-services, whereas the customers use the technology to make their processes more efficient and high-performing. Being the technology one of the main drivers for Industry 4.0 transformation, this differentiation strongly affects the opportunities that smart manufacturing introduction can bring to companies.

Also the other drivers of the transformation (e.g. product, processes, organization, governance) [26] can be related differently to the two perspectives of suppliers and customers. In addition, the expected impacts of Industry 4.0 in terms of measurable key performance indicators (KPIs) are not the same. While suppliers can benefit of major revenues for the increasing offering of digital solutions (made of services and products), customers can gain efficiency from a real-time controlled production, able to manage changes and predict failures and issues potentially generating downtimes or quality problems. All the aspects discussed above are presented in Table 1.

However, for the suppliers the transition towards Industry 4.0 is mainly supported by technological improvements, allowing them to develop their strategies through offering advanced PSSs. Here, the main challenges concern the acquisition of new technical competences, mainly to be used in R&D and IT departments. On the contrary, the most relevant business opportunities for customers involve operations management, for instance maintenance and quality practices or logistics issues. Also the workforce at the lowest level is involved, making the path to smart manufacturing more difficult [29], due to the complexity in acquiring technical competences about IT infrastructure and data management, coordinating actions among different departments, defining new practices in operations management, and estimating the return on investments.

Table 1. Suppliers and customers perspectives

	Business opportunities	KPI	Challenges
Suppliers	New digital business models	• Increasing of sales revenues from added services on products • New sales revenues from platforms and cloud-based services	• Privacy issues in sharing data with external stakeholders • Investment in integrated digital tools • Business partners not able to collaborate around digital solutions • Lack of digital skills in the workforce
	Digital engineering	• Reduced time to market, thanks to availability of integrated digital tools for product development • High level information from field for R&D improvements	
	Digital sales and marketing	• Better customer relationship with the possibility to offer personalized products/services	
Manufacturers	Vertical operations integration	• Faster decision-making • Improved quality, with real-time process control • Increasing of energy efficiency	• Investment in infrastructures for machines' connections • Cultural transformation to manage operations using digital technologies • Economic benefits and return on investment more difficult to estimate
	Horizontal integration	• Lower transport and logistics costs, due to real time supply chain optimization • Lower warehousing costs and spare parts management costs	
	Smart maintenance and service	• Preventive maintenance, thanks to real-time information from field • Increasing of asset utilization and availability	
	Digital workplace	• Better and faster training for operators • Increasing of productivity	

5 Conclusions

This paper presented an overview of the vision of Industry 4.0 in terms of key technologies and design principles. We illustrated the new paradigm of collaborative business processes to highlight its main impacts on traditional manufacturing. Discussing the point of view of suppliers and customers, it emerged that the former have to face more issues related to the transformation of operational processes, whereas the latter can benefit of the maturity of many key technologies that can be embedded in their products-services.

Such considerations call for the necessity to deeper investigate the different business opportunities of Industry 4.0 for suppliers and manufacturers, in order to provide proper advices about the design of path towards Industry 4.0, taking in consideration company-specific characteristics and requirements.

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Exploiting Lean Benefits Through Smart Manufacturing: A Comprehensive Perspective

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Abstract. Lean Production has proven to be a valuable methodology to improve productivity while reducing costs. Notwithstanding the countless successful lean implementations in the extant literature, others highlight its limitations, especially in production environments characterized by demand volatility, high product mix and reduced lot sizes. Technology is seen by many as a potential solution to such limitations, especially in the last years, with Industry 4.0 becoming an emerging frontier for the smart factories of the future. However, studies about the relationship between lean and smart manufacturing are scarce and often anecdotal. Therefore, the proposed work aims to fill this gap by developing a comprehensive model that links these two perspectives and serves practitioners to achieve lean's core goals in smart factories.

Keywords: Lean production · Smart manufacturing · Industry 4.0 · Lean and smart manufacturing

1 Introduction

Lean Production, intended as the worldwide diffusion of the *Toyota Production System*, has proven to be a successful driver for the achievement of world class manufacturing performance levels both in medium and large enterprises [1]. Notwithstanding the countless benefits that lean management can bring into an organisation, academic studies revealed that lean performance are compromised in presence of demand fluctuations [2] and that lean practices are most likely to fail in non-repetitive systems [3] characterized by "high product variety and low volumes" [4]. As a means of dealing with such turbulences, many researchers and practitioners have attempted to find alternative solutions, proposing better responses in the application of technology to their lean systems, intensifying the debate between the so-called "lean purists" and those supporting the combination of technology with lean practices [5]. Indeed, on the one

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hand, "lean purists" can in some instances view technology as an enemy for human labor [6] as well as a waste in terms of unnecessary costs and uncertainty within the company. On the other hand, "lean and technology supporters" believe that technology can be accepted in a lean system but only under the condition that it serves people and adds value to the process [7], for example in enabling problem-solving activities towards the achievement of lean's core goals. More recently, the diffusion of the new emerging frontier of Industry 4.0 has fueled this debate highlighting the existence of some hidden connections between these two perspectives. Given the nascent nature of the topic, existing scientific literature does not provide theoretical and empirical understanding of the lean and smart manufacturing overlap, including mutual supporting actions, benefits, as well as enabling and hindering factors. Therefore, this article aims at filling this gap by answering the following question: *What are the connections between lean and smart manufacturing?*

In the following section we present the adopted research methodology. Section 3 reports the findings of a literature review about lean production and Industry 4.0. Section 4 presents the theoretical model followed by its application to a case study of a manufacturing company presented in Sect. 5. To conclude, the last section presents the main research contributions and highlights further research directions.

2 Research Methodology

The research relies on a four-step process. In the first stage, an extensive literature review was carried out on the topics under study (lean production and smart manufacturing), as well as on their relationships in order to build the theoretical model. Secondly, the model was populated by means of industrial data, gathered from secondary sources (i.e., companies' websites, videos, non-academic articles and other online documentation, etc.) with the aim of identifying how smart manufacturing solutions available on the market can enhance the implementation of lean practices. Finally, the model was applied to a real-time case study of a manufacturing company in order to test its applicability and enhance its validity.

3 Literature Review

This section presents the dominant elements of lean production and smart manufacturing found in the literature, as well as the areas of integration.

Lean Production

Lean production is an approach that evolves multi dimensionally and gathers a large variety of management tools and "inter-related and internally consistent practices" summarized into four lean bundles: Just-In-Time (JIT), Total Quality Management (TQM), Total Preventive Maintenance (TPM) and Human Resources Management (HRM). Proponents of lean production suggest that the four lean bundles should be considered as a unique system [8] and that benefits on operative performance come from the synergic application of all lean practices and principles [9].

Lean Production and technology

Literature reports many technological applications already in use in the industry that allow to reach high levels of lean manufacturing sophistication [5, 10]. For example, technology fastens information sharing in the supply chain, facilitating the relation with suppliers and reducing lead time [11]. Moreover, it supports preventive maintenance activities [12, 13] as well as quality management [10], continuous improvement processes and defect prevention [14]. Furthermore, traditional lean tools have been modified through advances in technology, such as the "e-Kanban" system [15] or "ConWIP" and "Polca" systems to sustain the pull production schemes [13]. Although lean manufacturing can be applied without using ICT, investments in Information and Communication Technology are essential to increase the levels of lean manufacturing improvements [16]. Since the majority of lean manufacturing practices are information-intensive [14], the use of IT enables the exploitation of information within the organization itself (and the overall supply chain) in order to eliminate many examples of waste [13].

Industry 4.0 and Smart Manufacturing

Industry 4.0, also known as the fourth industrial revolution, refers to technical integration of Cyber-Physical Systems (CPSs) in all industrial processes where "components and machines become smart and part of a standardized network based on the well proven internet standards" [17]. Driven by the diffusion of ICT (including internet), the concept has been spread through different terminologies such as Smart Manufacturing and Smart Factory. According to [18], nine key technologies characterise smart manufacturing: additive manufacturing, augmented reality, big data analytics, cloud computing cyber security, horizontal and vertical integration systems, Internet of Things (IoT), robotics and automation, simulation. The combination of these technologies enables the realization of a smart manufacturing system [17] as summarized in the following table (Table 1).

Table 1. Main components of a smart production system

Smart product	A smart product is an intelligent product, conveniently equipped with sensors that collects process data during production. In this way, the process can be monitored in real-time
Smart operator	A smart operator is an employee equipped with wearable smart devices that allow him/her to get information inherent to his/her job
Smart machine	A smart machine is an intelligent device that uses machine-to-machine technology to make decisions and solve problems without human intervention
Smart workstation	A smart workstation assures reliable, economical and ergonomically processes, through changing its configurations dynamically without any loss of quality and productivity
Smart planner	A smart planner allows a better management and coordination of production activities, adopting IT as the main support technology

Lean and Smart Manufacturing

Information about the relation between lean and smart manufacturing is scarce and often anecdotal. Some scholars defined smart manufacturing as an advancement of lean production driven by the increased complexity and the raising demand for customized products [19]. Therefore, lean production has been considered as the necessary prerequisite for Industry 4.0 [20]. On the contrary, other scholars view Industry 4.0 as an enabler for lean implementation in that it addresses several of the barriers associated with a traditional lean implementation [21]. To this end, [21] creates a framework that summarizes barriers and challenges for lean development, proposing some solutions through Industry 4.0 implementation. [17] also proposes a framework where Industry 4.0 solutions support lean production, but it is limited only to the evaluation of *Kanban* and *Andon*. As a mean of filling the gap between these two paradigms and providing evidence about the hidden potential of Industry 4.0 to exploit lean benefits, a comprehensive model that integrates all the four bundles of lean production with the dimensions characterising the Industry 4.0 manufacturing approach is proposed.

4 The Theoretical Model

4.1 Model Creation

Given the definitions and findings reported in the above literature review, the model was constructed focusing the attention on the two macro dimensions of Lean Production and Industry 4.0, changing the perspective from a traditional to a smart point of view. In particular, the dimension "Lean Production" was articulated into the four lean bundles, as defined by [8], while the dimension "Industry 4.0" was divided into five sub-dimensions according to [17]. The model is presented in Fig. 1.

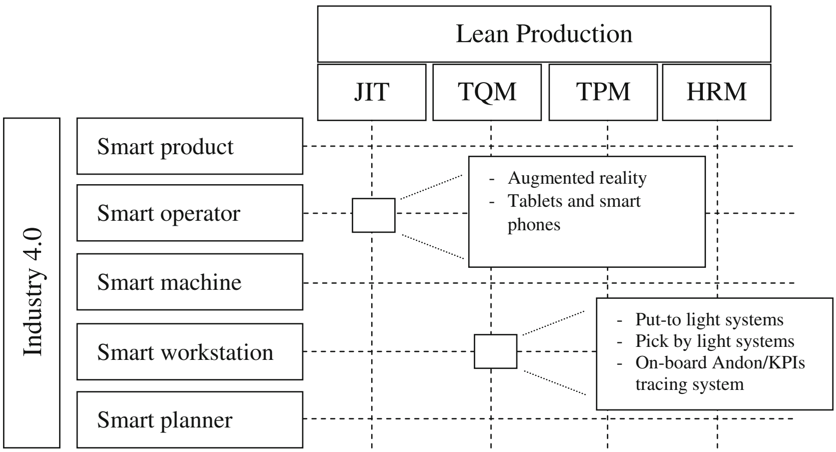

Fig. 1. The theoretical model

4.2 Populating the Model

The model was then empirically populated for analysing current solutions of smart manufacturing to enable lean implementation. In particular, it was filled using existing applications found on publicly available information collected from websites and company brochures. Some examples are reported below.

Smart Product. A product can provide through different sensors installed on board machines, operator, planners and workplaces all the information about its scheduling as well as its technical and production features. Achieved data can be re-elaborated through algorithms and analytics to improve process time (JIT) and quality (TQM), as well as to optimize equipment maintenance services (TPM). Moreover, real time information about product quality and lead times can support the implementation of training activities to improve operator capabilities in production (HRM).

Smart Operator. Augmented reality (i.e. smart glasses) enables continuous flow (JIT) and right assembly allowing error prevention (TQM), or support employees during preventive maintenance activities (TPM). In addition, smart devices make continuously available on the shop floor real-time KPIs, stimulating employees to empower their performances (HRM).

Smart Machine. A smart machine equipped with smart interfaces, can receive and send information about its production performances calling for fault-repair to avoid future break-downs (TPM) rather than low level of product quality (TQM). Moreover, smart interfaces installed on each single machine enable intra-communication across the production system, enhancing production and material handling efficiency and flexibility (JIT).

Smart Workstation. Smart devices in a workstation, by displaying working instructions through pictures and videos, can take the part of a poka-yoke system that can allow error detection (TQM) and training-on-the-job (HRM). Moreover, reconfigurable workstations re-adapt in real time on employees' characteristics and batch production requirements, so that lighting, font size and language can change in each work station on the basis of the worker characteristics (HRM). Finally, workplaces equipped with e-Kanban systems allow to exchange Kanban information making more efficient a production cycle (JIT).

Smart Planner. IT infrastructure allows to update *Kanban* to the new configuration requirements, synchronize dashboards with real-time data coming from the *Gemba*, as well as monitoring the sustainability and implementation of TPM activities. Thanks to IT infrastructure, the management can have continuously up-to-date information about the tasks performed by each employee in order to update the skill matrix.

5 Case Study

Alpha is a medium-size company and world leader in the design of cooling units and dispensing systems for cold drinks. Although lean production brought important improvements in the initial stages of its implementation at Alpha, limitations soon emerged, especially in the assembly area that is characterized by a high product mix and variable batch sizes. In order to overcome these limits, the company moved toward

Industry 4.0 by creating smart workplaces in the assembly lines in order to facilitate JIT activities, manage the high production variety and complexity and at the same time improve production process quality (TQM). On these premises, the first introduction of smart technologies in production in 2014 was eased by the affordability and availability of smart devices and the moderate investments required for *app* development. The project consisted on the introduction of some tablets to assist field-workers during assembly activities, as well as to support the production monitoring and problem identification. Each worker was then equipped with a tablet enabling pacing production through use of a takt-time counter available on the tablet interface. This option allowed the coordination of all the workers involved in the same line, establishing the rhythm of the production. A second technology was further introduced to support built-in-quality production, according to the *Jidoka* principle. In particular, the workplaces were equipped with an "Alert" system allowing any operator, in case of a problem, to stop the entire production line, call for the intervention of the technicians, support the intervention through an online root cause analysis, as well as track and trace maintenance and repair activities. As each field-worker becomes aware of the problems during the assembly and involved in the process improvement, the new technology allowed improvement of the workers problem-solving capabilities. Since the adopted technology initially presented some weaknesses that prevented the company from achieving its target performances, additional improvements were applied. In particular, intelligent mobile devices and algorithms were implemented to ease both on-the-job training activities and real-time performance monitoring. Thanks to the benefits provided by these tools, the activities of the shop floor were more transparent and easy to manage, allowing both field-workers and managers to concentrate on problem-solving activities to avoid production delays. The main changes were related to the introduction of a real-time and flexible scheduling system synchronized with work instructions and information on product configuration. The latter could be modified via web by each single operator. A specific algorithm was also implemented to show in real-time the trend of the main KPIs

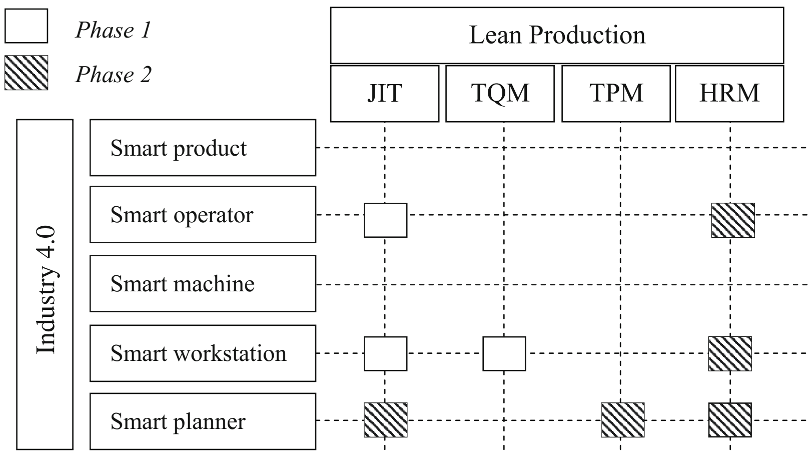

Fig. 2. Smart technologies for lean applications in Alpha

and turn them into valuable and actionable information. Finally, the system was developed to monitor each worker performance, updating his/her personal competences in a skills matrix in real time. The main smart applications introduced by *Alpha* to enable its lean manufacturing processes are reported in Fig. 2.

6 Conclusions

The relationship between lean and technology has generated different debates in the last decades. The model developed in this paper proposes interesting insights into how implementing smart solutions can lead to the amplification of lean benefits.

From a theoretical point of view, the proposed model is a first attempt to integrate lean and smart manufacturing dimensions in order to explore how these two production paradigms, in the past considered as competing, can be applied synergistically to achieve superior performance. The model is useful for practitioners who face challenges with traditional lean implementations, especially in environments characterized by highly variable demand conditions and assembly complexity. The framework can be used both before and after a shift toward the smart factory, but a fundamental prerequisite is the fact that the organization should have already mastered and applied the lean philosophy. Regarding companies that have already implemented smart solutions, the framework is useful to support further lean transformation. This comprehensive framework provides an overview of the state of the art of the smart implementation and brings synergies within the organization thanks to the integration of multiple perspectives.

Notwithstanding, the model presents some limitations. First of all, it offers only a static representation of possible as-is and to-be situations, lacking details of the transformation process over time. Therefore, the creation of a dynamic model can increase its implementation. Secondly, some connections remain uncovered, and for this reason further case studies are encouraged to identify more solutions and add further examples to the framework.

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Implementation of Industry 4.0 Technologies: What Can We Learn from the Past?

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Abstract. The fourth industrial revolution ("Industry 4.0") promises a multifaceted paradigm shift in manufacturing. This study aims to gain an in-depth understanding of what the transition to Industry 4.0 may involve. We do so by looking for, and learning from, experiences of similar shifts in the past. Specifically, we conduct a structured literature review of the rich operations management literature on Advanced Manufacturing Technologies (AMTs). AMTs were arguably central in the shift from the second to the third revolution in the second half of the 20th century. A review of the existing AMT literature allows us to infer relevant observations, theories, and findings for the emerging shift into Industry 4.0. We employ the review process defined by Tranfield et al. (2003).

Keywords: Industry 4.0 · Advanced Manufacturing Technology (AMT) · Literature review

1 Introduction

The fourth industrial revolution ("Industry 4.0") promises a multifaceted paradigm shift in manufacturing [1]. Industry 4.0 deals with the applications of intelligent products and production processes [2]. To date, studies of Industry 4.0 have encompassed three interrelated trends. The first aspect is related to the advanced and expanding technologies in manufacturing industries, which allow for the digital transformation of products and production systems into fully integrated and automated settings. Examples are the Internet-of-Things, big data, cloud computing (and cyber security), virtual reality and augmented reality, robotics and artificial intelligence, and additive manufacturing (3D printing) [3]. The second aspect is concerned with the implementation process and use of such technologies in manufacturing industries. In this regard, Industry 4.0 is defined as an enabler for communications in the form of Cyber-Physical-Systems [2, 4]. The third aspect deals with the impact of creating these digital ecosystems on organizations, industries, environment, and societies [5]. For instance, it is argued that implementation of Industry 4.0 can yield productivity gains, as well as other benefits, namely, quality improvement and greater flexibility of manufacturing industries [6].

In retrospect, it is clear that manufacturing underwent a similar shift in the second half of the 20th century, the third industrial revolution. More specifically, a generation of computing and automation opened up a new source of competitive advantage for

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manufacturing settings to move toward automated factories [7]. In this regard, Advanced Manufacturing Technologies (AMTs) were arguably central in the shift from the second to the third revolution.

An AMT can be broadly defined as "an automated production system of people, machines, and tools for the planning and control of the production process, including the procurement of raw materials, parts, and components, and the shipment and service of finished products" [8]. AMTs encompass a group of technologies that are hardware-based (e.g., computer numerical control, flexible manufacturing systems, and industrial robots) and software-based (e.g., computer-aided design, material requirements planning, and manufacturing resource planning), linked through advanced computing technology called computer-integrated manufacturing (CIM) [9, 10].

On the one hand, AMTs represent a number of advanced computer-based technological innovations, consolidated as a system, which can mainly enhance design, manufacturing, and administrative processes in production systems [11]. Such an integrated system of physical assets, software packages, and planning methods fits perfectly with the attributes of Industry 4.0.

On the other hand, organizations aim at creating competitive capabilities, namely price, quality of products, product line breadth, delivery capabilities, and flexibility, by implementing AMTs, ultimately resulting in high levels of performance [12, 13]. Several studies investigate the implementation aspects of AMT and what contributes to its successes and failures [9, 14–17]. Other studies deal with the effect of AMT on performance [18–21]. Implementation of AMT and its resulting effects have been widely investigated in the extant literature.

Thus, examining the literature of AMT and existing theories provides a reliable basis for gaining a deeper understanding of the dynamics of Industry 4.0. More importantly, this allows us to infer relevant observations, theories, and findings for the emerging shift into Industry 4.0. In other words, we learn from the past to prepare for the future of manufacturing [22]. Therefore, the objective of this study is twofold:

1. To summarize the body of research on AMT;
2. To discuss what can be learned from the AMT research for Industry 4.0.

2 Methodology

This research is based on a systematic review of the AMT literature. A systematic literature review is defined as "a written document that presents a logical argued case founded on a comprehensive understanding of the current state of knowledge about a topic of study" [23]. In conducting this review, we employ the review process defined by Tranfield, Denyer [24].

2.1 Identification of Keywords and Search Terms

This review is based on a journal search. Conducting a review based on a journal search ensures a certain level of quality [25]. In doing so, we develop a list of journals based on our preliminary research and journal rankings (see [26, 27]). Conference proceedings are not included in this review. The search keyword is "advanced manufacturing technolog*", and "AMT." The search field is mostly constructed from a combination of abstract (AB), title (TI), and keywords (KW). The primary result is 285 papers. In the following, we employ a round of selection criteria based on checking the scope relevance by title and abstract review, as well as evaluating access to the full manuscript. In that selection process, we do not apply any criteria for the number of pages, year of publication, or number of citations. The secondary result that is the focus of this review comprises 208 papers (see Table 1).

Table 1. List of journals, results, and fields of search

Title	Final Selection	Field of Search
International Journal of Operations & Production Management (IJOPM)	34	AB
Journal of Manufacturing Technology Management[a]	28	AB
International Journal of Production Economics (IJPE)	17	AB, TI, KW
International Journal of Production Research (IJPR)	16	AB, TI, KW
Journal of Operations Management (JOM)	16	AB, TI, KW
International Journal of Advanced Manufacturing Technology	13	AB, TI, KW
Technovation	11	AB, TI, KW
Industrial Management and Data Systems	10	AB
Journal of Engineering and Technology Management	8	AB, TI, KW
Computers and Industrial Engineering (CIE)	8	AB, TI, KW
Management Decision	7	AB
International Journal of Industrial Ergonomics	6	AB, TI, KW
International Journal of High Technology Management Research	6	AB, TI, KW
Journal of Manufacturing Systems (JMS)	5	AB, TI, KW
Decision Sciences	4	AB
Production Planning and Control	4	AB, TI, KW
Production and Operations Management (POM)	4	AB, TI, KW
Strategic Management Journal (SMJ)	3	AB
Harvard Business Review (HBR)	2	AB
Research Policy	2	AB, TI, KW
Academy of Management Journal (AMJ)	1	AB, TI
Academy of Management Review (AMR)	1	AB or TI
European Journal of Purchasing & Supply Management	1	AB, TI, KW
Organization Science	1	TI or KW

[a]Previously known as *Integrated Manufacturing Systems* (*IMS*) and *World Class Design to Manufacture* (*WCDM*) (http://www.emeraldinsight.com/loi/wcdm).

As recommended by Tranfield, Denyer [24], we employ data-extraction forms that include general information (e.g., title, author, and publication details), study attributes (e.g., objectives or research questions, context of the study, methods), and core contributions (findings, links to other concepts, information on growing themes, key results, and additional information). This process requires a clear documentation of all steps.

In doing so, we develop a simple coding system to classify the areas of prior research on AMT. Consequently, we classify 208 papers into four main clusters of AMT evaluation, AMT implementation, AMT results, and AMT contingency. Moreover, we have some papers that combine these classes. In the following, we assign each paper with two codes based on its core contributions. The first code relates to the overall contribution of the paper, which allows us to adopt a descriptive analysis, whereas the second code reflects other details about the papers, allowing us to portray the overall scheme of the AMT literature.

3 Findings

3.1 Descriptive Analysis

We first report on the frequency of the 208 publications from 1986 to 2016. Figure 1 shows that the publications on AMT are not evenly distributed, indicating a plethora of research during the late 1990s. In order to gain a detailed understanding of the trends and the focus of publications in the past, we classify our descriptive analysis into three decades: 1986–1995, 1996–2005, and 2006–2016.

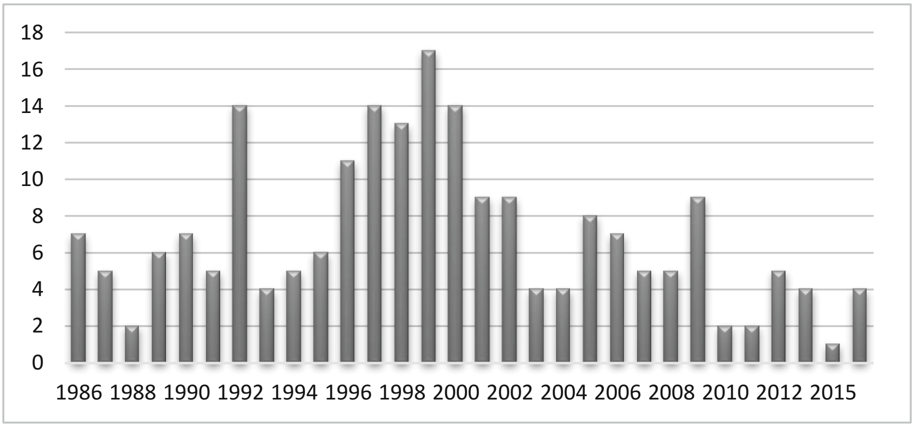

Fig. 1. Frequency of the publications in each year

The First Decade: 1986–1995. This decade shows that most of the publications were focused on AMT evaluation and AMT implementation (see Fig. 2). For instance, the results show high focus on the evaluation of investment, justification, and decision making, as well as elaboration on implementation issues.

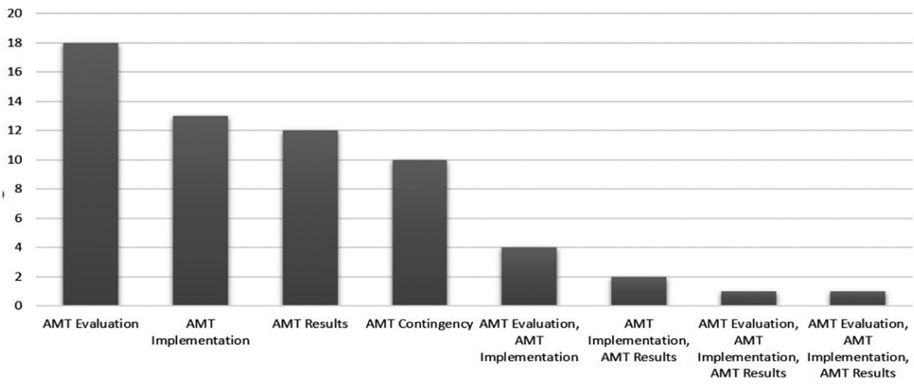

Fig. 2. The frequency of the clusters in AMT publications: 1986–1995

The Second Decade: 1996–2005. This decade shows significant attention to AMT results, although AMT evaluation still dominates (see Fig. 3). During this decade, scholars were elaborating on manufacturing and business performance, assessment mechanisms, success factors, and the gaining of competitive advantage.

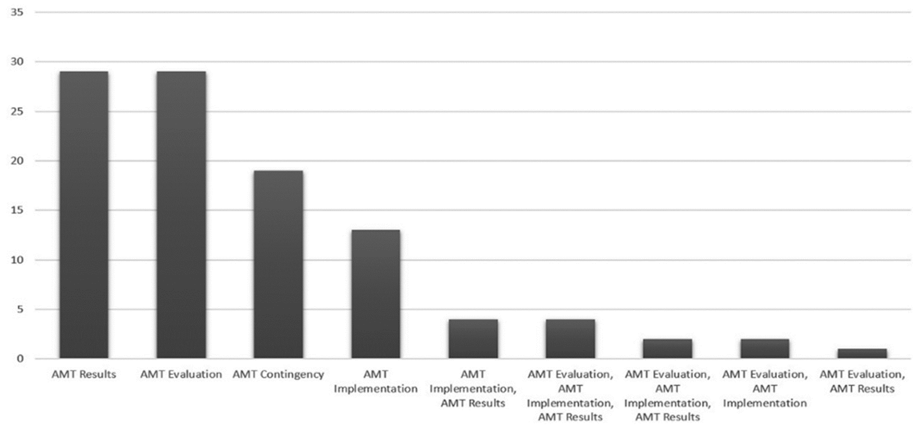

Fig. 3. The frequency of the clusters in AMT publications: 1996–2005

The Third Decade: 2006–2016. This decade represents attention by scholars to AMT contingency, although AMT evaluation remains most frequent (see Fig. 4). Examples of AMT contingency are size of the company, organizational characteristics, and implementation issues in developed versus developing countries and in the public versus private sectors.

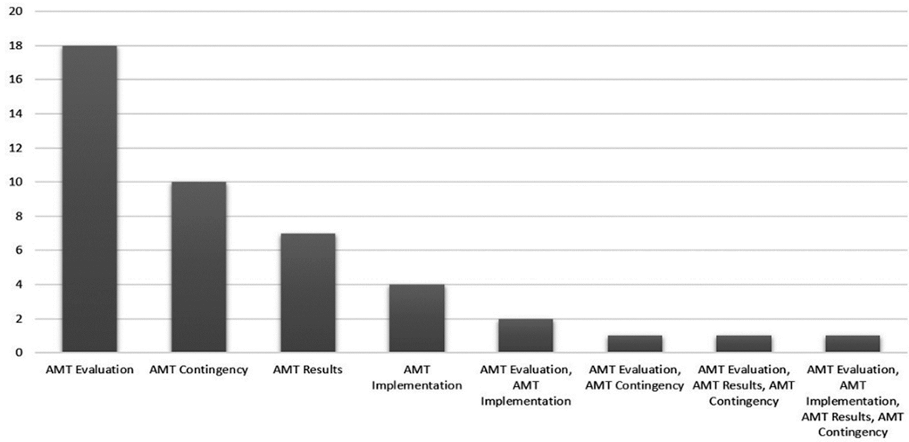

Fig. 4. The frequency of the clusters in AMT publications: 2006–2016

3.2 Thematic Analysis

Our literature review allows us to summarize the wide-spanning areas of prior research on AMT (see Fig. 5). This framework illustrates a brief summary of the results of the second code in our review. It represents an overview of the key parameters during the evaluation and implementation phases. Moreover, it classifies possible outcomes of

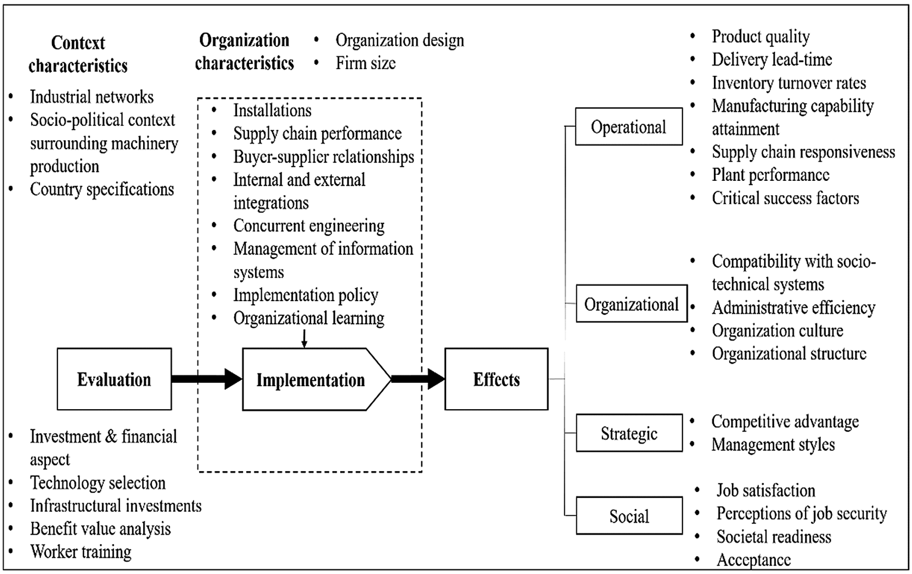

Fig. 5. Summary of the areas in the AMT body of literature

implementing new manufacturing technologies and shows the context variables that may influence this process.

4 Conclusion

The fourth industrial revolution is evolving, yet it has many similarities to its antecedent phenomenon, AMT. An examination of three decades of publications on AMT shows that the evaluation of new technologies, regardless of their maturity, has always been central to industries that plan to implement them. More specifically, analyzing the first decade implies that industries need to justify their decisions and carefully evaluate their investment in implementing new technologies. The second decade illustrates growing concerns about AMT results, mainly performance improvement, measurement issues, competitive advantage, and success factors. The third decade of AMT literature shows that some outcomes are likely to be influenced by contingent factors, such as organizational and national characteristics. Therefore, it is worthwhile for industries that are planning to implement new Industry 4.0 technologies to examine similar attributes in terms of AMT evaluation, implementation, outcomes, and contextual variables. To the best of our knowledge, the areas of investigations identified are potentially viable in the context of Industry 4.0 and to a certain extent can set the scene for the emerging industrial revolution.

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The IoT Technological Maturity Assessment Scorecard: A Case Study of Norwegian Manufacturing Companies

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Abstract. The accelerated use of technologies has led to what is termed the fourth industrial revolution, or Industry 4.0. It is based on machinery, robots, production lines, items and operators connected via the Internet to each other and to back-end systems, as a part of the Internet of Things (IoT). In this paper, we propose a new IoT Technological Maturity Assessment Scorecard that can assist manufacturers in adopting IoT-technologies. To demonstrate the Scorecard, we present a case study applying the scorecard in four Norwegian manufacturing companies.

Keywords: Industry 4.0 · Internet of Things · Maturity model · Manufacturing

1 Introduction

International competition, global sourcing of production and financial crisis calls for a new level of excellence in manufacturing. A fourth industrial revolution is envisioned based on innovations in technologies, smart materials and manufacturing operations. The revolution includes initiatives termed Industry 4.0, the Industrial Internet, Factories of The Future, and Cyber Physical Systems. A driving force for this development is the accelerated use of Internet of Things (IoT)-technologies [1]. The challenge for manufacturers is the escalating technological change, and they need a tool to measure and analyze their current technology level, assisting them in giving directions for adopting new technologies. A suitable tool for this is a maturity model together with a scorecard to assess the maturity level of a company. Maturity models serve as a reference to implement improvements while assessing one's own capabilities compared with others. Maturity assessment has been successfully applied in other industries, most notably the software industries [2]. There has been a growing interest in maturity models within many domains [2–4]. However, models for how to evaluate the technology maturity level of manufacturing companies are scant, and even more so are tools to support the use of models in decision-making. In this study, we present a model for measuring the IoT-technology maturity level of manufacturing companies, followed by results from a case study of using the model for four Norwegian manufacturing companies.

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2 Literature Review

2.1 Maturity Models

In general, maturity models outline a path to maturity, involving development stages building on each other until maturity is reached [3, 4]. In order to ensure research rigor, we follow the Comprehensive Research Framework for Maturity Model Research presented by Wendler [3]. This framework states that maturity model development should be an iterative process where each cycle consists of the three steps: Model Development, Model Application, and Model Validation. Model Development follows the seven research guidelines of design science research. Model Application and Model Validation are conducted by applying the model for assessing four manufacturers, using interviews and a survey for validation purposes. De Bruin et al. [7] has proposed a methodology that consists of six phases for development of maturity models (Fig. 1).

Fig. 1. Six phases of developing maturity model. (Adopted from de Bruin et al. [5])

2.2 Defining a Thing in the Internet of Things (IoT): The *4.0-enabled-object*

A crucial issue is to define what distinguishes IoT-technologies from earlier generations of technologies, namely mechanical-, electrical-, computer-technologies. Taken literally, Internet of Things means things connected to form a network. Using capitalized "Internet" signals that we mean the Internet communication network [6]. However, the literature is lacking a clear definition of what a "thing" actually is. To characterize a "thing", different terms are typically used. Some examples are "Smart Object", "Smart Thing", "Smart Product", and "Intelligent Product". In order to develop the IoT maturity model we need to define what we mean by a "thing" in IoT. Intuitively, a characteristic is that the "thing" must have the ability to communicate via the Internet. Either directly if the thing has Internet Protocol (IP) capabilities embedded, or in case the "thing" does not have IP capabilities, via a device that connect the "thing" to the Internet. Thus, for the purposes of this research we define the "thing" as a "4.0-enabled-object" with some characteristics that separate it from any-thing. I.e. a "4.0-enabled-object" should have some properties that separate it from objects in general, and from a "3.0-enabled-object" in particular. It should be an extension of a 3.0-enabled-object, so we start by identifying the characteristics of a 3.0-enabled-object. This implies an object that exhibits properties that was not in the 2.0 area. Following the analysis of the Fraunhofer institute [https://www.fraunhofer.de/], we define the PLC (Programmable Logical Controller) as the central 3.0-object. The PLC was designed for controlling manufacturing machinery and equipment. The PLC contained all three elements of a computer in one unit, namely the computer memory, processing capability and Input/Output (I/0) communication facilities. The PLC is thus the core component of the IoT-technologies. However, some additional requirements need to be included. According to Porter and Heppelmann [1], all smart, connected products from home appliances to industrial equipment shares three core elements. These three core elements are; physical components (comprising the product's mechanical and electrical parts), "smart" components (comprising the sensors, microprocessors, data storage, controls, software, embedded operating systems, etc.) and connectivity components (comprising the ports, antennas, protocols enabling wired or wireless connections with the product). While the smart components enhance the capabilities and the value of the physical components, the connectivity components enhance the capabilities and value of the smart components. In addition, the connectivity components enable some of the capabilities to exist beyond the physical product itself [1]. Based on this, we define a *4.0-enabled-object* as an object with three characteristics:

1. **Embedded PLC-element.** I.e. an electronic component with computer memory, processing capabilities and I/O communication facilities.
2. **Associated global unique identifier.** An IP-address if the object has IP-communication capabilities. Otherwise a globally unique identifier must be assigned, e.g. by GS1 following the AutoID standards which is typically used for RFID-tags.
3. **Global connectivity**. Wherever the object is, a two-way communication with the object must be possible. In practice, the object needs to be connected to Internet directly or via some middleware software. A non-IP object, like an object with an embedded RFID-tag, needs an intermediate device to connect it to Internet.

2.3 The Automation Pyramid

The IT-systems related to manufacturing are traditionally classified using the automation pyramid, as shown in Fig. 2.

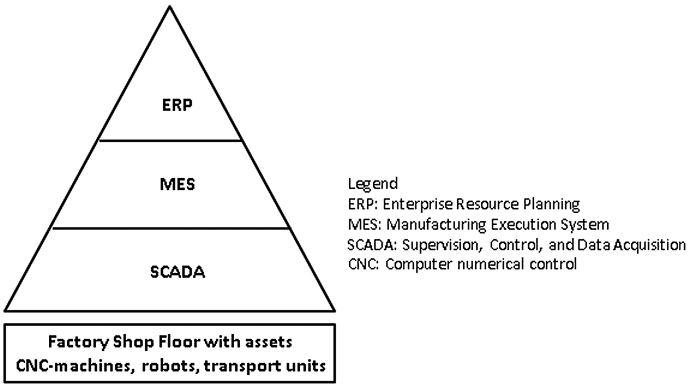

Fig. 2. The automation pyramid with three IT-system levels above the shop floor.

Note that some manufacturers might not have MES and/or SCADA layers. Humans operating the ERP-system might control the shop floor assets directly. The shop floor consists of assets like CNC-machines, industrial robots and transportation systems interacting with IT-systems that encompass supervision, control and data acquisition

(SCADA) capabilities. The MES level interact with the SCADA level below, and the ERP-level above it. The systems at each level can cover decision-making or simply act as a dispatching system for the level above. ERP includes long-term strategic and tactical planning integrated with business-related functions such as customer order handling and available-to-promise (ATP) checks.

The command communication direction in the automation pyramid is traditionally *vertical*, i.e. top – down, with lower levels responding to orders from above. The levels might be connected electronically, or human interaction is required to transfer information between the levels. More recently, the assets on the shop floor are 4.0-enabled-objects with the ability to communicate *horizontally* creating some local intelligence, i.e. they communicate among themselves without involving levels above. Furthermore, IT-systems are *internal* to the manufacturing company if they operate in a closed enterprise environment, and *external* if they can communicate in an open environment involving several enterprises. 4.0-enabled objects can communicate to each other, either indirectly via IT-systems in the automation pyramid, or directly with each other.

3 The IoT Technological Maturity Model

Our research follows the five first phases in Fig. 1 since the Maintain phase requires a longitudinal study.

Level 1: 3.0 Maturity: On level 1, an organization has reached maturity of the third revolution. The first characteristic is some use of “Track and Trace” technology, such as RFID and/or barcodes in the production and/or warehouse environment, but with limited functionality. The second characteristic, is that the organizations have implemented an ERP system to collect, store, manage and interpret data from business activities, such as product planning, manufacturing, inventory, marketing/sales, shipping and payment. The third characteristic is an initial automatization of the production and/or warehouse environment using at least one robot. The ERP level is typically operated manually with limited electronic communication with the levels below. The IT-systems are internal to the organization.

Level 2: Initial to 4.0 Maturity: Having one 4.0-enabled-object is the entry requirement. As a second characteristic, robots, machines and IT-systems communicate vertically. The third characteristic imply that assets and/or products can be remotely programmed, accessed, and managed by for instance the use of a PC, tablet, or a smart phone connected to the Internet.

Level 3: Connected: The organization have between two and nine 4.0-enabled-objects within the manufacturing assets and/or the products, with vertical communication. The 4.0-enabled objects communicates indirectly via a control system that is internal or external to the organization. Cloud computing is a way of supporting vertical communication if control systems are operated from a remote system via Internet. I.e. a platform for connecting devices and sensors in IoT. Cloud computing can be defined as being “able to access files, data, programs and 3rd party services from a Web browser via the

Internet, hosted by a 3rd party provider", following Kim [7]. A second characteristic is that at least one operation within the production and/or warehouse environment is automated.

Level 4: Enhanced: The assets and/or products can communicate horizontally and directly within a closed environment. Assets and/or products are internally connected. A second characteristic is that some operations in the production and/or warehouse environment have been automated. Meaning that for instance, robots, machines and IT-systems are connected into a production network, performing the production of e.g. standard parts. Alternatively, robots and/or automated transport carriers have fully automated at least a specific part of the inbound and/or outbound warehouse operations.

Level 5: Innovating: A first characteristic is that organizations need to have an internal supply chain control with an increasingly number of IoT-objects (at least ten) within the assets and/or the products. In addition, these IoT-objects need to have the ability of horizontal communication (e.g. robot-to-robot) and vertical communication (e.g. robot-to-Internet). A second characteristic is that the 4.0-enabled-objects are further developed and equipped with advanced features. More specifically, that the objects at this level have self-awareness capabilities, which means that the objects have the ability to know its own status and structure, as well as any changes to it, and its history [8]. A third characteristic is that the production and/or warehouse environment is extensively automated, e.g. the production and/or warehouse environment increasingly use robots replacing the manual workforce. A fourth characteristic involves organizational understanding of the importance of, as well as interacting to achieve, standardization (data standards, wireless protocols, technologies). Without standardization, the communication between asset-to-asset and product-to-product becomes hard, especially communication beyond organizational boundaries. Thus, standardization and interoperability both can be regarded as two especially central elements organizations should be engaged in at this level, since standards are needed for interoperability both within, and between various domains. Interoperability is defined as the ability of a system to interact with other systems, without application of special effort for integration, e.g. customization of interfaces, etc. Interoperability is established on the physical level; when assembling and connecting manufacturing equipment, on the IT-level; when exchanging information or sharing services, and on the business level; where operations and objectives have to be aligned [9].

Level 6: Integrated: There is an increasingly number of IoT-objects among both assets and products, and the organization has further implemented IoT-technology with 4.0-enabled-objects communicating directly with humans internally in their organization. This feature passes beyond self-awareness at the previous level, and includes the IoT-objects ability to use the information gathered in order to manage its own life cycle, including services, self-repair and resources. It also includes the ability to learn from experiences and the ability to improve operations [8]. A third characteristic is that the production and/or warehouse environment are highly automated, involving robots that perform a high degree of the production and/or warehouse operations, further replacing the manual workforce. A fourth characteristic, is that the connected robots, machines and products constantly and increasingly are exchanging various types of information. Consequently, the volume of the generated data and the processes that is involved in the handling of the data becomes critical and important to manage. Data management is a crucial aspect within IoT, and organizations at this level have a deep focus on the exchanged data with a plan and strategy for further data management. The organizations understand what information they need in order to create as much value as possible [10].

Level 7: Extensive: The range of the organization is extended from being merely internal, to embracing the organizations external network. A second characteristic is that the production and warehouse environment are highly automated, meaning that robots and machines performs a high degree of both production and warehouse operations, replacing a high degree of the manual work operations. A third characteristic is that organizations move from Data Management towards Big Data Management and extensive Data Analysis. Big Data is the result of an extensive implementation of new technology, and the enormous amount of data that arises from the internal and external communication, and the monitoring and measuring of objects (e.g. a robots and/or a products performance), in the business environment. Consequently, Big Data Management, which is the organizations administration and governance of great volumes, of both structured and unstructured data, becomes of crucial importance at this level. The aim of Big Data Management is to extract big data to gain business insights, which further means to ensure a high level of data quality and accessibility for business intelligence and Big Data analytics applications. The fourth main characteristic is developed from the third characteristic, namely that organizations at this level are actively engaged in Data Analysis, with the inspection, cleaning, transforming and modelling of data from sensors, machine-to-machine, and networks, in order to discover useful information and support business conclusions and decision-making [10].

Level 8: 4.0 Maturity: This is the final and optimal level on the maturity scale representing maturity of the fourth industrial revolution. A characteristic is the vision of optimal IoT-technology use in which all objects are connected to the Internet and seamlessly integrated, where objects communicate with other objects using common architectures, interoperability and open standards, enabling human intervention. A second main characteristic is that the production and warehouse environments are optimally automated, having manual work only because it is considered most appropriate. A third characteristic is that Business Intelligence and continuous improvement characterizes the organizations. Continuous improvement is enabled by continuous monitoring of real-time performance discovering design problems that testing failed to reveal. Further, smart factories will emerge, where the new capabilities of smart, connected machines are reshaping operations at manufacturing plants on their own, and where machines are linked together in manufacturing networks. In these smart factories, networked machines automate and optimize production. The key enabler for such a smart environment are seen to be Business Intelligence, which can be described as a set of techniques and tools for transformation of raw data - into meaningful and useful information for the purposes of analysis of business [1]. Thus, at this level, organizations have become predictive, meaning that organizations can forecast what can happen in the future, from the basis of Big Data management. For instance, predictive analytics can identify consumers buying behavior, which organizations can use for marketing trends, as well as production and capacity planning. It is believed that new business processes and models arise, since the smart, connected machines and products create new production requirements and opportunities. The final product assembly might be moved to the customer site, where the final step will be loading and configuring software or the product itself might be delivered as a service.

4 Case Study of Four Norwegian Manufacturing Companies

An in-depth study of four major companies was carried out to develop and refine the model in the development phase, and the final model was used to assess the companies. The four companies assessed in this case study were (1) a furniture manufacturer, (2) an industrial pipe manufacturer, (3) a ship equipment manufacturer and (4) a shipyard. Data was collected through in-depth interviews, meetings and discussion in workshops with the case companies. We found that all companies complied with the characteristics of level 1 maturity, except of company 3 that did not use RFID or barcodes. All companies complied with all requirements associated with level two without exceptions. Regarding level 2, all companies had at least two IoT objects with the ability to communicate vertically, and at least one activity being automated. However, only company 1 and 3 used remotely programming (tablet, smart phones) and access and management of assets or products. Thus, we consider all companies to have score that corresponds to a level 3 maturity. Only company 2 did comply to the requirements at level 4 by having more than two IoT objects with the ability to horizontally communicate. Moreover, this company applies extended automated production.

5 Limitations

This study is limited to look specifically at the IoT-technologies, while leaving out the consequences of their use on business process change, smart materials and smart manufacturing, which also are the ingredients of the Internet of Things in general, and complementary approaches like cyber-physical system, future factories, and Industry 4.0. Validation of the model covering its use in practice is ongoing work that requires longitudinal studies of which results will be reported at a later stage.

6 Conclusions

In this study, we have developed an IoT Technology Maturity Scorecard, reflecting the evolution of the use of IoT-technologies along a maturity scale with eight levels. It represents a presumed evolution path of the use of IoT Technologies by manufacturing companies. It may serve as a tool for management supporting the adaption of such technologies. The model can be a reference frame to implement an approach for improvements, and assessment of one's own IoT technology maturity level as well as being used in benchmarking against other manufacturing companies. We have demonstrated the IoT Technological maturity scorecard on four globally competitive Norwegian manufacturing companies, covering different manufacturing industries. Our findings show that three of these companies have a score corresponding to level three, "Connected", at the maturity scale, while one of the companies reached level four, "Enhanced", out of eight levels. Hence, these companies have potential to improve their maturity level significantly in their transition toward the fourth industrial revolution. The scorecard provide a useful tool for managers in their efforts in developing their organization in this direction.

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Optimal Scheduling for Automated Guided Vehicles (AGV) in Blocking Job-Shops

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Abstract. Promising developments and further improvements of cyber physical logistics systems (CPLS) and automated guided vehicles (AGV) lead to broader application of such systems in production environments and smart factories. In this study a new mixed integer linear program (MILP) is presented for the scheduling of AGVs in a flexible reentrant job shop with blocking. Optimal solutions to small instances of the complex scheduling problem in a make-to-order production, minimizing the make span, are calculated. Different numbers of jobs are considered. Feasible schedules for the machines and the AGVs are generated from different sized instances to evaluate the limits of the mathematical model.

Keywords: MILP · Job Shop Scheduling · AGV · Cyber physical systems

1 Introduction

The application of cyber-physical systems (CPS) generate new possibilities and challenges for the production planning and scheduling. Thoben et al. [25] state, that establishing a cyber physical logistics system (CPLS) can increase efficiency and flexibility in the production environment. The combination of smart manufacturing and logistics will generate the optimal value stream to fulfill real-time demands. Supporting that statement Auffermann et al. [3] state, the transportation systems will play an important role in the integration of cyber physical systems. Every production systems needs a flexible and dynamic material handling component. By now forklift trucks are able to identify the transported good and establish a communication to exchange information on the destination where the product wants to go [1]. Due to this fact, new decentral approaches and innovative services need to be established for a one piece flow in a manufacturing environment, especially in small and medium sized businesses considering cellular logistics systems.

These businesses usually use a job shop layout with a number of jobs, each combining a set of operations. These are processed by assigned machines in a job specific sequence. In nearly all instances, material handling systems are used to move, buffer and store raw material as well as work-in-progress. Those are called Job Shop Scheduling with Material Handling (JSSMH) or Job Shop Scheduling Problem with Transportation (JSPT). Taking into account the type and number of AGVs, picking up materials after an

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operation is completed and providing it to the next machine, the problem is called Job Shop Scheduling with Autonomous Guided Vehicles (JSP-AGV).

2 Problem Description

A job shop is given, if a set of n independent jobs $J = \{J_1, J_2, \ldots, J_n\}$ has to be processed on a set of m machines with $M = \{M_1, M_2, \ldots, M_m\}$. Each job $J_i \in J$, with index i for the job and j for the operation, can be described as a sequence of operations o_{ij} on machine $\mu_{ij} \epsilon M$ with the processing time p_{ij}. For every operation, a set of machines $A(j)$ is assigned, which can possibly process it, representing optional parallel machines. The processing order will be called precedence constraint. Once an operation is started, it cannot be interrupted (called preemption) and only one operation can be processed on a machine at a time. Reentrant processes are also considered. They are typical for semiconductor manufacturers or similar production processes with extremely expensive machines. Operations are processed on the same machine twice, with at least one intermediate step in between. This situation occurs, if a product is tested after assembly, repaired and tested again or more than one layer of coating is applied to the product. Exemplarily, Fig. 1 shows the correct sequence of operations with $O_{i,j+2}$ on machine M_k after O_{ij+1} on Machine M_{k+1} and O_{ij} being processed on M_k earlier.

Regular job shops consider infinite buffer space between two intermediate operations, one on each side of the machine. In case of absence of the intermediate storage place, the problem can be considered as blocking environment. In the blocking scenario, machines cannot process any other operation until the last processed object has been cleared/unloaded from the machine. The operation of a processed job has to remain on the machine until the next machine is available. This situation is presented in Fig. 1, with $B_{i,j+1}$ (dashed red box) being the blocking time added to the process duration of $O_{i,j+1}$. These circumstances will delay the start of the next operation of the upcoming jobs. This situation is well known in industrial environments and commonly found in scheduling train-yards or surgeries in a hospital.

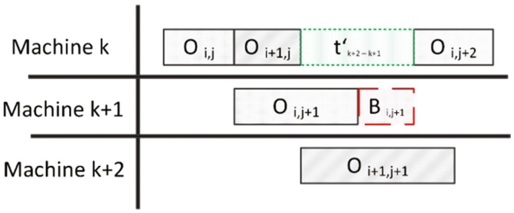

Fig. 1. Empty travel times and blocking are considered in the new linear model. (color figure online)

Different optimal solutions to the problem have been presented, for example graph based solutions improved by Branch & Bound (B&B) by Mascis et al. [21] solving a job shop environment with blocking. New approaches to solve the problem with B&B-Algorithms, considering setup times [14] are known from literature and have been calculated without setup times on a CPU-GPU combination [8]. A heuristic solution generating a schedule by particle swarm optimization is provided by Zhao et al. [29]. Using a single criteria tabu-search [6] or multi criteria tabu-search [20] seems to be promising as well.

Adding transport operations to the job shop problem, the formulation to classify the environment used by Graham [13] must be enhanced by material transport operations T_{ij}, representing the transportation when o_{ij} is processed on machine μ_{ij} and o_{ij+1} is processed on machine μ_{ij+1}. Also empty travel operations T'_{ij} (green dotted box) have to be considered, subject to the same rules as T_{ij}, seen in Fig. 1. Taking into account the transport operation of an AGV and the absence of a buffer at the machine, there is a crucial dependency between the schedule of the machine and the AGV. These can be solved by a nonlinear model provided by Zeng et al. [27], a linear problem considering assembly and batches [2] and a linear model with handover times reviewed by Poppenborg et al. [23]. Other mathematical formulations are provided by Caumond et al. [7] considering a single AGV with limited buffer and Fazlollahtabar considering multiple AGVs and turning points for deadlock resolution [11]. Given that scheduling AGVs in a job shop is considered NP-hard due to the simultaneous scheduling problems (i) of the machines and (ii) the AGVs in the job shop [22] typical approaches are heuristic algorithms. Scholz-Reiter et al. [24] presented a solution for general dual resource constrained problems dynamically adjusting scheduling rules based on the environment, which can be adopted to AGVs. Another solution was presented by Ulusoy using a Genetic Algorithms (GA) for the simultaneous scheduling of AGVs and a Flexible Manufacturing System (FMS) with 4 workstations [26]. Different hybrid approaches combining GA with other methods have been tested as well. Another approach presented by Baruwa is based on colored petri-nets which is providing a fast heuristic solution [4]. Graphical solutions are provided by Lacomme using a memetic algorithm on a non-oriented disjunctive graph and Zhang using a shifting bottleneck procedure based on a disjunctive graph [19, 28].

Considering the possible optimization criteria in general, the minimization of the make span is sufficient [22]. Fazlollahtabar et al. [10] presented the minimization of the make span (Cmax) as a goal criterion, but considered (weighted) tardiness or the mean flowtime as minimization criteria as well.

3 Scenario

The considered environment in this paper is a $J6, R2 \mid prec,\ t_{jk} = t_{kj}, t'_{kl} \mid C_{Max}$ using Graham's notation enhanced by Knust [18]. The scenario and slight variations are commonly used for benchmarking [9] as well as the RoboCup Logistics League (reference http://www.robocup-logistics.org/ for more information). Four machine groups (MG 1–4) with 2 parallel identical machines in MG 1 and MG 3 as well as 2 single machines in MG 2 and MG4 are feed by two AGVs (R1-R2), used for material movements. Each order consists of 5 transport operations, executed by the 2 AGVs, and 4 machine operations (one on each group). The considered scenario is depict in Fig. 2. Scenarios closely related to this one have been proposed for AGV schedule comparison by [5] and used by [4, 27]. Instead of combining the load and unload station in one location, different locations, similar to [23], have been considered for this contribution.

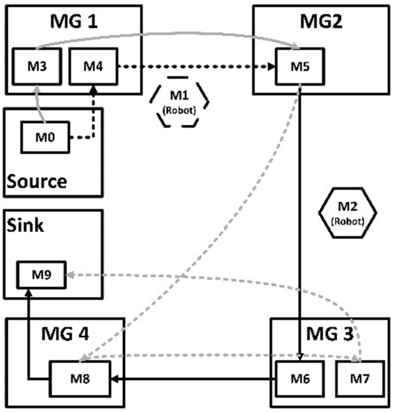

Fig. 2. In this example the 2 jobs take simple routes through the system, including 5 transport operations.

The products take a certain route (grey and black lines represent different orders), defined by the product type given at the first entrance into the shop. Due to the operation sequence of the given orders, proceeding constrains are assumed. If a machine has processed an operation, it is blocked until the next transport operation unloads the machine. No operation can be substituted by another machine and no operation can be skipped. Machine breakdown and maintenance are not considered. The first operation of each robot is the pickup of a product from a transfer station and making it available to the first machine. As mentioned before, the transport time depends on the layout of the machines. In Fig. 2, transport operations with solid lines are processed by Robot M2 and dashed lines are taken care of by Robot M1. The optimal assignment has to be calculated, see Sect. 4. The last operation is delivering the final product to the sink (transfer station M9), disposing the product from the shop floor. The movement of the AGV is not bound by any loop or network. The AGV takes the shortest path, calculated on a given map. A transport operation contains the pickup, the transport and the drop off of a product. The loading capacity of the AGV is one object per transport operation. In this paper, the transportation time is considered to be a given amount of time, depending on the position of the machines. Once an AGV has completed the operation and is idle, it stays where it finished the task. Dwell and idle points are not considered in this study. Enhancing the notation of Gröflin [15] with the ideas of Poppenborg [23], leads to a model with reentrant processes, blocking and transfer times as well as the possibility to consider set-up times for each order. The model divides every operation into multiple steps and synchronizes the start of a step with its predecessor's steps. This mixed integer linear model has been used for all following calculations.

4 Experimental Results

All calculations are done for a static scenario, where all jobs are known prior to the start. For both models, the same set of jobs was considered. Calculation in this case were done on Intel® Core i7-2600 and solved with Gurobi 7.0.2 [16] modelled with AMPL [12]. In Fig. 3 the CPU Calculation times are presented for instances with increasing number of jobs. It can be seen, that with an increasing number of jobs the calculation time increases drastically, as expected.

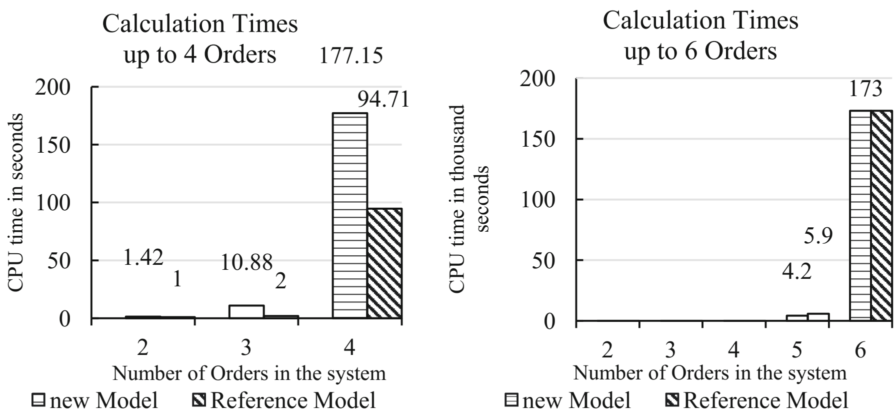

Fig. 3. The calculation time increases drastically with the addition of jobs, especially from 5 to 6 orders, resulting in more than 48 h calculations without an optimal solution.

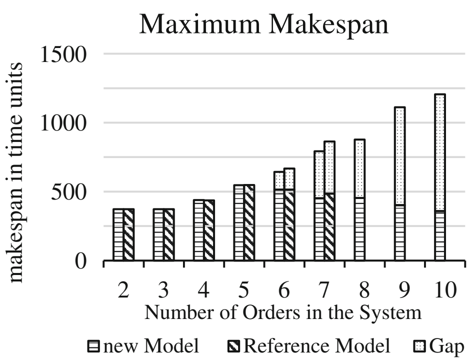

Fig. 4. Calculations for more than 5 orders are aborted after 120 min, resulting in a gap.

Taking into account the fact that the solver did not find an optimal solution for 6 and more orders after 48 h, the solver time limit for all further calculations was set to 120 min. During that time, the solver should be able to find a feasible solution but not the optimal answer. This holds up to 10 jobs of the new model, but not for the reference model. After 120 min the solver was not able to calculate a feasible solution for 8 and more orders in the reference model. In Fig. 4 the best solution for Cmax is presented. For all instances with more than 5 orders the feasible solution after 120 min (7200 s) calculation time and its gap are displayed. The gap is the difference from the last feasible solution to the lower bound, being zero proving an optimal solution. Still these results proof optimal solutions for small instances up to 5 orders.

The development of the gap over time can be seen in Fig. 5. In the figure it can be seen that the time to calculate the first feasible solutions seems to depend on the size of the problem. Increasing the number of AGVs, machines or operations will lead to rising calculation times as well, but the impact has not been tested so far. The detailed convergence behavior will be looked at in the future. The effect of applying dynamical influences to process- and transport times has not been evaluated so far. The different feasible solutions and gaps due to the different notation of the models, which can be seen in Fig. 4, have to be analyzed as well.

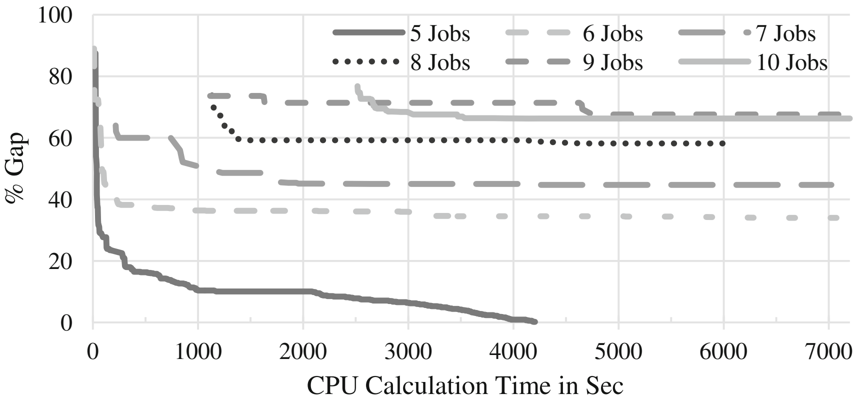

Fig. 5. The larger the instance the longer the first feasible solution takes to calculate.

5 Outlook and Conclusion

Considering a small process like a flexible manufacturing system with no more than 4 machine groups and 2 AGVs, the developed MILP provides an optimal near real time solution for online applications, up to 4 orders in the system. Considering 5 to 10 orders, feasible but not optimal solutions can be presented within reasonable time frames. This shows the amount of orders as a crucial variable to the problem. The usage of powerful solvers and the use of cloud infrastructure can improve the results to a certain extent. It has to be take into account, that real complex production systems can contain multiple FMS being supplied by more than two AGVs. This leads to the fact, that this approach can no longer be used for the efficient scheduling of large systems. Concluding, the small amount of orders which can be calculated motivates the search for faster algorithms which can cope with larger amounts of orders.

In further research, it has to be evaluated how the program behaves on a rolling time horizon base, to be able to represent the dynamic behavior of a plant, for example, machine failure or priority order. Moreover, in further research other approaches to the larger instances of BJS-AGV problem, such as dynamic rule-based dispatching of AGV's, have to be considered, developed and evaluated. These new approaches, e.g. Heger et al. [17], can be assessed in comparison to the optimal solution provided by this model.

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Deployment Architecture for Energy and Resource Efficient Cyber Physical Systems

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Abstract. Energy and resource efficient manufacturing has become one of the most relevant research topics, for the increasing attention to sustainable development at planetary level. This work focuses on deployment of a Cyber Physical Production System in a laboratory setting in Technical University of Braunschweig, Institut für Werkzeugmaschinen und Fertigungstechnik (TUBs IWF), with the aim of improving production systems operation in terms of efficiency in resource usage, taking inspiration by the work developed in Politecnico di Milano by some of the authors of this article, focusing on a production system energy aware control, explored so far by means of simulation experiments.

The objective of this article is studying alternative ICT architectures for the CPS-ization of a production line, namely, a serial line, which matches the main requirements needed from Cyber Physical Production Systems (CPPS), machine to machine communication and local processing, in preparation to deployment, with support of state of the art technologies, such as OPC-UA communication. The proposed solution is interesting for industry, as it shows a practical solution for application on the shop-floor of the Cyber Physical Production systems approach in the vision of Industry 4.0.

1 Introduction

Energy and Resource Efficient (ERE) manufacturing has become an important research topic, both as industry is one of the major world energy consumers, as well for the need of sustainable development at planetary level [5]. Furthermore, availability of technologies such as Internet of Things (IoT) are paving the way to the vision of Industry 4.0 and Cyber Physical Systems (CPS), with important improvements in the efficient usage of energy and resources in manufacturing [7].

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2 Related Work

This work focuses on the vision of the Cyber-Physical Production Systems (CPPS), by exploiting embedded systems and network capabilities and proposes (i) the application of a novel approach to ERE control of a serial line, based on heuristic rules, and (ii) an ICT architecture fit to the application of the proposed control to an actual line used for educational purposes. Related work will be addressed in the next sections.

2.1 ERE Autonomous Machine Control

Although production systems performance has been extensively studied over the years, only recently, at factory and production line level, [1,2,10] have studied planning and scheduling methods able to level energy consumption peaks to reduce energy related expenses. Among the most interesting contributions, [8] has started to study effective use of machine tool stand-by modes, while [3,4] have explored energy-aware switching off-on policies at machine and line level; nonetheless, the existing models are still incomplete: they focus only on energy consumption and are based on statistical models of stochastic inter-arrival times, neglecting availability of real-time data for local processing.

Some of the authors of this article have recently studied [9] an energy-aware control based on heuristic rules for a serial line, based on three basic functionalities: (i) each machine builds and continuously updates its digital twin, including upstream buffer and operational states[1], plus foreseen end of processing; (ii) each machine shares its digital twin with the other machines, and (iii) when a machine ends processing, depending on its and other machines' state, can autonomously decide its current state, e.g. enacting stand-by mode. This autonomous control has been studied by [9] with simulation experiments in different configurations and with different sets of heuristic rules, and has shown interesting potential resource savings.

2.2 CPS Digital/Physical Architectures and Communication

The most interesting developments for our work are related to digitisation reference architectures and communication in manufacturing. As [6] puts in, Cyber Manufacturing Systems (CMS) and Industrial Internet of Things (IIoT) are the industrial counterparts of CPS and IoT and are not individual technologies, but are instead an interdisciplinary mixture of mechatronics, computer science, production systems theory and communication. With respect to communication, the CMS infrastructures raise new challenges for communication as information exchange [6]. Furthermore, common "reference architectures [...] for the development of solutions by multiple actors" are needed[2], as can be the case of CMS. An

[1] We refer to ISA-TR88.00.02 machine and unit states definition, extended with stand-by state - ISA, 67 Alexander Drive, NC USA.

[2] https://ec.europa.eu/digital-single-market/en/digitising-european-industry.

example reference ICT architecture is proposed by the EU project BEinCPPS (www.beincpps.eu).

Among the communication standards for CMS, OPC-UA[3] is the most promising standard architecture at application layer for connection of an automation cell with the factory level, integrating machinery and workstations.

3 Aim of the Research and Approach

This work focuses on deployment of a Cyber Physical Production System, based on the autonomous control studied by [9], in a laboratory setting (Experience Lab) in Technical University of Braunschweig, Institut für Werkzeugmaschinen und Fertigungstechnik (TUBs IWF), with the aim of improving production systems operation in terms of efficiency in resource usage, and leads to the following research items, discussed in below sections: Sect. 4.1: system requirements for autonomous control in the line; Sect. 4.2: data and communication structure; Sects. 5.1 and 5.2: alternative deployment architectures.

4 Research Findings

4.1 System Configuration and Requirements

The line studied in this work, used for educational and training purposes, is composed by machine modules (including drilling, press, heating tunnel) linked by transfer line (transport belt system + RFID. Each module is equipped with Siemens PLCs, providing communication over industrial Ethernet and sensors for energy and compressed air consumption monitoring. Each machine module, by sharing its digital twin with the other modules, should be able to change state to stand-by when possible, in order to save resources, such as energy and compressed air.

4.2 Conceptual Model of the System Under Study and Autonomous Control

Table 1 shows the main elements of digital twin data structure of each machine i in the serial line.

Figure 1 shows the conceptual model of the cyber physical system that builds up one generic machine. The model is built in Modelio (www.modelio.org) with SysML, a specialized language for System Engineering design, development and validation, and is represented by an Internal Block Diagram, showing the main components and the information data exchange among them.

The state of each machine (i) must be updated depending on the following events: (a) entry of a part into upstream buffer (i); (b) entry of a part into machine (i); (c) exit of a part from machine (i). The corresponding methods

[3] https://opcfoundation.org/about/opc-technologies/opc-ua/.

Table 1. Digital twin data structure for ERE control (main elements)

Variable	Description and unit
PT[i]	Processing time of machine i (exogenous)
TT[i]	Time threshold for activating stand-by in i (exogenous)
cjExpectedExitTime[i]	Expected exit time from i of job j

are listed in the 'ERE control machine i' block which updates the variables of the 'Machine i digital twin' block and receives external data such as presence and expected exit time of an upstream job. Information exchange is also shown with the physical counterpart of machine i, such the events related to entry and exit from the machine and buffer and with the environment, such as exogenous parameters processing time (PT).

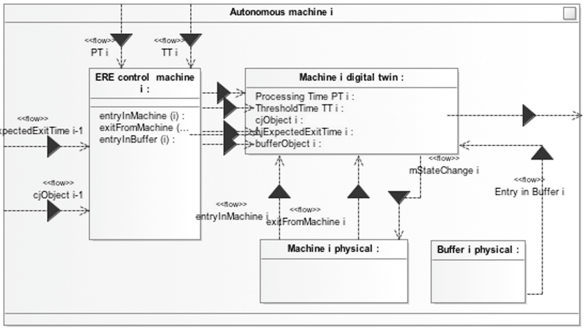

Fig. 1. SysML internal block diagram of Autonomous machine i

The proposed ERE control has been studied with different heuristic rules sets; for the scope of this article we will study the CurrentJobAware (CJA) policy proposed in [9], which is based on the comparison between the time interval available for machine i after end processing before next job arrival and the threshold time (TT), over which it is feasible and convenient to switch machine i to stand-by (as proposed by [8]). The difference, if positive, triggers stand-by mode transition.

5 Conceptual Design of the ICT Architecture for the CPS-ized Line

5.1 Centralized and Distributed Approaches

In order to deploy the CJA to an actual production line, two approaches are considered: a centralized execution of CJA policy on a single computer or server

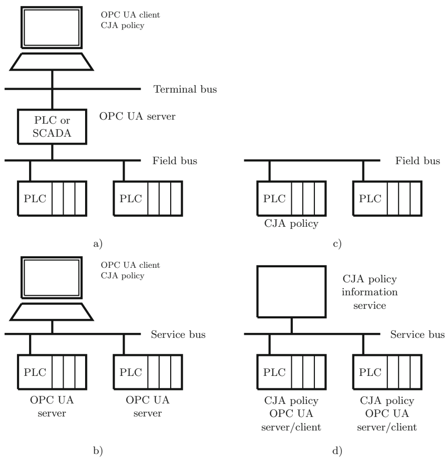

Fig. 2. Considered implementation options for CJA policy

and a distributed execution of the policy directly on the affected PLC of the machine.

A central approach has several advantages. The overall architecture is simple. Due to the clear distinction of tasks and competencies, the maintainability is increased. Since all digital twins are on a single computer, the amount of exchanged data is considered small and communication between digital twins is instant. Despite the increased maintainability, a single point of failure is introduced in the system.

Using a distributed approach may appear more reliable. On the other hand, the amount of exchanged data may be increased since each PLC communicates with each other. Furthermore, in a changing setting, each PLC has to be reconfigured in order to execute the CJA policy correctly. The implementation of a subsidiary information service is suggested to overcome this problem and publish updated configurations to the PLCs. A failure in the information service does not directly lead to downtimes on machines since the policy itself is executed on the PLC.

However, in both cases further backup policies are required in order to ensure an operational mode in case of a system failure (e.g. bus error, CJA policy stopped working). For instance, a heartbeat signal can be used to recognize failures and active the backup policy, e.g. leaving standby mode. In case of a central approach, the CJA policy may be extended by a redundancy system to increase reliability.

5.2 Integration of CJA Policy

Depending on the given or desired automation system, multiple deployment options exist. Hereafter, four options are presented. Since a computer based

CJA policy execution uses OPC UA for communication, most options are based on this standard.

Figure 2(a) shows a deployment scenario based on large scale plants with a separate field bus and terminal bus for security and reliability. The CJA policy is executed on a computer connected to the terminal bus of the plant. The SCADA system or a PLC providing a OPC UA server is used as broker between digital twins and physical machines. Building on an existing system, this approach does not require new connections between the existing systems.

Alternatively, the computer running the CJA policy can be connected directly to the service bus of the plant (Fig. 2(b)). As already mentioned, OPC UA becomes common among PLC vendors, which provides a unified protocol stack for communication with the PLCs regardless of its vendor.

As shown in Fig. 2(c), the CJA policy can be implemented on a single PLC. Unless the PLCs are not already connected, no further connections are required. Communication can be based on a vendor specific or common protocol.

The last considered scenario deploys the CJA policy on each PLC of the machines (Fig. 2(d)). In this scenario, OPC UA can be utilized for communication or a common vendor specific protocol is used in case of a heterogeneous setup. The implementation of a subsidiary information service is suggested as described in Sect. 5.1.

5.3 On-Going Experimentation

We are currently experimenting the central approach option (see Fig. 2(a) deployed in (i) an OPC UA server, implementing the data structure presented in Sect. 4.2, deployed into the IWF Experience Lab and (ii) a CJA policy deployed in a OPC UA client on a laptop computer. OPC UA server is implemented on SCADA System SIMATIC WinCC[4] while the OPC UA client exploits Open Source OPC UA implementation open62451 (https://open62541.org).

The system is composed by five machines in a serial line, with parameters and energy profile as in Table 2. In this first experiment phase, the signals coming from the line (such as part finished, processing time left and consumed energy) are simulated by a WinCC program running on a personal computer.

Table 2. Machine parameters and energy profile

Parameters	Power consumption
Mean PT[i] = 15 s	Execute power [i] = 20 kW
Sigma PT[i] = 4 s	Stand-by power [i] = 1 kW
TT[i] = 3 s	Idle power [i] = 10 kW
Ramp-up time [i] = 2 s	Ramp-up power [i] = 40 kW

[4] http://w3.siemens.com/mcms/human-machine-interface/en/visualization-software/scada/simatic-wincc/Pages/default.aspx.

In the first experiment set-up, besides showing a first validation of the solution, with the CJA policy controlling only the fourth machine in the line we aimed at checking out step by step the correct triggering of the CJA policy. The experiment has been run with an inter-arrival time (IAT) of 30 s, obtained by having all parts to be produced loaded on the first machine buffer at the beginning of the run, with a first machine processing time of 30 s. We have run four test runs by varying the number of parts produced from 2 to 20 parts. Output of the test run is the total make-span MS (s) and the total energy consumption of machine 4 (CEn) on which the CJA policy is implemented.

The current line configuration, with a machine saturation around 50%, allows 15 s available time (due to difference between average cycle time and processing time) to trigger the CJA policy nearly each cycle. On the other hand, the energy profile is characterized by interesting trade off between idle mode and standby overall energy consumption, as a stand by cycle generates each time a power up cycle, with energy consumption peak of 40 kWh for 2 s. Table 3 shows results of first four test runs (where CEn = Consumed energy, MS = make-span):

Table 3. First test run results

Test run	Parts (nr)	CEn No CJA (kWh)	MS No CJA (s)	CEn CJA (kWh)	MS CJA (s)	CEn delta(%)	MS delta (%)
Run1	2	0.46	132	0.25	137	−45 %	+3.8%
Run2	4	0.73	196	0.51	209	−31 %	+6.6%
Run3	10	1.51	377	1.18	380	−22 %	+0.8%
Run4	20	2.86	699	2.43	703	−15 %	+0.6%

The first test runs are promising: energy saving could be in the long run more than 15% of the baseline, even in a system affected by disturbances, considering as well the trade off between idle time and standby + power up energy consumption, while running on one machine only. Furthermore, it appears that the make-span might be increased maximum to 6%, which can be reduced easily by more advanced versions of CJA policy, able to trigger a power-up state change in advance (e.g. 2 s), to have the machine ready in idle mode right when needed.

We are currenly extending each of the four test run, such as running the same run more times while allowing different disturbances series to affect the system, and then averaging the results in order to get more sensible assessment of the experiment values reported in Table 3.

6 Conclusions and Further Steps

This work discusses two alternative approaches, centralized and distributed, for the deployment of the ERE autonomous control under study in the TUBs IWF

Experience Lab, evidencing their characteristics and drawbacks, in terms of manteinability and reliability. For this, deployment scenarios with different configurations options, leading to different degrees of centralization have been identified. The work is based on state of the art methods and tools, such as OPC-UA communication and model based design (SysML), as proposed by previously cited EU project BEinCPPS.

The centralized approach appears to be easier for students able to work with tools such as MatLab, but should be deployed by taking into account disturbances and synchronization problems. The distributed approach based on local processing in embedded systems, might be more reliable and interesting from an industrial point of view, but needs more efforts.

The first performed test runs are promising, as they show CJA policy can obtain significant energy savings, potentially with no substantial effect on the line productivity, even with a simple version of the ERE control running only on one machine of the line. Limitation of the experiments run so far are that we have performed only one test run for each combination of system configuration and parts produced and the design of experiment should be extended to accomodate more system parameters variations (e.g. interarrival times and threshold time).

Further steps for this work, besides completing a full design of experiment to study the behaviour of the CJA policy on the whole line, include further implementation, experimentation and evaluation of the CJA policy and of the alternative ICT architectures discussed in this article, such as the distributed approach (e.g. Fig. 2, option d), with extension of experiments to other potentially interesting sets of ERE heuristic rules, including disturbances/failures, and, finally, study of the proposed approach to more complex production configurations, such as flow shops or job shops. Furthermore, possible field of research is the study of how each machine can autonomously identify its expected processing time and threshold time, taken in this work as exogenous parameters.

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Optimization of Production-Oriented Logistics Processes Through Camera-Based Identification and Localization for Cyber-Physical Systems

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Abstract. The use of sensor data as well as the combination of different data from diverse systems in production and logistics lead to new opportunities for monitoring, controlling and optimization of processes within the scope of Industry 4.0. New developments of camera-based systems support this trend, which is particularly relevant for the control of cyber physical systems (CPS). This paper discusses a new approach for camera-based dynamic identification and localization, including speed and orientation determination, in combination with joined data form different sources and data analysis for CPS. In order to assess the potential of the approach, various possibilities and methods for camera-based optimizing CPS are discussed. A production-oriented logistics application shows the technical feasibility of the approach.

Keywords: Camera · Camera-based sensor · Combining data · Logistics · Cyber-Physical Systems · Optimization · Visualization · Industry 4.0

1 Introduction

Increasing customer requirements and individualized products lead to a growth of complexity in production processes and the amount logistics processes due to distributed production sites and higher complex delivery networks [1]. To meet these higher requirements, a new level of organization and control of the entire value chain over the lifecycle of products is necessary [2]. This is summarized under the term Industry 4.0 based on Cyber-Physical Systems (CPS). CPS are embedded open-ended socio-technical systems and enable a range of new functions, services and features for production, logistics, engineering, coordination and management processes as well as internet services [3]. An essential basis is the availability of all relevant information in real time through directly captured physical data by sensors and networking of entities involved in the value creation as well as the ability to derive optimal value-added flows from data obtained [2].

Industry 4.0 contains vertical integration and networking of production systems [4]. These aspects include the areas of sensor networks as well as intelligence, flexibility and

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changeability of systems through comprehensive solutions. In particular, sensor networks provide a new way of process understanding by permanently collecting and analyzing sensor data from production and logistics. [5] This includes further development of camera-based sensor technology to intelligent, configurable and networked sensor systems with case-specific and adaptive measurement strategies [6]. After an overview of related work, we show an approach using camera-based sensors in combination with joined data from different sources, data analysis and visualizations to analyze and control CPS to improve production-oriented logistics. An implementation in a modular production system and opportunities of the approach are discussed subsequently.

2 Developments in Sensor Technology and Related Work

Various methods for obtaining production and material flow data, such as manual data collection by employees, applications of auto-ID techniques (bar code or RFID techniques), subsequent analysis of film recordings, analysis of production documents and statistics or data collection from ERP systems are available [7]. Through the continuous development of sensor technologies, new and more effective methods for obtaining these data could be developed [8].

Camera-based data collection systems can provide a useful complement to existing data collection methods. This increases the availability of distributed information from a wide range of sources, which also have to be analyzed in real time and can be used for system control. Providing information for self-control becomes increasingly important. New camera models for camera-based systems have the capability to build the function of different sensors and to generate virtual sensor data in the desired quality. This allows an analysis of the effects for sensor-specific and process-specific parameters on situation analysis [9].

Concerning the use of camera-based sensors in logistics, the number of applications and research projects is limited [10, 11]. Computer vision is used as a method for realizing and replacing different sensors on forklifts trucks with just one technology at the project “Staplerauge” [12]. The replacement or supplementation for various sensors such as localization of hoist height determination and fork-occupied detection leads to decreasing integration costs on forklifts trucks and background IT-systems. In practice the technical feasibility and a high potential of the vision-based state monitoring for forklifts has been proved [13].

A different approach pursue the marker-based location of resources at the project MarLO [8]. Fixed infrastructure is equipped with appropriate video sensors to detect optical markers on different mobile logistics resources like forklift trucks. Marked objects are tracked from the outside and the acquisition and calculation systems are firmly connected with the sensor processing units. This system is advantageous for spatially restricted application environments as well as for free surfaces, in which numerous mobile operating means are used.

At the project tracing intelligent logistics objects (TiLo) the feasibility of data acquisition and analysis by the industrial image processing and the use of simulation studies are demonstrated [14]. The used camera covers only individual areas and the obtained data is only used for simulations. There is also no connection of the camera data with production and sensor data.

The presented projects often show only individual elements of Industry 4.0. A comprehensive connection of camera-based data with further production data analysis and evaluation in combination with visualization in real time and for simulation is not achieved in the production environment.

3 Technical Concept

In addition to the necessary basic conditions, the technical concept includes four stages. First, the type of identifiers as well as the type of identification and localization methods are defined. An interface to existing production databases is created subsequently. In a third step the camera-based data and the data from the existing systems have to be prepared and evaluated in order to make decisions and to support workers through appropriate visualizations in a final step. Such virtual sensors are a step ahead to reach Industry 4.0 goals. Figure 1 shows the complete process.

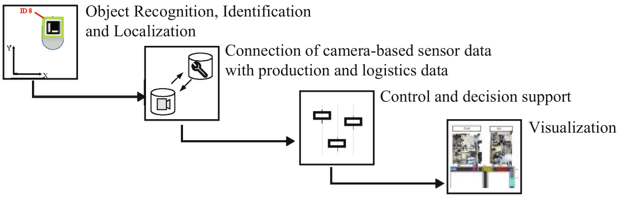

Fig. 1. Complete process of the approach

3.1 Requirements and Necessary Conditions

The use of camera-based sensors needs various minimum requirements and conditions, which must be taken in order to achieve a secure identification and localization of objects in a required quality. For locating different equipment by camera-based systems, two essential technical approaches are possible. Either the mobile object itself captures its surroundings. For this purpose, cameras are installed directly on the objects and markers are placed firmly in the environment. Or the mobile object is captured, realized by cameras attached in the infrastructure and markers mounted the objects.

The size of the covered area is to be taken into consideration. Depending on the design, several camera-based sensors have to be used for larger areas. This leads to an increase in system complexity. Furthermore, the type of the relevant objects have to be taken into account. In addition to natural identifiers, artificial identifiers can be used too. The size of the objects observed as well as the distance leads to minimum requirements for the resolution of camera-based sensors. Influence on the minimum sampling rate of the sensors has among other things the speed of the objects. The light conditions on the spot have an influence on the quality of the object detection. These factors influence the exact design of the camera-based sensors.

3.2 Image Processing and Localization Algorithm

Because artificial identifiers often lead to a more stable detection of objects, further matrix codes are discussed. ArUco markers are synthetic square marker composed by a black border and an inner binary matrix containing a number as an ID. The ID and the direction and size of these markers is easy to detect with software libraries to analyze camera images, like the open source computer vision OpenCV. For the recognition of the markers, they need at least the space of about 30×30 pixels of the camera image.

The resulting data of the recognition – ID, Coordinates of the edges – are used to compute more derived information: direction and speed of the objects, distances to other objects etc. These data may be seen as received from virtual sensors and are saved for further investigation. The object itself does not need any sensors or wireless communication facilities, but if it is able to communicate, it could be provided with all these data concerning itself or all other marked objects. The data seems to come from a superset of sensor built in – virtual sensors. To reach the goals of Industry 4.0, these data may be distributed to the different elements of the production in real time.

3.3 Connection and Processing of Data from Different Sources

A software interface to relevant production database has to be implemented to read the state of all involved elements to combine these data with the data of marker recognition and derived data together with the timestamp to build a database of the production process containing all relevant information. This data could be used to monitor the production process just in time or later in simulations. Section 5 discusses these possibilities.

3.4 Visualization and Worker Support

These compacted data from different sources are used to visualize the production process in a different view like augmented vision or a virtual picture of a system. The augmented vision combines the real camera image with additional superimpositions. Thus provides a detailed insight into systems along with necessary added information. The camera images are not necessary needed any longer for the virtual view – may be stored for some time for controlling purposes – and the compact sensor may be transferred to any place to see the production in real time or later. The commented and with all information added data can be used to monitor and control the production. Based on this added data new decisions could be made to optimize production processes.

4 Demonstrator and Implementation on an CPS

The presented concept is implemented in a modular production system shown in Fig. 2. This CPS produces individualized valves in small batches up to lot size 1. A work piece carrier equipped with a RFID tag contains orders, work plans and work pieces. The production line consists of six connection points for various production modules and a conveyor belt circuit. To realize an improved material flow control, the system has two switch points to skip stations. Each module is decentral controlled via its own PLC. Orders and certain production steps are also documented centrally in a MES with appropriate databases. In the first module, three different basic bodies are provided from stock. The second module performs several machining operations, such as drilling. Quality control is performed in the third module. A robot assembles individual components of a valve in the fourth module, which can subsequently be stored in the fifth module. Module six commissions and deliveries finished orders to customers.

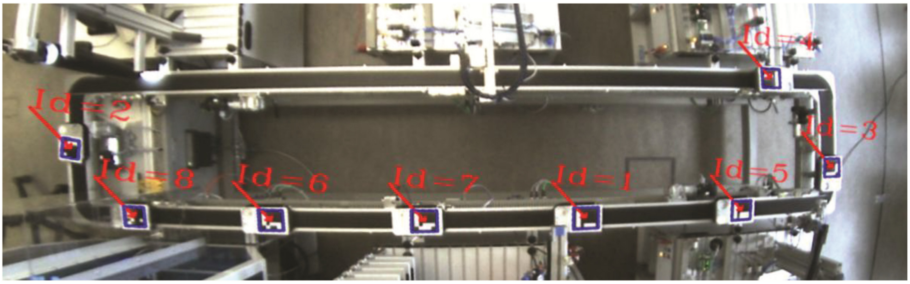

Fig. 2. Augmented camera picture

Based on this system, various hardware changes were performed based on the process shown in Fig. 1. This includes in a first step the placement of ArUco markers on the work piece carriers for identification and localization. A camera was installed centrally above the modular production system and provides images of the whole system. The analysis software, located on an external PC, recognizes the parameters of all markers inside the image and continuously calculates the position of all carriers almost in real time, shown in Fig. 2. The parameters of the markers (ID, position of the center and the position of the corners of the markers) are stored in a database table together with time stamps. The alignment, the speed and the direction of movement of the markers can be calculated from these image sequences. This design of the camera system is easy to implement with minimal interferences of the production and logistics processes.

Secondly, the production databases of the MES were connected to the software through a two-way interface. During the data connection and analysis, the tables of the production database are constantly read out. These data are combined with the data from the position calculation of the markers. According to this, in a third step the system derives different evaluations and results. In the example shown in Fig. 3, eight carriers are used. Two carriers (3 and 5) being filled with a basic cylinder. Carrier 3 moves to the station “Camera” for a quality check. Carrier 5 transported its basic cylinder to the station “Driller” and waits for the completion of the drilling process.

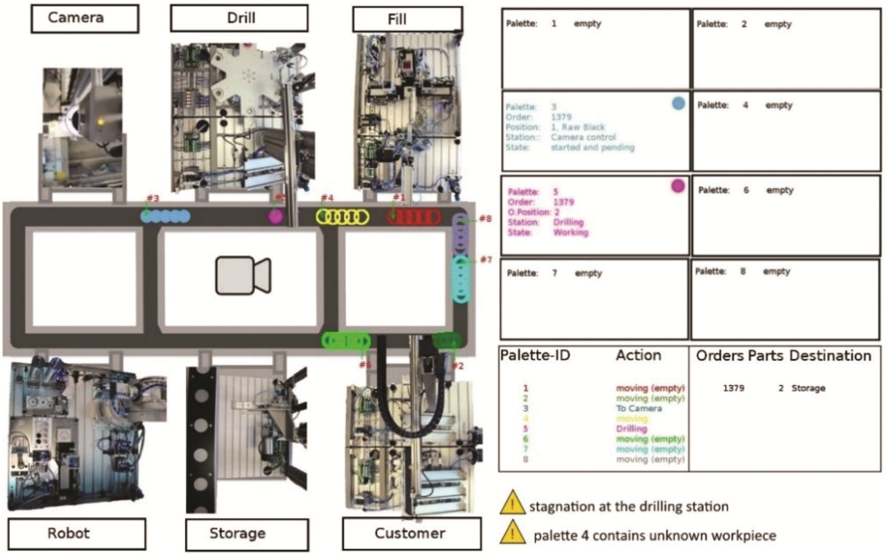

Fig. 3. Virtual view of the system with camera-based identification and analytics

The detailed view of production and logistics processes leads to abilities for self-optimization, self-configuration and self-diagnosis, which are essential for Industry 4.0. Standstills of the conveyor belt can be detected immediately. The blockage of the belt by a jammed carrier also between the stations triggers an alarm message. In addition, the evaluation determines the service life of a carrier at a station, whether the processes run stably or require more time than usual. The position of the individual carriers is determined continuously and independently from sensors of the individual modules. This allows a more precise localization of the carriers and a higher transparency of logistics processes. The position and the type of parts on the carriers can also be determined precisely. The software identifies the markers of the loaded parts and evaluates the images in combination with the data from the MES. Thereby a plausibility check of the work pieces (presence, color and diameter) is possible. Different lengths of processing steps on individual modules can cause queues, which cannot be adequately regulated by the decentralized control, without an image of the entire system.

In addition to a real time evaluation, the data can be used for later simulations too. Without intervention in the plant, the influence of different parameters and strategies on the production can be tested. This includes changes in the belt speed, changes in the duration of individual production steps or influence of the distance of the stations. Layout decisions and optimizations can also be determined.

Several views are implemented for the visualization of the system within the fourth process step. One view shows the camera image of the plant with augmented information of identified carriers and important parameters from the production database. Figure 3 shows the virtualized representation of the plant with the current status of the orders, work pieces and work piece carriers. This view gives a good overview of the production and logistics processes including messages and warnings.

5 Optimization Methods and Opportunities of the Approach

The presented concept leads to a shift of hardware functions to software functions via software modules. These software modules are the basis for higher flexibility and changeability for CPS and in production-oriented logistics.

The presented camera-based systems have the advantage that they do not need a direct connection to the existing controls of the systems. Therefore, they collect information independently from existing automation and control data of production plants. Changes of the camera and evaluation software can be made during production. This leads to minimal disturbances in production and logistics. In this way, camera-based systems can collect data on details that cannot be captured or can only be captured at great expense by installed sensors in existing production facilities.

The continuous connection of identification and localization with different production data can be used to monitor a production. Already in a simple structure, an augmented representation of the current production is possible over the network or internet. Standstills of transport systems, such as conveyor belts, can be detected immediately and an alarm message can be triggered. Processing and handling times of production stations can be determined and evaluated, too. Without direct encroachment on plants, data for simulations can be collected. The data can be used to test the influence of different parameters and strategies in production and logistics. Thus leads to an evaluation and optimization of individual production stations, identification of bottlenecks and to improved layout decision for production networks. In addition to the presented possibilities, there are numerous other possibilities for optimization for CPS in Industry 4.0:

- Providing high-resolution state data and relevant information to entities and systems in real time through directly captured physical data and data analysis for an adaptive production control
- Plausibility comparison with the signals from other sensors, e.g. combination of artificial with natural identification features or production data
- Replacement and extension of various existing sensors
- Continuous monitoring and Real time control of processes
- Increasing the transparency and system understanding of the production and logistics facilities by recording and analyzing services and loads
- Support for workers through clear visualization and decision-making
- Later made simulations based on the data could help to discover and eliminate weaknesses and errors and to optimize production

6 Conclusion and Outlook

In this paper, various possibilities for the use of camera-based sensor data in production and logistics were presented. Camera-based sensor technologies become more effective, more powerful and more cost-effective, and will be used largely in logistics and production systems. By combining the resolved sensor data with other data from the production and logistics, CPS control can be improved and optimized. The presented methods of visualization provide a good basis for system monitoring and decision support of workers. Therefore, combining of different data resources leads to an improvement and optimization of processes. The technical feasibility was demonstrated by an implementation in a modular system with production-related logistics processes.

In the further work, additional implementations for evaluation will be developed. This will includes extended use and combination of different data sources as well as new methods for visualization of data and providing relevant information for CPS in Industry 4.0.

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Automaton-on-Tag: An Approach for an RFID-Driven Production Control with Mealy Machines Stored on an RFID Tag

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Abstract. In this paper, we present an approach to how to store production plans directly on an RFID tag in the form of an automaton. Based on a modular manufacturing system, this enables manufacturing systems to become more flexible and changeable and, in addition, reduces the engineering effort for adaptation in an existing plant. The connection between different production modules is implemented via carriers and a Mealy machine that is stored on an RFID tag. This machine's states represent the production steps of the product on the carrier.

Keywords: Data-on-Tag · Automaton-on-Tag · CPS · Modular manufacturing system · SOA · Mealy machine

1 Introduction

Production plants are facing a dynamic environment. The emerging demand for individualized products (down to one-piece production) to similar costs compared to bulk products and competitive in quality, price and availability results in changing challenges during the lifetime of a plant [1]. This is especially for manufacturing systems with a high degree of automation challenging. Nowadays these systems are highly complex so that they are often less flexible or changeable. Due to their complexity, adaptions and reconfigurations can be very time consuming. Flexibility and changeability are two requirements to meet the challenges of the dynamic environment. Concepts, aspects and technologies emerging with the buzzword "Industrie 4.0" are enablers to reduce complexity within a production system, whereupon flexibility and changeability can be gained. A central concept of Industrie 4.0 are Cyber-Physical Systems (CPS). CPS are smart machines, warehouse systems, resources or products that are able to communicate with each other and control each other [2]. Products become due to CPS clearly identifiable, are localizable, know their production history, their current production state and alternatives to get to their target state [2]. Another aspect of Industrie 4.0 is that storing and processing of information should be close to the physical location where the information origins from or where the information is needed [3]. This results in a decentrally

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organized, robust and flexible process of data processing [3]. In this paper, we describe an approach to how to reduce complexity and gain more flexibility in a manufacturing system by the application of Industrie 4.0 approaches. We use RFID tags to let objects, i.e. products, become CPS and store the whole workflow in the form of a Mealy machine on it, thus guiding the product through the production process.

This paper is structured as follows: After a short introduction, explaining the problem, motivation and a short introduction to a possible solution, in Sect. 2 the background and related work is discussed. Section 3 presents a possibility of a decentral data management. In Sect. 4, we demonstrate the concept Automaton-on-Tag, whose implementation is demonstrated in Sect. 5. This paper concludes with a summary and an outlook towards future research topics.

2 Background and Related Work

2.1 Typical Information Flow in Automated Manufacturing Systems

Nowadays the information flow in a manufacturing system is often centralized and strictly hierarchically structured. Several IT-systems are used to perform different tasks and communicate with each other across different hierarchy levels.

Initially a production order will be registered in an ERP-System. This order will be handed over to the MES that is in charge of the production process and handles all following decisions, including scheduling of orders and assigning of orders to machines [1]. Via Supervisory Control and Data Acquisition (SCADA), manual interventions into the manufacturing process are possible and a representation of the current state of the manufacturing system is visible. PLCs control the physical manufacturing process via sensors and actors. This structure leads to high complexity of the manufacturing system and within the procedure of controlling and scheduling of the production. This causes that even simple changes in a running production process will effect adaptations in different IT-Systems.

2.2 Modular Plants and SOA

An approach for a reduction of the complexity within a manufacturing system is seen in decentralization and modularization, so that single control tasks are spatially and chronologically separated and that these tasks can be executed autonomously by the modules [4]. This approach leads to a dissolving of the strictly hierarchically structured automation pyramid, shown in Fig. 1 (left). For that, each machine or different machines related to each other will be capsulated in a module. Each module features one or several services according to its functionalities. This leads to a Service-Oriented Architecture (SOA). SOA is a concept originating from the IT, based on services. Each service represents a certain functionality and provides only this functionality to other services [5]. The implementation of the functionality inside of the service is not visible from outside the service [5]. In the SOA concept all services are loosely coupled, so they operate independently from each other, their interactions are stateless, asynchronous and not context-related [6]. Applications and production workflows in SOA are a composition of different services, which together fulfill a mission [5]. Due to the loose coupling of the services, manufacturing systems become more flexible and changeable.

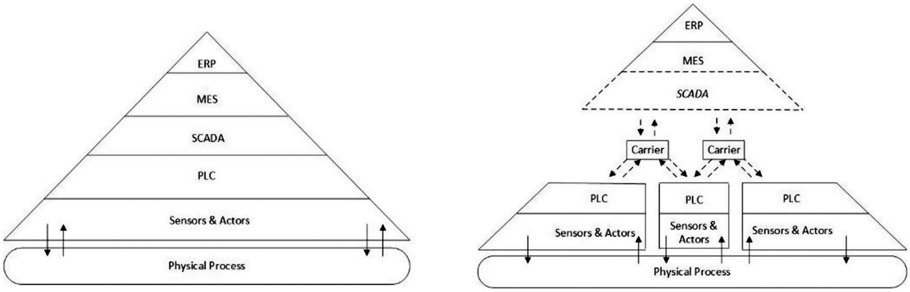

Fig. 1. Typical automation pyramid (left) & modularized automation pyramid (right)

3 Decentral Data Management in Modular Plants

3.1 A Possible Structure of the Automation Pyramid in a Modular Plant with RFID-Driven Production Control

In a modular manufacturing system each module offers at least one service. Due to this, the rigid automation pyramid gets softened. We propose an approach for an RFID-driven production control. All related information to a product will be directly linked to the product or a carrier, transporting the product through the manufacturing system. The RFID tag contains all relevant information to control the production process. Thus, it is also able to realize the communication between the modules and the IT-Systems.

The right side of Fig. 1 shows a way to divide the automation pyramid and the communication structure when using a modularized manufacturing system and carriers to realize the communication. While some SCADA functionalities might be integrated into the MES, a typical SCADA system cannot be used if a plant's modules are only connected by carriers.

3.2 Requirements and Existing Work for a Decentral Data Management

In most use cases, RFID tags are only used as an identifier for objects, storing just a unique identifier, despite the fact that the tag has enough capacity to store object related information directly to it [7]. Often object related data are stored in a backend system [7]. This approach is called "data-on-network" [7]. The approach data-on-network brings several disadvantages, like a high complexity and the circumstance that all modules are dependent on a constant network connection to a master database. A possibility to solve these problems is storing all the objet relevant data directly on the tag, as mentioned above. This approach is called "data-on-tag" and leads to a decentral data management [7]. [8] define some rules and requirements for the implementation of a data-on-tag approach, which have to be considered to develop a sustainable approach for a decentral data management:

- Implementation of a low cost memory, to consider the case, that the memory is connected to the product for the whole life cycle. A consequence of this is the application of a method, requiring a small amount of storage space.
- Sufficient product storage space, to store all manufacturing information.
- Flexibility of the data structure, so that the data structure is easy adoptable to new conditions.
- Expandability of the memory, to provide the option to extend the related information to an external storage space, if the memory does not remain on the product.
- Fast read and write access to the memory to ensure an efficient production process.

A further requirement for a sustainable approach of a decentral data management is the consideration of a possible flexibility within a production process. The description model of the production workflow on the RFID tag has to be able to consider different possibilities within the production process, like loops, alternative branches or fixed steps.

An existing approach for a decentralized data management is presented in [9]. Based on the idea of using agents for controlling the production process, the approach is called Agent-on-Tag. The core aspect is to store a whole agent on a RFID tag. Every time the RFID tag is connected to a module or a machine, the executables will be executed and the runtime variables will be updated. This is only applicable for RFID systems and tags with a huge storage space and a fast speed for reading and writing the RFID tag [9]. Thus, it does not fulfill the requirements mentioned above.

[8] present an approach for a decentral data management in a modular plant. They store the current manufacturing state on the tag. Every time the RFID tag is connected to a module, the module compares the current manufacturing state of the product with the requirements to execute the manufacturing service of the module. With this method, they are not able to consider different possibilities within the production process, like loops and alternatives.

4 Automaton-on-Tag

4.1 Selection of a Description Model

To meet all requirements defined above, we use three types of information, stored on the RFID tag. First, there are data needed for identification and description of the related product. Second, there are data needed, for controlling the production process and third, there could be a need for production related data. These production related data could be used to reconstruct the production process ex post. The focus in this paper is on the second type of data, the data for controlling the production process. A possible method to meet the described requirements above is to describe the production process in form of an automaton on the RFID tag. Automatons are mathematical models to describe discrete event processes and systems and consist at least of different states and edges, connecting the states [10]. The state of the automaton is exactly defined and the automaton can only be in one of a finite number of states at any given time. In this context, a state represents a fulfilled service of a module, so that the current state is the last executed production step. Through the edges, the states are getting related to each other. If there is a connection between two states, a change from the current state to the other is possible. Thus, the edges define possible paths through a network of states, describing the sequence in which the production steps has to be fulfilled. Since in a manufacturing process the transitions from one state to another are related to certain preconditions, for instance Step A has to be fulfilled before Step B, the transitions have to be linked to some conditions, which have to be fulfilled before a change from one state to another is permitted. In this context these conditions are linked to the edges. In manufacturing systems modules might not only offer fixed services, but also services that provide some options. An example for this circumstance could be the fictional service painting. This service can be executed with different colors. So there is a need for parameters to define the way how each module executes its services. These parameters can also be linked to the edges. A specification of an automaton, enabling the consideration of both these requirements, is the Mealy machine. In a Mealy machine, the transition from one state to another depends on an input [10]. An output is determined by its current state and the current input [10]. The input can be interpreted as a condition considering the production history. Depending on the current state and the condition, the output specifies the services to be executed.

4.2 Data Structure on the Tag

To store the Mealy machine on an RFID tag, we use three data components. 1. current state, representing the last executed production step, 2. production history, representing all the executed services and 3. edges. The current state expresses the last executed step in form of a number representing the fulfilled service. This data component is necessary to define the current position within the Mealy machine. The production history is realized as an array, containing the number of invocations of each service. Edges contain the source and the target state, the condition that needs to be fulfilled to choose this edge and a parameter, specifying the execution of the services. Figure 2 demonstrates the declaration of two user defined types that are used by each module's controller to interpret the RFID tag data as a Mealy machine. The first type contains the current state, the production progress and an array of edges. These edges are defined by the second

```
TYPE st_AoT :
    STRUCT
        identifier      : USINT;                    // Carrier ID
        activeState     : USINT;                    // Currently active state of the Mealy machine
        currentStatus   : ARRAY[0..5] OF BYTE;      // Current production progress
        edges           : ARRAY[0..9] OF st_EdgeAoT; // Array of edge elements
    END_STRUCT
END_TYPE

TYPE st_EdgeAoT :
    STRUCT
        sourceState     : USINT;                    // Source state of this edge
        targetState     : USINT;                    // Target state of this edge
        targetStartTime : DT;                       // Timestamp: target service started
        targetEndTime   : DT;                       // Timestamp: target service finished
        condition       : ARRAY[0..5] OF BYTE;      // Condition that activates this edge
        parameter       : USINT;                    // Parameter of this target state's service
    END_STRUCT
END_TYPE
```

Fig. 2. Data structure of Automaton-on-Tag

structure. While we use a simple integer as an identification number, the Electronic Product Code (EPC) might be more suited for industrial use. The EPC is a universal identifier, providing a unique identity assigned to physical objects, unit loads, locations, or other identifiable entities. Additionally we extended the edges with time stamps. This enables a chronological reconstruction of the production history and allows the monitoring of each module's processing time and every products lead time.

4.3 Processing of the Data

Through the described data structure, the complete Mealy machine becomes representable on the RFID tag. As RFID tags are only able to communicate passively the active part of the communication has to be fulfilled by the module. Every time an RFID tag comes to a module, the module has to read the data, process them, update them, and write them on the RFID tag. This procedure happens as follows: if an RFID tag comes into the range of the RFID reader of a module, the module itself starts to read the information on the tag. Beginning with the first edge, the PLC compares (a) if the current state, stored on the RFID tag is equal to the source state of the edge, (b) if the target state of the edge is equal to the state the module is representing and (c) if the condition relating to the edge is equal to the production history. If an edge fulfills these three conditions, this edge's parameter will be transmitted and the target service's start time will be set. After executing the service, its end time will be updated. This is followed by a physical transport to the next module, where the procedure happens again. If the condition of an edge is not fulfilled, the PLC checks, if the last edge is reached. If this is not the case, the next edge will be selected and the procedure happens again. If the last edge is reached, there was no intention to execute the service of the corresponding module within the production flow of the product and the product will be transported to the next module.

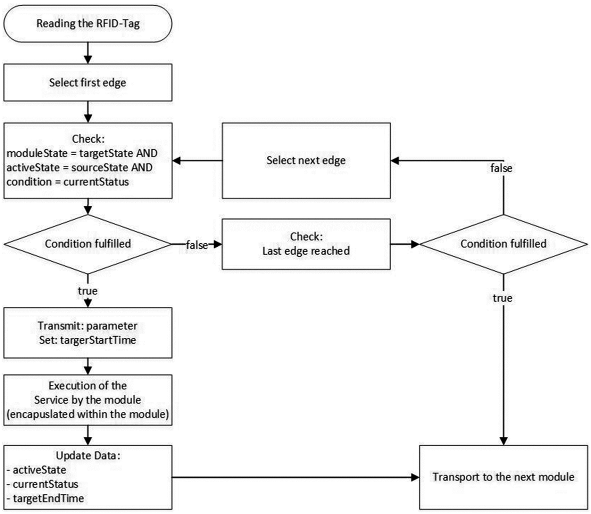

Fig. 3. Flowchart of the processing of the data

Figure 3 describes the sequence of the data processing in form of a flowchart. This procedure and data format enables the consideration of loops and alternatives within the production workflow. Loops are realized through the conditions of the edges. Equivalent alternatives are realized through equal source states and equal conditions of the edge, but different target states. Due to the interaction of the components and the dynamic data structure the object carrying the RFID tag becomes a CPS, which is able to navigate itself through the production process and which is able to communicate with the different modules.

5 Implementation

The concept Automaton-on-Tag has been implemented in a modular manufacturing system, which is dedicated to the production of individualized cylinders. The RFID tags are integrated into the carriers of the cylinders. The modular manufacturing system consists of six independent production modules connected via a conveyor belt. Each module is equipped with an RFID reader to communicate with the RFID tags of the carriers that pass the module on the conveyor belt. The layout of the conveyor belt ensures that all carriers will pass every module as often as necessary. Due to the implementation of Automaton-on-tag the manufacturing system becomes more flexible: Each module just has to know which services it offers, the specific control code for the execution of the services is encapsulated within the module, hidden from the control of the production process. The implementation of the communication between the modules via the carriers results in a loose coupling of the modules and the separation from a centralized IT System. This enables a flexible adaption of the manufacturing system to dynamic changes by integrating or removing certain modules. The MES just has to know how many modules of each type are integrated to be able to release an optimal amount of production orders into the production process. Changes in the running production workflow can be done at any time without the consideration of several IT systems by adjusting the data on the RFID tags, e.g. by using a handheld RFID reader.

6 Conclusion

In this paper, we presented a concept for an RFID based production control in a modular manufacturing system. All necessary information is stored on an RFID tag, which is directly linked to the product. The interpretation of the data in form of a Mealy machine is suitable because it does not need much capacity on the RFID tag and enables a dynamic representation of complex production plans, including loops or alternative routes. The benefits of this concept are manifold: The whole system becomes more independent from a centralized backend system, making it far more resistant against disturbances and interruptions [8, 9]. The manufacturing process becomes more flexible and changeable because the communication via RFID tags enables an easy addition or removal of modules. In addition, changes in a running workflow can be done easily because adjustments will be written directly onto the RFID tag related to a product. Further research questions which arise around MES in a loosely coupled modular plant are: How can an

MES be aware of the modules and their services if it is not directly connected to each module? Future research might profit from the research around so called Module Type Packages (MTP). MTP are a promising way to describe the communication interfaces and functionalities of process plant modules [11].

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The Role of ICT-Based Information Systems in Knowledge Transfer Within Multinational Companies

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Abstract. This paper focuses on the internal network of multinational companies (MNC) and aims to investigate the role of information systems (IS) based on modern information and communication technologies (ICT) in transferring knowledge between different plants of the MNC, a subject still debated in the literature. To shed more light on this relationship, we propose that in the context of the MNC, the plant's role in the knowledge network has to be taken into consideration.

The analysis is based on a case study approach with interviews conducted at thirteen manufacturing plants. Data analysis shows that plants can have two basic roles in the knowledge network: knowledge senders or knowledge receivers. Knowledge sending plants see IS less supportive in transferring knowledge, while most knowledge receivers rely heavily on some form of IS. Furthermore, IS proved unhelpful if the quality of data entered in the system was low, or when strategic support to allocate resources to use IS was missing.

Keywords: Information Systems · Knowledge transfer · Manufacturing network · Multinational Companies

1 Introduction

Manufacturing companies have changed their way of producing products. Traditionally, a manufacturing company had one plant and served the world out of this plant. Today, many companies produce their product portfolios in a network consisting of several plants located in different countries. These plants represent the building blocks of the internal network of multinational companies (MNCs). To coordinate these plants, the flow of knowledge has been recognised as of key importance [5, 8, 27].

Beside the knowledge sending and receiving units, and the knowledge itself, benefits of a knowledge transfer process are also influenced by the connection between the sending and receiving unit [16, 24], including the mechanisms and channels used to transmit the knowledge [3]. Gupta and Govindarajan [9] show that these transmission

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mechanisms and channels positively influence the amount of knowledge shared, both at sending and receiving units. Almeida et al. [3] demonstrate that MNCs use a multitude of different transmission mechanisms to move knowledge across different intra-firm units. They also show that MNCs put a heavy emphasis on using information systems to facilitate knowledge transfer, including shared databases, common communication software, standardised design tools and file formats, company intranets, etc. Reviewing the literature on knowledge transfer within MNCs, Song [22] argues however that existing studies provide only limited information on how these transmission systems are used to transfer knowledge, and how their usage influences the benefits of the knowledge transfer. Thus, this paper aims to fill this gap by focusing on the role of a specific type of transmission systems, namely information systems (IS) based on modern information and communication technologies (ICT), in facilitating the knowledge transfer process within MNCs.

The role of IS in knowledge transfer is debated in the literature. While most of the studies find that IS supports knowledge transfer [e.g., 2, 11, 12, 23], some authors challenge this view [10, 20] arguing that IS can hardly contribute to organisational knowledge transfer [13, 19]. This paper aims to contribute to this debate by proposing to take into consideration an additional factor, namely the role of the plant in the intra-organisational knowledge sharing processes within the MNC. Thus, we aim to answer the following research question (RQ):

How supportive are information systems for transferring knowledge between different plants of a multinational company?

2 The Role of Plants Within the Knowledge Flow in MNCs

Knowledge transfer processes within an MNC are generally carried out between a knowledge-sending and a knowledge-receiving plant [9, 16, 26]. In this process, the driver for knowledge transfer is mainly the knowledge-receiving plant, as it faces problems that it cannot solve alone. After the knowledge transfer, the perception of the knowledge-receiving plant defines the knowledge transfer success [17].

Vereecke et al. [27] identified four distinct roles of a plant. They analysed the engagement of the individual plant related to the frequency of knowledge sending and receiving, innovation sending and receiving and whether the plant hosted visitors or how frequent own employees were sent to other plants. Based on this, Vereecke et al. [27] derived four plant roles, namely (1) the isolated plant, (2) the receiver, (3) the hosting network player, and (4) the active network player.

Szulanski [25] suggests to take into account the following elements when analysing knowledge transfer: the two actors of the knowledge transfer process, i.e. the knowledge-source and the knowledge-recipient, and the channel of knowledge transfer. The knowledge-source in our case is the knowledge sending plant within an MNC that needs to have the willingness and capacity to share knowledge with other units from within the network. On the other hand, knowledge receivers need to have the ability to absorb, i.e. identify, assimilate and exploit the knowledge provided by the sender. The main attention related to the channel has been on the *relationship between knowledge-sending and* *knowledge-receiving plants.* Within the channel, transmission mechanisms play an important role, as these mechanisms can support the knowledge transfer process [1, 3]. Literature discusses a wide range of mechanisms through which knowledge can be shared [7, 9, 22, 26], ICT/IS being among the most fundamental ones [3].

3 The Role of ICT-Based IS in Knowledge Transfer

Modern ICT-based IS play a crucial role in today's MNCs. According to O'Brien and Marakas [18, p. 4] "an information system (IS) can be any organized combination of people, hardware, software, communications networks, data resources, and policies and procedures that stores, retrieves, transforms, and disseminates information in an organization". IS in general can help the purpose to create, store, process, retrieve, transfer and apply data and information within organisations [2]. Here we focus mainly on the transfer component as we are interested in how ICT-based IS supports the knowledge transfer process between different plants of the same MNC.

Bigliardi et al. [4] argue that these systems based on information and communication technologies can be efficiently and effectively used to share intra-organisational knowledge. IS tools that make knowledge explicit, enable its transfer within multinational companies [14, 21]. Such tools include groupware, computer-supported cooperative work (electronic knowledge repositories, wikis), intranet, e-mail, portals and online communities [4, 6]. Iyengar et al. [11] show that the use of ICT systems significantly contributes to the effectiveness of the knowledge transfer at the receiver side as well. Jasimuddin et al. [12] bring several case examples where knowledge repository systems largely supported the knowledge transfer process between senders and receivers, but they also note that the correct introduction and classification of information in such systems is an important factor for receivers to find relevant knowledge. Sook-Ling et al. [23] offer further case study evidence for the usefulness of IT-based systems, such as knowledge repositories and e-mail systems, in sharing intra-organisational knowledge. Summarising the role of IS in knowledge transfer, Alavi and Leidner [2] argue that the positive contribution of these systems to the knowledge sharing process is based on three enabling factors: (1) IS has the potential to extend the reach of the internal network by connecting different isolated actors, (2) offers an increased variety of communication channels, and (3) it enables a faster access to knowledge sources.

Despite these enabling factors, several authors have criticised the general assumption that IS can significantly support the transfer of knowledge within an organisation. Alavi and Leidner [2] emphasise that if there is no overlap between the sender and receiver in their underlying knowledge base, then "the real impact of IT on knowledge exchange is questionable" (p. 112).

Roberts [20] also questions the role of IS in transferring knowledge, and argues that IS can not entirely replace the face-to-face interaction between sender and receiver, as "the transfer of know-how requires a process of show-how" (p. 439). Knowledge transfer requires socialisation, willingness to send and receive, and trust between the sender and receiver, which can be built via personal interactions. Hislop [10] raises similar critique, arguing that all knowledge has a non-codifiable element (that is not transferable via IS), and is deeply embedded in the activity, and social and cultural context of the knowledge sender. In light of these arguments, it is not surprising that Mageswari et al. [13], for example, have not found any significant relationship between IS utilisation and intra-organisational knowledge sharing. In their literature review, Panahi et al. [19] also conclude that the role of IS in knowledge transfer is currently uncertain (with supporting and opposing arguments both co-existing in the literature), and call for further research in this field.

4 Methodology

To gain an understanding of knowledge transfer, and especially of how IS supports the knowledge flow in manufacturing networks, we examined thirteen plants and analysed 24 examples of knowledge transfer projects. We used middle-range theory development [15], by linking theory and empirical work. We derived dimensions from theory and refined them through case study research. Eisenhardt and Graebner [14] recommend the case study approach for research interests such as ours, since the topic is not well documented and relatively unknown. The qualitative research approach provided us with deep insights into the selected case plants and allowed us to generate new insights. The plant level was selected as the unit of analysis to gain information in the needed level of detail.

An equal number of cases (three to four) was targeted in each of the four countries involved: Switzerland, Romania, Albania, and Macedonia. Field data were collected during 2016. The main method of data collection was a semi-structured interview, uniformly applied in each country. Researchers have participated in multiple interviews in different countries to enable a uniform understanding of data collection. After the data collection, the case data was first analysed within each respondent plant, followed by a cross-case analysis within and across countries.

5 Data Analysis

To provide a detailed answer to our RQ, we first analysed the position of each individual plant within the knowledge network of MNCs. Based on interview data we tried to assess the extent to which each individual plant participates in (1) knowledge sending and (2) receiving, in (3) innovation sending and (4) receiving, and in (5) offering versus (6) receiving employee training (cf. [27]). Each of the six measures was rated with interviewees on a scale from None (0) to High (3), with Low (1) and Medium (2) as intermediary values, and a sum of these measures was computed at the end (Table 1).

Based on these ratings the overall position of each plant in the knowledge network has been assessed by adding up all sending/offering scores (i.e. knowledge sending, innovation sending, offering trainings) and subtracting the total score of receiving (i.e. knowledge receiving, innovation receiving, receiving trainings). Plants in the table are sorted based on their overall position. An overall score above zero indicates that the plant is more actively engaged in information and knowledge sending activities, and thus it can be categorised as a knowledge-sender (S2, S3, S1), while a negative score indicates that the plant should be viewed as a primarily knowledge-receiving unit (A3, M3, R1, R3, A1, M1, A2, A4, R2).

Table 1. The position of interviewed plants in the knowledge network

Plant code	Sum of position	Plant code	Sum of position
S2	2.5 + 3 + 3 – 1 – 1 – 1 = **5.5**	R1	2 + 1 + 2 – 3 – 3 – 3 = **–4**
S3	2 + 3 + 3 – 2 – 1 – 1 = **4**	R3	2 + 1 + 1 – 3 – 3 – 3 = **–5**
S1	2 + 1 + 3 – 1 – 1 – 1 = **3**	A1	1 + 1 + 1 – 3 – 3 – 2 = **–5**
M2	3 + 3 + 1 – 3 – 3 – 2 = **–1**	M1	0 + 1 + 1 – 3 – 2 – 2 = **–5**
A3	2 + 2 + 1 – 2 – 2 – 2 = **–1**	A2	0 + 0 + 1 – 3 – 0 – 3 = **–5**
M3	2 + 1 + 1 – 2 – 3 – 3 = **–4**	A4	1 + 1 + 0 – 3 – 3 – 2 = **–6**
(continued in next column)		R2	1 + 0 + 1 – 3 – 3 – 3 = **–7**

Sum of position = Total sending/offering score – total receiving score

Thus, to investigate the role of IS in knowledge transfer, we divide our analysis into two parts, the first related to net knowledge sending plants (Table 2), and the second to knowledge receiving plants (Table 3). Interviewees were asked to identify one or two recent knowledge transfer projects and to rate and discuss the role of modern ICT-based IS in supporting knowledge exchange.

Table 2. The role of IS in knowledge transfer at knowledge sending plants

Plant code	Knowledge transfer project	Role of IS	IS support
S1	Product transfer to US plant	*Helpful for storing information, but face-to-face meetings and employee exchange were more used*	Partial
	Implementing a production line in a French plant	*All necessary knowledge was provided in a common database, but the knowledge intake was refused by French plant*	No
S2	Skilling up Polish plant	*The common online platform used was helpful, because the high quality of the data introduced*	Yes
	Product transfer to Polish plant	*Although an IS was in place for knowledge transfer, it could not be used due to bad data quality*	No
S3	Process introduction in a HU plant	*The transfer of crucial knowledge could only be carried out through personal interaction*	No

Table 3. The role of IS in knowledge transfer at knowledge receiving plants

Plant code	Knowledge transfer project	Role of IS	IS support
R1	Implementing lean techniques	*Online platforms were frequently used to ask experts for best practices*	Yes
	ERP implementation	*Face-to-face trainings had to be used, only some information was acquired through IS*	Partly
R2	New component manufacturing	*New product with fast growing sales: know-ledge exchange was mainly human-to-human*	No
	Implementing an Industry 4.0 project	*The project involved a lot of standardised information which were provided through IS*	Yes
R3	Implementing a TPM system	*IS was used to transfer project management information from other units with experience*	Yes
	Implementing work safety standards	*IS was only partly used to receive the new standards and then monitor KPIs*	Partly
A1	Inventory reduction	*Video conference used to share knowledge on recycling, leading to inventory reduction*	Yes
	New product manufacturing	*Steps of new product implementation, that was documented and shared through IS*	Yes
A2	Changing product „recipe”	*For quality HQ decided to change the recipe of a product, sharing a how-to manual through IS.*	Yes
	Standardisation of controlling	*IS tools helped the HQ to transfer a standardised communication guideline with authorities*	Yes
A3	Improving production standards	*Sharing documentation and manuals with other plants through IS*	Yes
	Improving safety standards	*Incremental improvements of safety standards through IS in a periodical manner*	Yes
A4	New product introduction	*IS helped to transfer new product knowledge from HQ, introduced in the local market*	Yes
	Product transfer from Austrian plant	*Lack of a common system made hard to exploit the whole facilities and efficiency of IS*	Partly
M1	New product manufacturing	*A centralised IS was used to transfer knowledge that was fully standardised*	Yes
M2	New raw material introduction	*Measures from the intranet portal was used together with experts' support*	Yes
	New product manufacturing	*Intranet portal was combined with regular meetings on project development*	Partly
M3	Production process improvement	*Quality and process related knowledge acquired from central database*	Yes
	Implementation of safety standards	*Too much time needed to process the overloaded knowledge content in the system*	No

Interview data indicated that although all knowledge sending plants had multiple, cutting edge IS in place, they were only rarely used. Bad quality of data introduced in the system was one of the reasons mentioned. For some of the projects, IS was simply not used because the complexity of the project required a more intensive face-to-face interaction. The only response supporting the contribution of IS to the knowledge exchange was offered for a project, which was of strategic importance for the company, and thus enough resources were deployed for the proper functioning of the system.

On the other hand, knowledge receiving units generally use IS to support the transfer of knowledge. Compared to knowledge sending plants, in general, they perceive that IS offer much more support for knowledge transfer. Several respondents argued that IS actually represents the first and foremost channel for acquiring knowledge, which is afterwards complemented with face-to-face knowledge sharing.

Both cases where IS was not reported as being supportive for knowledge transfer from the knowledge-receiving manager's perception had bad data issues: for one project (R2, new component manufacturing) the data was mostly missing due to the innovative nature of the product and the time pressure around manufacturing its components, while for the other project (M3, implementation of safety standards) the system had stored high quantities of useful information (hundreds of safety standards), but it was organised in a manner that "required a lot of time to process".

6 Discussion and Conclusion

This paper looked at the role of ICT-based IS in the intra-organisational knowledge transfer within the internal network of manufacturing MNCs. Our results show that, indeed, in most of the cases IS plays a central role in transferring knowledge between different units, which is in line with the mainstream assumptions in IS literature [3, 11]. However, in line with the case findings of Jasimuddin et al. [12], we also argue that the data quality and strategic commitment towards using IS for transferring knowledge is an important precondition. Besides offering further support for previous findings, our results bring important new insights as well. We argue that the role of the plant in the internal knowledge network (i.e. knowledge sender or receiver) has to be also taken into consideration. Our findings show that this distinction can offer at least a partial explanation for the debated role of IS in knowledge transfer [e.g., 19, 20].

Knowledge sending plants in our sample see IS less beneficial for transferring knowledge. We argue that knowledge senders have to transfer complex knowledge "packages", which contains both codified and tacit knowledge elements. This explanation is in line with the practice-based approach of knowledge transfer put forward by Hislop [10]. Thus, for a successful knowledge sending project, transmission mechanisms that are able to transfer non-codifiable knowledge are absolutely essential, i.e. different forms of personal interactions are more important for sending knowledge.

Knowledge receiving plants, on the other hand, report that IS is helpful in most of the knowledge transfer projects. We argue that in a receiver position, the plant is motivated to find the relevant knowledge for a certain situation or problem. Regardless of the type of the knowledge searched for, the most convenient way to acquire it, is to transfer it through an IS [cf. 11]. If this transfer is not enough, IS-based knowledge transfer was complemented in several cases by face-to-face interactions or trainings. Thus, in contrast to knowledge senders, receiver plants see IS as a primary enabler of knowledge transfer that may or may not be complemented with personal interaction.

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Conceptual Development Process of Mass-customizable Data Analytics Services for Manufacturing SMEs

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Abstract. In the Industry 4.0 era, numerous manufacturing enterprises have tried to obtain a smart manufacturing system. A key component of a smart manufacturing system is data analytics to support optimal decision-making in production systems. Consequently, many IT service providers have developed data analytics services. However, many small- and medium-sized enterprises (SMEs) have very low penetration of data analytics services compared to large enterprises because of the low profitability for IT service providers. Mass-customizable data analytics (McDA) services, which can be applied to various manufacturing SMEs, can give IT service providers the opportunity to increase their sales and thus their profits by applying services to more companies at little extra cost. This paper proposes a conceptual development process of McDA services for manufacturing SMEs and suggests future research issues. We believe that this paper can contribute to the dissemination of a smart manufacturing system.

Keywords: New service development · Data analytics service · Manufacturing SMEs · Intelligent manufacturing

1 Introduction

In the Industry 4.0 era, numerous manufacturing enterprises have attempted to adopt smart manufacturing systems to enhance their competitiveness [1, 2]. Smart manufacturing systems support intelligent decision-making for quick responses to new situations using real-time data [1, 3]. A key component for realizing smart manufacturing systems is data analytics [4]. Data analytics for smart manufacturing systems supports optimal decision-making by facilitating diagnosis, optimization, and prognostics for many problems in production, such as scheduling and equipment maintenance, based on manufacturing data [1]. Consequently, many IT service providers have recently tried to develop data analytics services.

However, because of the low profitability for IT service providers, manufacturing SMEs have very low penetration of data analytics services compared to large enterprises. One of the reasons for the low profitability is that the way in which most IT service providers develop customized services on a one-to-one basis is very costly [5].

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Mass-customizable data analytics (McDA) services, which is developed in a one-to-many manner, can give IT service providers the opportunity to increase their sales and thus their profits by applying services to more companies at little extra cost.

Despite the advantages of McDA services, they are difficult to systematically develop because there is no knowhow or guidance for IT service providers with little experience on their development. Therefore, we developed a conceptual development process model that can serve as a reference for McDA service development.

This paper proposes a conceptual development process of McDA services for manufacturing SMEs. The proposed development process was constructed by reviewing related literature and actual data analytics service development projects. We conducted research with various manufacturing SMEs and the Korean government (Ministry of Trade, Industry and Energy). This paper is organized as follows. Section 2 reviews the relevant studies to understand the proposed process. Section 3 describes the proposed conceptual development process of McDA services for manufacturing SMEs. Finally, Sect. 4 summarizes this paper and suggests future work.

2 Literature Review

This section reviews two studies to define the activities needed to develop McDA services: the common new service development (NSD) process [6] and cross-industry standard process for data mining (CRISP-DM) [7]. The NSD process is used to define activities for developing service concepts that are commonly needed for manufacturing SMEs. CRISP-DM is used to define activities for data analytics. The reviewed studies are considered basic knowledge in this paper.

2.1 Common New Service Development Process

Studies on the NSD process have organized activities for service development well. In particular, Kim and Meiren [6] formed a common NSD process based on six existing NSD processes. The common NSD process consists of five activities: opportunity identification, customer understanding, concept development, process design, and refinement and implementation [6]. Opportunity identification is recognizing opportunities for new services or improvements in existing services. Customer understanding is defining the target customers and identifying their needs. Concept design is generating the service concept based on the service opportunities and customer needs. Process design is developing the processes by which the service is produced and delivered. Refinement and implementation is testing and performing pilot runs of the service; after necessary enhancements and adjustments, a full-scale launch of the service is made, and a post-launch review is conducted.

2.2 Cross-Industry Standard Process for Data Mining

The following study of process model for data analytics is used to define data analytics activities. Among the many process models for data analytics, CRISP-DM is the most widely used because it works well in most data analytics [8]. CRISP-DM consists of six activities: business understanding, data understanding, data preparation, modeling, evaluation, and deployment [7]. Business understanding focuses on understanding the project objectives and requirements from a business perspective and then converting this knowledge into a definition of data analytics to design a preliminary project plan that achieves the objectives. Data understanding starts with an initial data collection and proceeds with activities in order to get familiar with the data, identify data quality problems, discover first insights into the data, or detect interesting subsets to form hypotheses for hidden information. Data preparation covers all activities to construct the final dataset from the initial raw data. For modeling, various modeling techniques are selected and applied, and their parameters are calibrated to optimal values. Evaluation involves determining if some important business issue has not been sufficiently considered. Deployment is an activity of deploying data analytics and giving the guidelines for using it.

3 Conceptual Development Process of Mass-customizable Data Analytics Services for Manufacturing SMEs

This section presents a conceptual development process of McDA services for manufacturing SMEs using IDEF0 representation. The development of the process was initiated by a literature review and our project of developing cloud services for situational analysis and decision-making based on manufacturing big data.

3.1 Overview of IDEF0

IDEF0 is an activity modeling method that is designed to describe activities and the relationships between them [9]. Activities in the IDEF0 model are influenced by inputs, controls, outputs, and mechanisms (ICOMs). Each activity receives certain inputs, is constrained by controls, and derives output by various mechanisms.

The IDEF0 model is hierarchically structured according to the detail level of the representation. Figure 1 shows A-0, which represents the most general level of McDA service development. Inputs are the items changed by the activity. In the McDA service development, manufacturing decision-making problems, SME needs, and the initial data correspond to the inputs. Controls are factors that trigger the activity and constrain its execution. Characteristics of common problems, data analytics applicability, real service cases, workflow components, and user requirements correspond to the controls. Outputs are the results of the activity. McDA services and evaluation results correspond to the outputs. Mechanisms are means used to perform the activity. Service developers, data analysts, programming tools, and users are the mechanisms in this case.

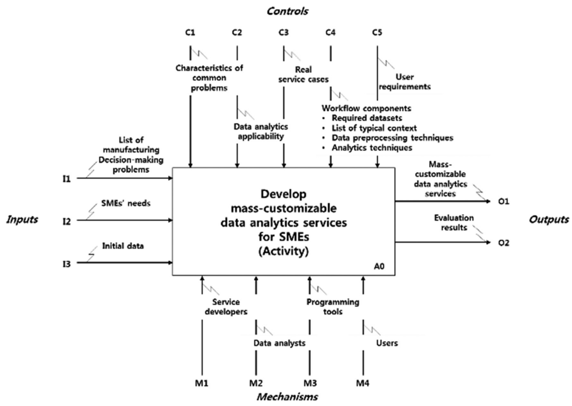

Fig. 1. Basic IDEF0 representation of an activity overlaid on McDA service development's A0

3.2 Level-1 Activities

This section defines nine level-1 activities decomposed from A0 based on the reference processes mentioned in Sect. 2. Table 1 presents which activities of the reference processes are referenced in level-1 activities and what changes. The activities are semantically divided into two main phases: massification (A1–A4) and customization (A5–A9). In the massification phase, the service concepts that are commonly needed by many manufacturing SMEs are developed, and the analytics workflow is designed in advance. During the customization phase, the analytics service is customized to the manufacturing SMEs. A data analytics process that concentrates on the customization is costly and time-consuming because this has to be done separately for each manufacturing SME. Thus, in order to increase the efficiency, tasks should be conducted in the massification phase as much as possible, and only tasks for which customization is essential should be left in the customization phase.

Table 1. Level-1 activities of proposed development process

Proposed development process				Reference process		
Phase	Activities		Changes	Activities of common NSD process	Activities of CRISP-DM	
Massification	A1	Identify common problems	• See opportunity as solving the decision-making problems that are common in the manufacturing industry	Opportunity identification		
	A2	Understand SMEs	• Set customer to SMEs	Customer understanding		
	A3	Develop service concept		Concept development		
	A4	Design analytics workflow	• Unlike CRISP-DM, design a data analytics workflow in advance	Process design	Data understanding-1 • Understand the data that target data analytics services commonly use	Modeling-1 • Select modeling techniques • Generate test design
Customization	A5	Check context for customization	• Perform business understanding and data understanding simultaneously		Business understanding	Data understanding-2 • Understand the initial data for what applies
	A6	Prepare data			Data preparation	
	A7	Build analytics model	• Let programming tool perform it automatically according to a pre-defined analytics workflow		Modeling-2 • Build model • Assess model	
	A8	Deploy analytics service		Refinement & Implementation	Deployment	
	A9	Evaluate analytics service			Evaluation	

3.3 Proposed Development Process

This section describes the proposed development process consisting of level-1 activities using IDEF0 representation. Figure 2 shows the conceptual development process of McDA services for manufacturing SMEs. Each activity is discussed below.

A1 Identify Common Problems. Developing services for decision-making problems that occur only in the applicable company cannot be widely applied to other companies. This initial activity derives manufacturing decision-making problems that can be universally solved and widely occurring in various manufacturing industries and companies. Various manufacturing decision-making problems such as production scheduling, quality control, inventory management, and equipment maintenance can be collected based on a literature review and case studies. The service developer makes a list of common manufacturing decision-making problems by extracting problems with common characteristics from the collected problems. There are two criteria used to characterize common problems: industry-wide commonality and technically universal resolvability.

A2 Understand SMEs. This activity identifies the needs of SMEs and derives the requirements of the data analytics service. It is necessary to collect the needs of SMEs by consulting with domain experts, focus groups of manufacturing SMEs, and case studies before this activity. Next, service developers review whether the collected needs are met through data analytics. Finally, the needs that can be met through data analytics are defined as the requirements of the service. An example of a service requirement may be a reduction in equipment maintenance costs.

A3 Develop Service Concept. In this activity, the target service concept is generated on the basis of common problems that meet the service requirements of SMEs. The service objectives and data analytics goals are determined to satisfy the requirements. As an example of an abstract service concept, it can be defined as providing data analytics that diagnose equipment failures in real time to reduce maintenance costs. Service developers should refer to actual service cases to develop a concrete service concept.

A4 Design Analytics Workflow. This activity involves designing the analytics workflow, which is the operational processes of the data analytics service. It begins with defining the required full dataset to solve the problem of the target service concept. Typical contexts, which are the cases that are typically considered in data analytics for a particular environment, are then defined. Next, the appropriate data preprocessing techniques and analytics techniques for each context are determined. Finally, the analytic workflow is designed by combining the techniques appropriate to each context at each analytic step, such as data preprocessing and modeling.

In practice, when data analytics services are being developed for diagnosing equipment conditions, typical required data are defined, such as vibrations, acoustic, pressure, moisture, humidity, temperature, and enviroment. Through interviews, case studies, and review papers, we can assume the following typical contexts: satisfying all requested data, no labeled data for equipment conditions, imbalanced data, etc. If there is no labeled data for equipment conditions, the unsupervised learning technique may

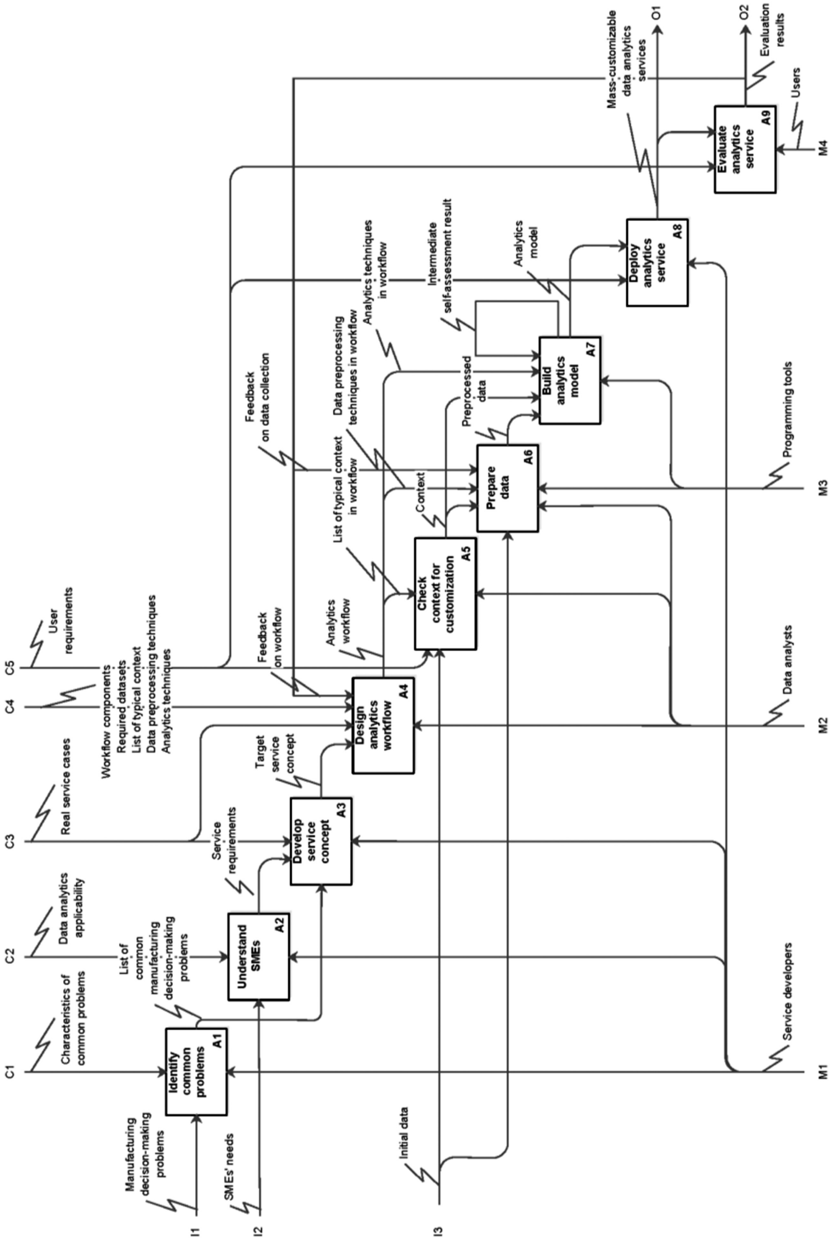

Fig. 2. IDEF0 model of 'Develop McDA services for SMEs'

be suitable for modeling. The analytics workflow is designed by combining the techniques suitable for each context.

The history of the workflow must be stored and managed in the system. Accumulated analytics workflow histories can help with automating all phases of data analytics in a variety of contexts. Even if a new context occurs, it can be customized with minor modifications.

A5 Check Context for Customization. This activity, which is the first of the customization phase, checks the context of the application target. Data analysts compare the initial data and the user requirements with the typical context of the previously designed analytics workflow and select the most similar context among the defined contexts.

A6 Prepare Data. This activity includes all tasks for constructing the initial data to match the required dataset in the analytics workflow as much as possible. Tasks in this activity are often performed multiple times, and the order is unspecified. Tasks include data collection, data cleaning, data integration, and data formatting.

A7 Build Analytics Model. In this activity, the analytic techniques specified in the analytics workflow apply. The modeling techniques are applied to build the data analytics model, and their parameters are calibrated to optimal values. The best data analytics model with optimal hyperparameter settings can be found through self-validation.

A8 Deploy Analytics Service. In this activity, the service providers deploy the data analytics service. Service providers transform the analytics model into a service that reflects the user's service requirements. Finally, the McDA service is deployed to manufacturing enterprises.

A9 Evaluate Analytics Service. In the final activity, service users review and evaluate the developed data analytics service based on user requirements and the performance of data analytics service. If the performance of the data analytics is insufficient, the cause is categorized as an insufficient dataset or incorrect workflow. If the poor performance is due to a deficient dataset, the service developer should go back to A6 to prepare a dataset that best meets the required dataset. If it is due to wrong workflow, the service developer should return to A6 to add the workflow for this context.

4 Conclusion and Future Work

McDA services can be applied to various manufacturing enterprises in a one-to-many manner. In this paper, we formalize activities and their relationships in our reference process model using IDEF0 for developing McDA services for manufacturing SMEs. Based on our reference process model, we expect IT service providers to be able to easily develop McDA services for manufacturing SMEs. Furthermore, this paper is expected to contribute to the proliferation of smart manufacturing systems in manufacturing SMEs.

Several future works are needed. First, the specific tasks and outcomes needed in each activity should be presented through an application of the proposed process to a wide variety of manufacturing SMEs. A relevant project is in progress, and the issues can be identified after all the activities are performed. Second, a system capable of providing McDA services should be developed. We are currently working on an architectural design for McDA services based on cloud services and service-oriented architecture [10]. Third, standardization is important for interoperation of the sensors and systems of various manufacturing SMEs with the data analytics service system.

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A Thesaurus-Guided Framework for Visualization of Unstructured Manufacturing Capability Data

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Abstract. Manufacturing companies advertise their manufacturing capabilities and services on their company website using unstructured natural language text. The unstructured capability data published on the web is a rich source of formal and informal manufacturing terms and knowledge patterns. Through systematic mining of a large collection of capability text, new semantic models and knowledge graphs can be extracted that can be used as the stepping stone of more formal ontologies. The objective of this research is to develop a framework for better understanding, analyzing, and summarizing manufacturing capability data that is available on the websites of manufacturing companies. The findings can support supply chain decisions and may result in the discovery of new trends and associativity patterns in the data. The focus of this paper is on demonstrating how visual analytics (VA) tools can be used for gaining insights into manufacturing capability and the associativity pattern among the capability entities labeled by various terms. A visual analytics system, named Jigsaw, is used for exploring the connections between various entities such as process, material, industry, and equipment across the documents in the experimental dataset.

Keywords: Manufacturing capability · Thesaurus · Visual analytics · Jigsaw

1 Introduction

Manufacturing capability can be defined as the "firms' internal and external organizational skills, resources, and functional competencies to meet the requirement of the changing economic environment" [1]. Manufacturing capability is a multi-faceted entity represented through different criteria such as quality, processing capability, production capacity, flexibility, product innovation capacity, and performance history. Capability data is often presented in both structured and unstructured formats. The structured capability data can be found in proprietary application databases connected to the enterprise legacy systems of the company. The unstructured capability data is available in plain text form, often written in a loose narrative style, on the websites of manufacturing companies. The structured data is more amenable to complex query and quantitative analysis whereas, the unstructured data cannot be readily analyzed and

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understood especially when dealing with very large quantities of capability text. The objective of this research is to develop a framework for better understanding, analyzing, and summarizing the manufacturing capability data that is published on the websites of manufacturing companies. The findings can support supply chain decisions and may result in discovery of new trends and associativity patterns in the data. For example, it would be useful to classify and cluster manufacturers based on their similarities with respect to process and material capabilities and competencies proclaimed on their website. This would provide supply chain decision makers with better insight into the capabilities of prospective suppliers during supplier selection and evaluation process. Another motivation for analyzing unstructured capability data is that there is a wealth of manufacturing knowledge hidden in the text which, if mined systematically, can result in discovering interesting rules and patterns that were otherwise unknown. Such trends and patterns could inform early upstream decisions in the product design lifecycle.

In previous research, a supplier classification method based on Naïve Bayes text classification technique was implemented. It was observed that capability-based classification can result in accurate supplier groups with unique capability attributes [2]. This paper focuses on applying visual analytics to large collections of capability data. Visual Analytics (VA) combines automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and complex data sets [3]. VA has been used in the manufacturing domain for visualizing different types of manufacturing data such as simulation, quality control, and distribution and sales data [4–6]. The literature search, however, did not reveal any work related to applying visual analytics for exploration of manufacturing capability data. There are multiple VA-based tools and systems available to conduct visual exploration of domain-specific data [7]. In this research, Jigsaw [8] is used as the VA-based tool due to its powerful document analytics features and functions and also its simple, intuitive interfaces. The primary unit of analysis in Jigsaw is an "entity". In manufacturing capability text, examples of entities include, processes, materials, industries, and equipment. One of the novelties of the proposed text analytics framework is that it is guided by a formal thesaurus of manufacturing capability terms that provides the dictionary of entities, or concepts, required as input by Jigsaw. Additionally, an automated Entity Extractor Tool (EET) is developed in this work to streamline the data collection and preparation process.

This paper is organized as follows. Section 2 provides a brief description of the Manufacturing Capability Thesaurus. The data collection and preparation method is described in Sect. 3. The visual analytics examples and results are presented in Sect. 4. The paper ends with the conclusions in Sect. 5.

2 Manufacturing Capability Thesaurus

In the proposed visualization method, the unit of analysis is an entity or a concept. A concept is "a unit of thought, formed by mentally combining some or all of the characteristics of a concrete or abstract, real or imaginary object. Concepts exist in the mind as abstract entities independent of terms used to represent them" [9]. For example, the concept of operating a machine tool manually can be labeled by terms such as *manual machining*, *conventional machining*, or *traditional machining*. There are thousands of concepts in the manufacturing domain that provide domain experts with the necessary vocabulary when describing the manufacturing capability of a machine, a production plant, or a supply chain composed of multiple companies. Most text analytics techniques require a predefined list or dictionary of concepts that can be used for tokenizing the documents in a given data set. The dictionary of concepts is sometimes generated automatically using machine learning techniques based on a corpus. However, the caveat being that automatically-generated dictionaries are often contaminated by noise. Furthermore, creation of a dependable corpus is a demanding task. In this work, a semi-automated method is used for creation of a high quality thesaurus of capability concepts, called the Manufacturing Capability (MC) Thesaurus.

The MC Thesaurus contains the typical concepts, and their associated terms, that are often used for describing the manufacturing capabilities of suppliers. Contract manufacturers may use terms and phrases such as *precision machining*, *tool and die making*, *turnkey services*, *build-to-order manufacturing, small to large volume production runs* to explicitly describe their technical capabilities, capacities, expertise, and/or services. Also, they may provide examples of parts they have produced or industries and customers they have served in the past to advertise specific abilities or skills. Another complicating factor is the short hand vocabulary in every industry that is only meaningful to the individuals that are immersed in that industry. A thesaurus can be used for semantically linking the seemingly disparate terms in different subcategories of manufacturing industry, thus reducing terminological ambiguities. In the presence of a comprehensive thesaurus of manufacturing capability terms, it is possible to readily translate each website into a concept vector model that is more suitable for quantitative analysis. Also, the MC Thesaurus provides the necessary entity dictionaries that are required as input to different document analytics tools such as Jigsaw. The MC thesaurus is a formal thesaurus in a sense that it uses SKOS [10] (Simple Knowledge Organization System) for syntax and semantics. As an open-source thesaurus with explicit semantics, the MC thesaurus can be shared as linked data to be reused by dispersed users.

Each concept in SKOS has exactly one preferred label (*skos: prefLabel*) and can have multiple alternative labels (*skos: altLabel*). For example, as can be seen in Fig. 1, *Screw Machining* is the alternative label for *Swiss Machining* as it is used frequently for referring to the same concept.

MC thesaurus currently contains more than 800 capability concepts categorized under six concept schemes as listed in Fig. 1 (right). Also, concepts can be made related to one another using *skos: related* relation. For example, *Swiss Machining* is related to *Small Parts* and *Automatic Screw Machine*. By connecting the concepts using *skos: related* relation, the MC thesaurus becomes a network of semantically related concepts.

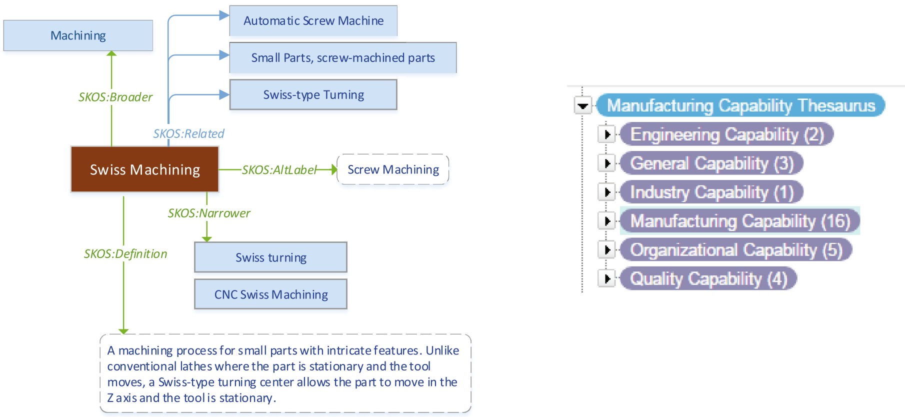

Fig. 1. Concept diagram of Swiss machining process in MC thesaurus (left), the concept schemas of MC thesaurus (right)

3 Data Collection and Preparation

The raw data that is used in this research is *Unstructured Capability Data*. For this research, *Unstructured Capability Data* is defined as a text, in natural language, that provides direct or indirect pointers to the technical and non-technical capabilities of manufacturing companies. In this research, the capability data is collected from the websites of North American companies in contract manufacturing industry. The core services provided by the target suppliers are primarily in the area of precision CNC machining. The concept vector for each capability text is generated using the *Entity Extractor Tool* (EET) that is developed for this research. The entities are essentially the concept labels from the MC thesaurus that occur in the text. The EET receives the plain text, that contains capability data, or the URL of a supplier website as the input, and generates the list of detected concepts and their frequencies as a CSV file. Figure 2 shows the screenshot of the input page of the Entity Extractor Tool. If a URL is provided by the user as the input, the EET creates a preview list of the pages from the same domain as the provided URL depending on the user-specified crawling depth. Usually a crawling depth of one page returns most of the important sub-pages that are directly hyperlinked to the homepage but occasionally a depth of 2 or more might be required to capture the useful text. The user can then eliminate the pages that seem irrelevant to capability information by simply unchecking the box in front of them. Typically, the pages under Capabilities, Services, or Processes link contain useful data with capability relevance that can be included in the entity extraction and analysis processes.

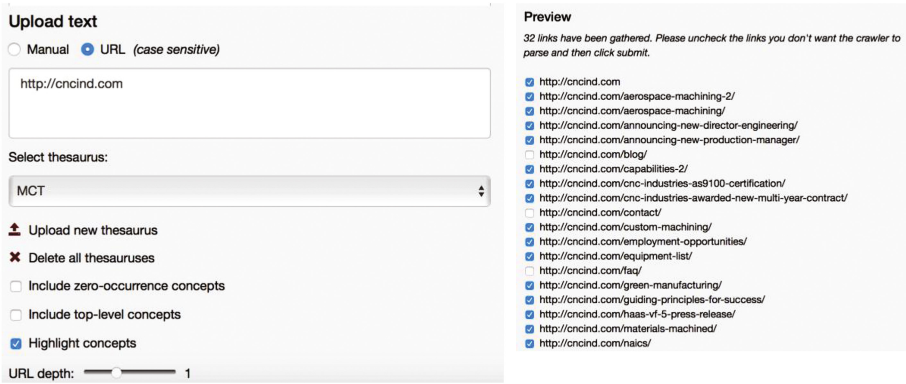

Fig. 2. The input screen of the EET (left), The list of pages retuned for a given supplier. Only the relevant pages are selected to be included in the entity extraction process (right).

Figure 2 (right) shows the list of pages returned by the crawler for the example company. Note that, in this case, the user has checked only the pages that most likely contain capability data. The text for all crawled pages is gathered and aggregated as a single *document*, with a ".txt" extension, and then it is submitted for analysis. The analysis entails identifying MC Thesaurus concepts and their frequencies in the document. Figure 3 shows the result of analysis for the example company. As can be seen in this figure, CNC Machining Center, Aerospace Industry, and Defense are the concepts with high frequency for the example supplier. Therefore, it can be concluded that, most likely, this company provides CNC machining services for aerospace and defense industries.

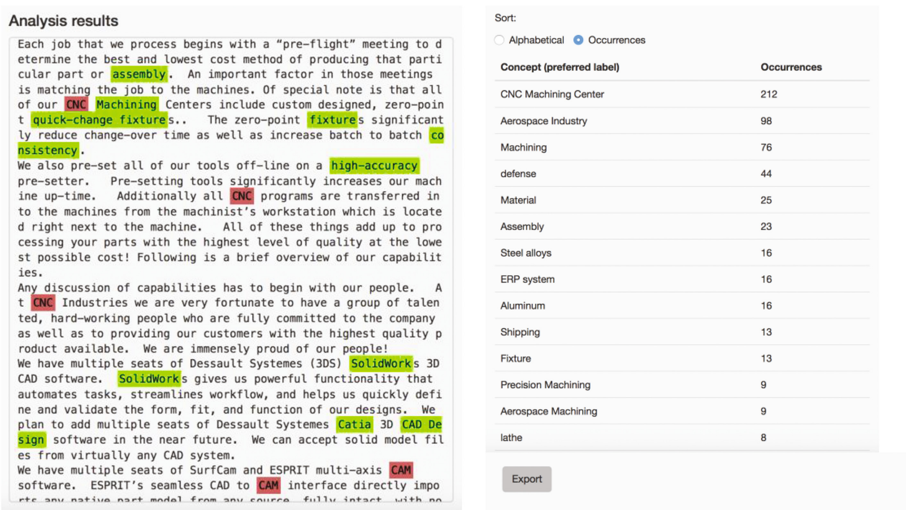

Fig. 3. The result of crawling together with the generated vector model

The entity extractor tool is capable of identifying both preferred and alternative labels for the MC concepts. The terms highlighted in green are the preferred labels and the terms highlighted in red are the alternative labels. The frequencies of alternative labels are added to the frequency of their corresponding preferred label. The user can export the vector model of each supplier as a CSV file with two columns, namely, concept (preferred label) and its frequency (number of occurrence in the extracted text).

Once the vector models, or the facets, of the documents are created, they can be used for different types of capability analysis. This paper focuses on visual analysis of both the generated vector models and the raw text documents.

4 Visual Analytics

An experiment was designed and conducted to visualize capability data for a dataset collected from Thomas Net[1] website which is a web portal for manufacturing sourcing. For this experimentation, 40 suppliers in contract machining industry were selected and their capabilities and qualifications were verified manually. The sample was intentionally formed such that half of the selected suppliers are qualified as heavy machining suppliers and the other half are qualified as complex machining suppliers.

4.1 Visualization of Concept Vector Models

The vector model of each text contains the manufacturing capability features of the supplier corresponding to the capability text. Enabled by the EET, it is possible to quickly generate a large collection of vector models (CSV files). The vector model can be directly used as the input to visualization tools. As an example, Fig. 4 shows a scatter diagram built based on a sample of 20 suppliers, randomly selected out of the starting pool of 40 suppliers. This diagram shows a combined view of heavy machining and complex machining capabilities. The capability score for each supplier is calculated based on the ratio of the number of the concepts pointing to heavy machining (or complex matching) capabilities for the supplier over the number of all heavy machining (or complex machining) concepts available in the MC thesaurus.

$$Score_i^{HM} = \frac{nc_i^{HM} . N_i^{HM}}{nc_T^{HM}}$$

Where, $Score_i^{HM}$ is the Heavy Machining (HM) score for the ith supplier, nc_i^{HM} is number of HM concepts for the ith supplier, nc_T^{HM} is the total number of HM concepts in the thesaurus, and N_i^{HM} is a normalizing factor that takes into account the total number of concepts detected for the ith supplier.

[1] http://www.thomasnet.com.

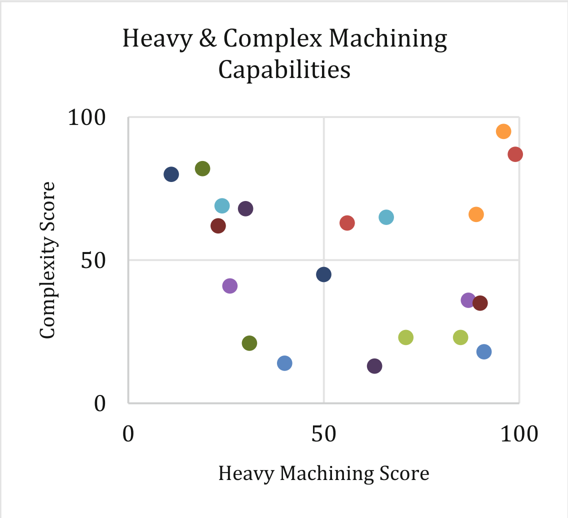

Fig. 4. Scatter diagram showing the combined view of complexity and heavy machining capabilities

4.2 Document Visualization Using Jigsaw

Although the vector model of capability documents provides an effective representation for computational analysis, it does not always provide a complete picture of supplier's capability. The completeness of the vector model directly depends on the completeness of the thesaurus. Therefore, it is necessary to supplement the vector-based analysis with more in-depth analysis that uses the entire document as the input. For this purpose, the Jigsaw analytics system, an existing tool developed at Georgia Tech, is leveraged in this section. Jigsaw is a visual analytics-based system that represents documents and their entities visually and displays the connections between entities across documents [8]. Entities are connected if they appear in one or more documents together. There are multiple mutually-coordinated visualization frames, called *Views*, that provide different perspectives onto data. List view, graph, view, scatter plot view, document cluster view, and grid views are among the most important views in Jigsaw. Jigsaw was originally developed with the objective of helping investigative analysts, in domains such as intelligence and law enforcement, build theories and formulate hypotheses based on a collection of documents.

In this work, Jigsaw is evaluated experimentally to assess its effectiveness when analyzing manufacturing capability documents. The same set of 40 suppliers used in the previous analysis was imported into a Jigsaw project as a batch of text files. Each capability text is treated as a document in this project. Four categories of entities, namely, *industry*, *material*, *process*, and *equipment*, were also created to build the underlying entity model of the project as shown in Fig. 5. Dictionaries of these entities were directly obtained from the MC thesaurus. This experiment was geared toward exploring connections between companies, industries, processes and materials. The numbers in parenthesis in the left image in Fig. 5 show the number of entities under each category that are observed in the documents. The entities that are synonyms were aliased together. For example, Swiss Machining and Screw Machining were aliased together because they both point to the same concept in the MC Thesaurus.

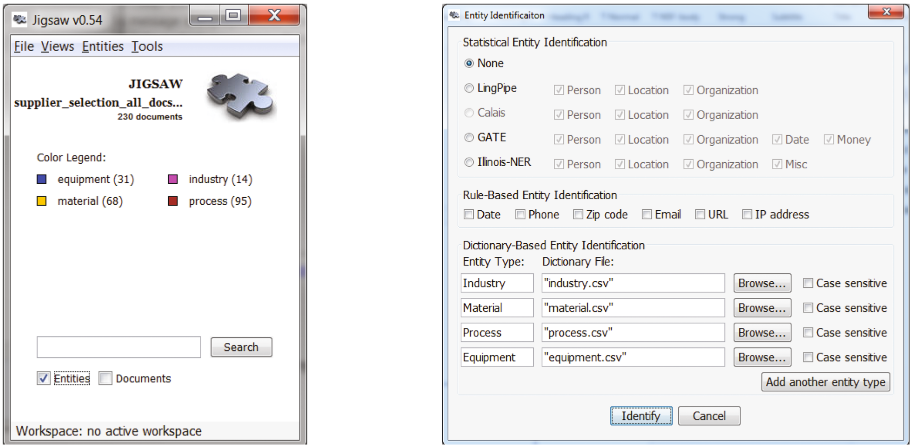

Fig. 5. Four categories of Entities were imported to Jigsaw based on the vocabulary extracted from MC thesaurus

Figure 6 shows one possible list view built based on the input dataset and entity model. The list view provides multiple reorder-able lists of entities. Also, the documents themselves can be added as a list to visualize the links between the connections and entities. In Fig. 6, documents are listed in the third column from the left. The strength of connection between entities and documents are represented by different hue saturations of a common color. For example, in Fig. 6, the selected industry entity,

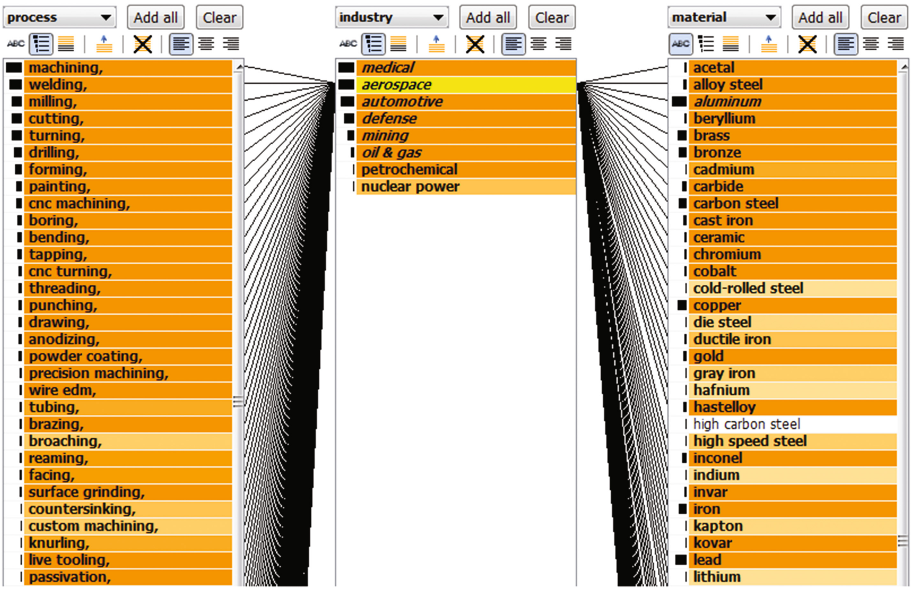

Fig. 6. List view in Jigsaw

aerospace, has a stronger connection with *machining* compared to *broaching* listed under the process list, hence has a more prominent single color hue saturation. The connection between aerospace industry and various engineering materials is also visualized in this view. For example, as expected, *aluminum* has a stronger connection with aerospace industry when compared to *high carbon steel*.

Figure 7 shows the graph view of the dataset. Each white rectangle in the graph view represents a document and the circle, colored nodes represent entities. An edge linking a document to an entity means that the entity is observed in that document. A mouse click on each document node expands or collapses the node to show or hide the links between the document and the entities. It should be noted that most of the edges in Fig. 7 are hidden for the purpose of demonstration and readability. The graph view can be rearranged to obtain more informative views. For example, in Fig. 8, the nodes are automatically arranged based on centrality to the document-type nodes. In this view, one can see that *automotive*, *tubing*, and *vertical machining center* are more central (i.e. relate to more documents) than other nodes of the same type, *nuclear power*, *open die forging*, and *automatic bar feeder*. This view presents an overview of all the relationships and help identify single entities that only relate to a single document, e.g. *open die forging*.

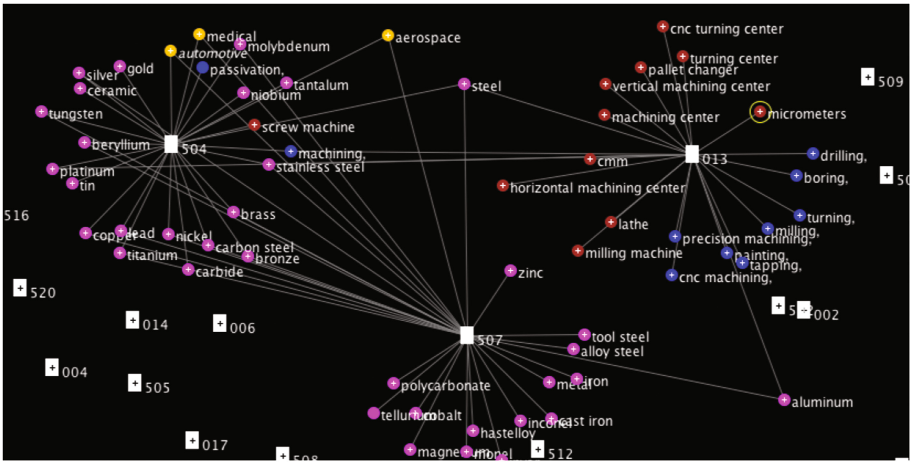

Fig. 7. Graph view in Jigsaw

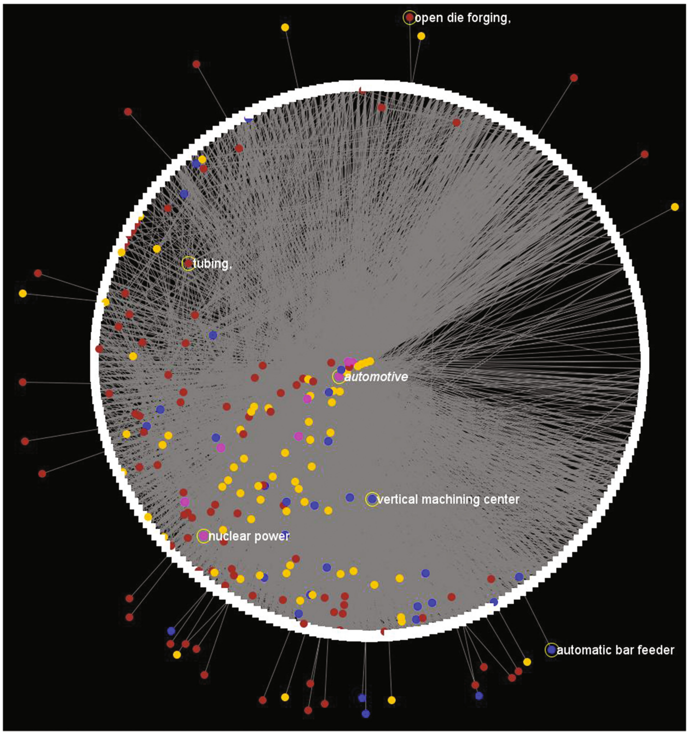

Fig. 8. A different arrangement of nodes in the graph view. Documents are arranged in a circular layout with all other entities located around the circle. Entities with more connections are located closer to the center.

5 Conclusions

This paper presented the preliminary results of using visual analytics tools for summarizing and analyzing manufacturing capability text. The Entity Extractor Tool was developed to automate the text extraction and document vectorization process. The MC Thesaurus was used to provide the Jigsaw model with the required dictionaries of entities. Only four entities were included in the experimental evaluation but in the future experiments, more entities will be included. Based on this evaluation, Jigsaw can be effectively used for capability visualization. It is easy to get started with Jigsaw but there is a learning curve involved when attempting to effectively use its multiple views in coordination. More in-depth experiments will be conducted in the future based on a larger data set to extract useful capability information from the text. Also, the EET will be integrated with Jigsaw to provide a more reusable pipeline for various text analytics and visualization purposes.

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Virtual Load Machine as Test Environment for Industrial Storage Applications

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Abstract. The market share of renewable energy is rising all over the world and leads to a more and more volatile energy supply. The challenge of keeping supply and demand constantly balanced is getting more complex and dynamic. Large scale energy consumers like industrial facilities need to take on an active role in the energy system and adapt their energy consumption to the energy availability. Denoted as energy flexibility this approach controls the energy consumption by changing e.g. the production plan. Storage technologies decouple offer and demand of energy, that end-users are enabled to adapt their energy consumption. Testing new applications for storages can be technologically demanding and is associated with high costs. This paper proposes a hardware in the loop test environment, with which hardware integrations and control strategies of electric storage systems can be tested on a small scale.

Keywords: Energy storage · Load flow · Smart grids

1 Introduction

Renewable energies increase the share of fluctuating energy supply within the electric grid. New strategies for balancing the grid need to be developed. One approach is an active consumer role, which adapts its consumption to market signals. The major challenge for industrial consumers is to control their power consumption with little impact on manufacturing [1]. Stable power supply is a major requirement for a production site and therefore new solutions for energy distribution on factory level are developed. The energy consumption from the external supply grid can be controlled by an intelligent energy management, that combines private energy generation, energy procurement, energy storage and the production as energy consumer [2]. Major challenges of the smart grid approach is to run the production smoothly and cost-effectively as well as to ensure a high security and quality of supply [3].

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2 State of the Art

In particular energy storage solutions are a key technology to decouple energy production and consumption within factory. High technological standards for storage solutions in industry, are a major challenge and it is demanding to find an economic application. Current applications of electrochemical energy storages are mainly used to compensate power interruptions and instabilities within the grid [4].

Solutions to shave of power peaks in an industrial environment without the proof of the economic benefit is shown by Putz et al. [5, 6]. The application validates the technical feasibility of supercapacitors within a machine, but the implementation is specifically adapted to a single machine.

In the field of battery research, lifecycle predictions are an important research topic. Fatigue algorithms are used to calculate degradation of battery technologies [7–9]. Commercial battery solutions are tested through standard procedures, which use synthetic load profiles at constant current, load amplitude and temperature [10, 11]. For industrial applications life-cycle evaluations with real load profiles are essential.

A storage needs a converter technology to be embedded into an industrial environment [12]. As these technologies interact between storage and process, they need to be considered in experimental setups for evaluation. Kesler et al. and Jonke et al. show a concepts of an adjustable consumers connected to the electronic grid. These systems can be used to test components connected to an electric grid [13, 14].

In literature a hardware in the loop specifies test environments, with which developed hardware or physical systems are tested through realistic input parameters. In the research area of smart grid technologies implementations and control algorithms are evaluated with hardware in the loop environments [15, 16].

3 Evaluation of Newly Developed Smart Grid Technologies

Industrial environments offer a great variety of possible applications for storage systems. Interesting applications within the scope of production planning are process efficiency, process quality and possibilities for decoupling electric load. An optimized operation strategy should allow for the transient load characteristic of each process step. At the grid connection a characteristic load profile of every machine and process can be detected, whereas the overall load within the local grid can be optimized with respect to a variety of objectives [12].

Storage solutions change the power characteristics through a controlled feed-in and feed-out of power. These solutions consist of a control algorithm, a converter technology and the storage. The storage system needs to be profitable as well as technologically save. Simulation tools are on one hand suitable to develop new solutions for a specific application, on the other hand are simulations always limited to the model assumptions. Further challenges within real implementations can only be evaluated on a hardware level.

A platform, which enables testing control algorithms, as well as converter and storage technologies, opens up an intermediate step between simulation and full scale field applications and therefore, enables to improve the predictions of simulation models. This work presents a Hardware in the loop test environment, which emulates the power draw and the production behavior of a machine. The system can be configured to emulate a measured load profile and change system states like a real production machine. With the single-machine-test-environment (SMTE) storage applications on a machine level can be analyzed and validated (Fig. 1).

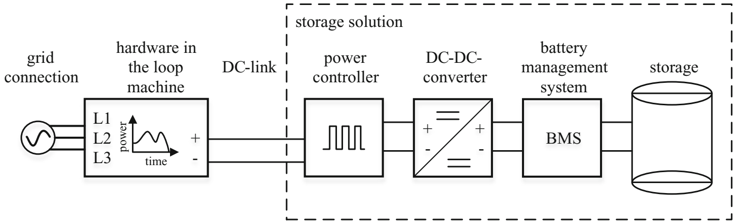

Fig. 1. Single-machine-setup as a test environment for storage solutions.

The developed test environment is appropriate to test control algorithms on a hardware level, examine storage degradation based on real load profiles and the coupling between all hardware components. As a result storage systems within a smart-grid can be evaluated for a variety of production environments.

4 Design Specifications

The basic idea of the system is to map the load profile of a production machine into an experimental setup. In this scope the SMTE has to represent the energetic as well as the production characteristics. Information about the product type, lot size and operational availability affect the load characteristic of a machine are transferred within production. Different product types change the characteristics through specific process parameters. Lot size affects the grid load through the appearance of down-times and changeover-times. Furthermore operational availability is the prerequisite for the operation of a machine and the overall equipment effectiveness adds unforeseen interruptions, setup and loading times.

Figure 2 shows the electric load of the different process steps of an injection moulding machine. As the injection time is an example for a machine parameter, which is specific to the product. Lining-up the different load profiles in order of the process steps result into the product-specific load profile of the machine. Whereas the plasticization time (warm-up, injection), the timeframe for holding pressure, as well as the ejection process vary with each product type.

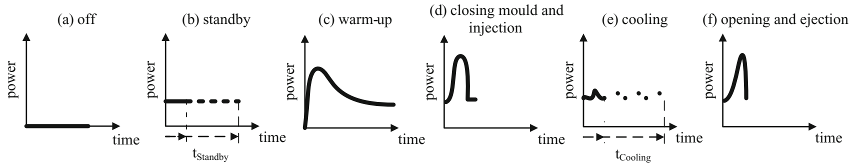

Fig. 2. Showing the specific load profiles separated for different process steps: (a) off, (b) standby, (c) warm-up, (d) closing mould, (e) injection, (f) opening and ejection.

The proposed hardware in the loop machine will be able to follow a specified production plan. For instance does the schedule plan to produce two lots. The first lot consists of 100 pieces of product A and the second lot consists of 200 pieces of product B. The machine will follow the schedule and simulates the energetic load of the first lot with the process specific parameters for product A. For the changeover to product B the machine will simulate the power draw of the standby state. Afterwards the machine load of the second lot will be simulated with the process specific parameters of product B.

State of the art are two storage topologies. The first possibility is the integration into the DC-link of a production machine and the second possibility is the integration within the AC-grid in front of the rectifier. The planned design opens up the possibility to evaluate both topologies as the SMTE offers a DC-link as well as to a three phase contact.

5 Design of the Hardware Concept

The main function of the machine is a controllable power consumption on a DC-link as well as on a three-phase power connector. The proposed concept consists of an asynchronous machine, which is connected in Y-connection to the grid (Fig. 3). A standard cage induction motor with two poles and a rated power of 750 W is selected.

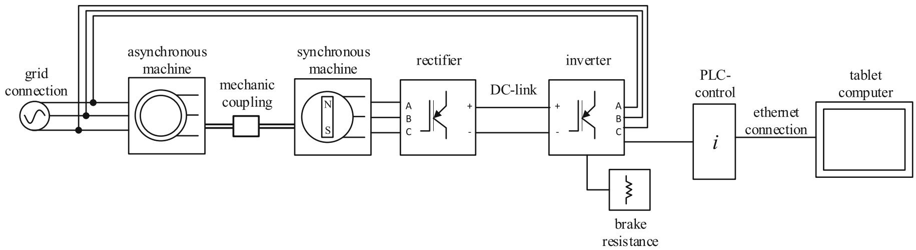

Fig. 3. Design of the planned machine concept to simulate various energetic foot-prints of a production machine.

The asynchronous machine is mechanically coupled to a synchronous servo-motor, which is fed through an inverter. The inverter draws power from a DC-link, which is fed by an unregulated rectifier. State of the art servo-controllers can control the torque of the synchronous machine. With the assumption of negligible losses in the synchronous machine and the power electronics, the mechanical power equals the electrical power drawn by the Inverter. As it is assumed that the asynchronous machine holds the angular velocity ω of the system stationary. The power-usage of the machine can be controlled by changing the synchronous torque τ_{syn} (1).

$$P_{el} \approx P_{mech} = \tau_{syn} \cdot \omega \tag{1}$$

The PLC-control calculates the torque input to the inverter from the targeted power, which should be drawn by the SMTE. The machine is controlled through a human machine interface on a tablet computer. Via Ethernet connection the SMTE can be configured and the current machine and production state is changed.

6 Proof of Concept

Input signals for the SMTE are dynamic and so the operation of the whole system cannot be assumed to be in steady state. A simulation model of the dynamic system is built-up to show the system behavior. The model was build-up in MATLAB Simulink and a reference scenario with an injection molding machine is performed.

6.1 Simulink Model for Transient Performance

A given dynamic model of an induction motor from the MATLAB Specialized Technology library is used. The machine is driven by an ideal voltage supply with three phases at 50 Hz. The synchronous machine is wired in a star connection, while the inverter is modeled as an ideal voltage source over the three phases. The torque forming current is controlled by a PI-controller, which is fed with the error value $e(t)$ of the desired torque τ_{set} divided by the synchronous motor torque constant K_T and the measured q-current $i_{q,is}$ (2).

A rigid coupling between induction and synchronous machine is assumed, whereas the sum of asynchronous torque τ_{as} and synchronous machine torque τ_{syn} accelerates an inertia Θ of 0.0015 kgm^2 (3).

$$e(t) = i_{q,is} - \tau_{set}/K_T \tag{2}$$

$$\Theta\dot{\omega} = \tau_{as} - \tau_{syn} \tag{3}$$

6.2 Simulation of an Injection Molding Machine

For the simulation the load profile of a typical injection molding machine is used. Figure 4 shows the measured power draw of an injection molding machine. The cycle includes closing the mould, injection of the polymer, holding pressure to compensate shrinkage and ejection of the parts with opening of the mould. The maximum power that can be reached by the SMTE is specified by the power limit of the asynchronous machine. The whole load profile of the injection moulding machine $P(t)$ is scaled down, to match maximum machine power performance. Therefore, the profile is scaled by the maximum measured power value max($P(t)$) and the power limit of the asynchronous machine $P_{as,max}$ (4). The torque input values of the synchronous machine $\tau_{set}(t)$ are calculated by dividing the power set points $P_{set}(t)$ by the nominal rotational frequency of the asynchronous machine ω_{as} (5).

$$P_{set}(t) = P(t)/\max(P(t)) \cdot P_{as,max} \tag{4}$$

$$\tau_{set}(t) = P_{set}(t)/\omega_{as} \tag{5}$$

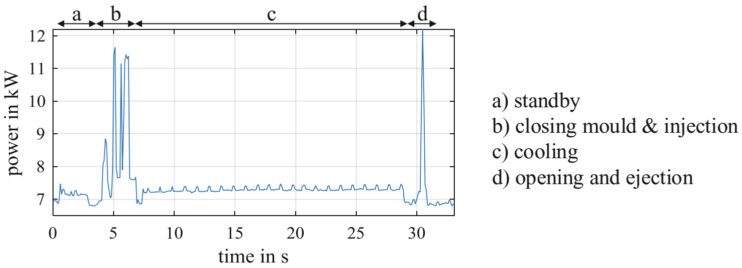

Fig. 4. Power draw over time for a typical injection molding cycle

As the load profile is just a small window of the whole measurement and starts with the first injection, all upstream states are skipped and setpoint value starts an offset of 7 kW. The simulation would start with an unrealistic discontinuity. This discontinuous step needs to be avoided to prevent oscillations. A continuous time series is added to the load profile by adding a linear rise from zero to the first torque value of the measured load profile.

6.3 Results

The simulation validates the transient performance of the overall system.

a) shows the simulated electrical power of the inverter fed into the synchronous machine in comparison to the specified power value. The deviation in relation to the demanded power is shown in
b) The deviation between simulated and specified power is up to fifteen percent. As the mould is closed the load has a peak, before the injection is a constant load. At the end of the profile the load profile has another peak as the machine builds-up the holding pressure. Afterwards the mould is opened and the parts ejected and the load sinks back to the standby level.

There are three sources of error which cause the deviation in power and torque. The first part is caused by the transfer performance of the control. High frequent peaks are delayed and lead to error in torque. In areas of a high gradient the deviation rises up to eight percent because of the limited dynamic of the electrical machines. The second reason for the deviation is the mechanical inertia of the system, which delays the system response. The third part for error is caused by the set point calculation. The machine follows the specified torque with a constant offset of 1.5% within the timespan from 13 to 34 s. This deviation can be explained by the neglect of power loss P_{loss} within the synchronous machine (6). The electrical power of the real system P_{el} is the sum of mechanical power P_{mech} and power loss in the synchronous machine and inverter P_{loss} (6). As the power loss is neglected the calculated set point for the torque is higher than required.

$$P_{el} = P_{mech} + P_{loss} \tag{6}$$

The aim of the system is to follow the emulated load profile within an error band of ten percent.

b) shows that the system has a limited dynamic as the desired error band is stridden with high power gradient. The system dynamics can be improved by tuning the control, whereas in future a particular control design will be examined (Fig. 5).

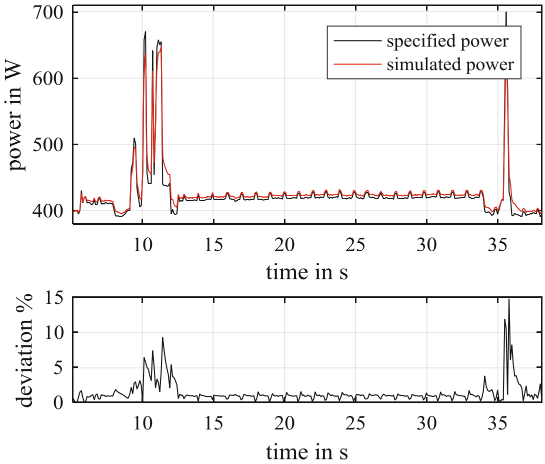

Fig. 5. (a) Comparison of power input versus simulated power draw by the synchronous machine. (b) Deviation between set point and simulated power draw from the synchronous machine.

7 Conclusion

The approach of an experimental setup, which represents the performance of a generic production machine is introduced. Modelling the production and energetic characteristics is in focus of the proposed design concept. Different electric loads are emulated by an asynchronous machine with the torque of a servomotor. It is shown how the process of an injection moulding machine can be replicated on the machine in a small power scale. Through evaluation with a transient simulation in MATLAB Simulink it is shown, that the system can be stable controlled by the proposed controller. Dynamic performance of the machine is limited by the controller and the mechanical inertia. Deviations between set output and simulated output are explained. The neglect of losses within the inverter and the synchronous machine leads to a small deviation, which does not put the application of the machine on risk. The proposed system is a major part within the evaluation of storage applications within an industrial smart-grid, as a high variety of scenarios can be run on the same topology. The test environment is appropriate to test control algorithms on a hardware level, examine storage degradation based on real load profiles and the transient coupling between all hardware components.

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The Influence of Big Data on Production and Logistics

A Theoretical Discussion

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Abstract. Information is a crucial factor for companies in all lines of business. Within the years the requirements to do business have changed and got more complex. Due to recent developments and trends such as Industry 4.0, Cyber-Physical-System, data and/or information is omnipresent. In this context Information logistics is a relevant discipline to deliver the right information element. To attain this goal, it is essential to manage and supply efficient data and information. Therefore, this paper deals with trends and models behind Big Data and the influence on production and logistics.

Keywords: Big data · Smart data · Production · Big data patterns · Information logistics

1 Introduction

Big Data, Smart Data, Data Analytics are common words today which even concern business matters. Under the theme Industry 4.0 the manufacturing industry elaborates on the creation of increasingly intelligent, autonomous and decentralized subsystems that should lead to more competitive production and logistics processes. However, it is not only the access to new technologies and new methods of technical integration, information is an essential asset for this approach. No service, no production can be understood without the fundamental perception of information to implement logistics scientific approaches through optimized supply chain [9]. Therefore, the effective and economic integration of information and decision-making bodies is relevant [2].

Due to recent developments and trends - such as Industry 4.0, Big Data, Smart Data and Data Analytics - data and/or information is omnipresent. This apparent advantage can be quickly turned into a drawback: an oversupply of data that are not beneficial information to their environment also includes more disadvantages than potential for a company. In this context Information logistics is a relevant discipline: In short the goal of information logistics is to deliver the right information element, in the right format, at the right place at the right time [12]. To attain this goal it is important to manage and supply efficient information. This is then of essential importance for the production. Therefore, this paper deals with the cornerstones of information management, the importance and principles of big data for logistics and production in particular.

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Data science requires both domain knowledge and a broad set of quantitative skills, but there is a lack of literature on the topic and open questions. Therefore, this paper focuses on the gap between data management and logistics and elaborates on the individual models and methods. A recently mentioned research project is also presented in this area.

The remainder is structured as follows: First the focus is put on terms and definitions to define the research background. Then the gap to production and logistics is bridged. Finally, the paper concludes with an outlook and a future industrial use-case.

2 Terms and Definition

As the discipline of information management is a wide area and no clear definitions exist, this paper gives a rough overview of the most important terms for the research that underlies this paper.

2.1 Data and Information

Talking about the quality of information in general and for logistics in particular, it is important at this point to define the terms data and information to connect information and logistics in a more appropriate way (Fig. 1).

- Character: a letter, number, or other symbol used in writing, especially in printed text or on a computer [6].
- Data: data is raw. It simply exists and has no significance beyond its existence (in and of itself). It can exist in any form, usable or not [1]. Today organizations generate large amounts of multi-spectral data. In view of its discrete form, data in itself may not be very useful, so it is often referred to as the original knowledge asset. When data is processed into a context, it becomes information. [5]
- Information: For this paper the relevant definition of information is defined as something that is conveyed or represented by a particular arrangement or sequence. Bali et al. mentioned that information is data that has been arranged into a meaningful pattern and thus has an identifiable shape [5].
- Knowledge: knowledge is the appropriate collection of information, such that it's intent is to be useful. [1] Knowledge is a deterministic process and a mix of framed experience, values, contextual information, expert insight and grounded intuition that provides an environment and framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of knowers [1].

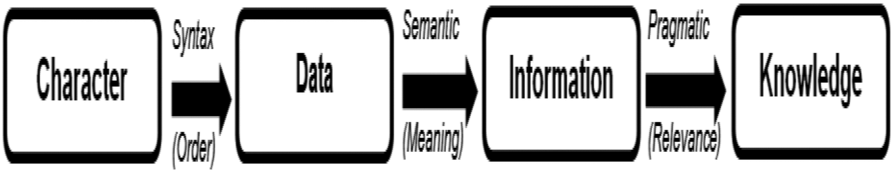

Fig. 1. Interconnection between data, information and knowledge [4]

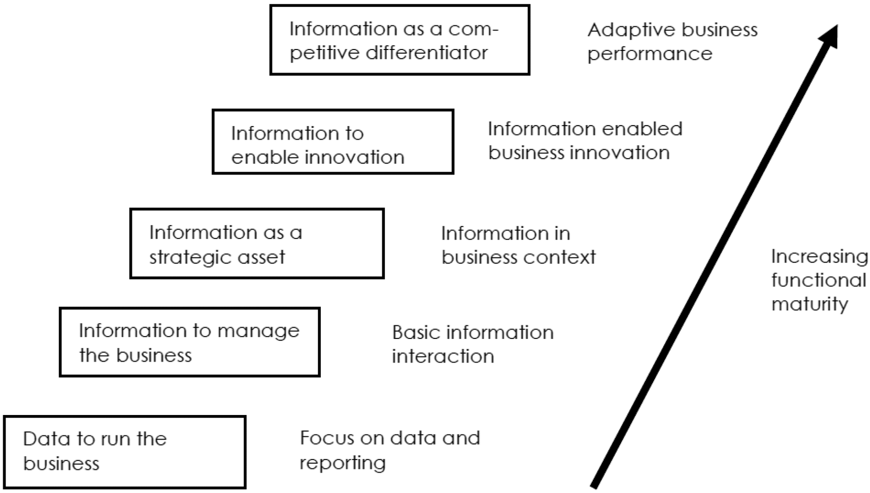

Fig. 2. Business Information Maturity Model [3]

When talking about data and information it is also interesting to have look on IBM's "Business Information Maturity Model" which defines five levels of data management, shown in Fig. 2. The focus of data at the lowest level is an operational perspective. At the next level, Information is used to manage the company. Information becomes a strategic asset at the next level. At the forth level Information becomes to some kind of special expertise. Finally, at the top level, Information is a competitive advantage and therefore often need to be protected against external actors. Here we finally talk about the creation of real business value [3].

It, however, is not that easy to reach the fifth level of the maturity model, as nowadays the data flood is so huge in companies that it gets always more difficult to distinguish between data and meaningful information. Therefore, in the context of logistics and especially information logistics the classical "6Rs" have to be adopted to the "8Rs of Logistics" (Fig. 3).

In this context it is important to have a look on Big and Smart Data and then concentrate on the impact on logistics and production. Here Production logistics will be defined as all operational purchasing, in-house material flow, in-house material handling, operational distribution and information flow processes which do need to be organized, controlled, executed and optimized in order to supply necessary raw-materials, perform manufacturing operations and physically distribute finished goods to customers [8].

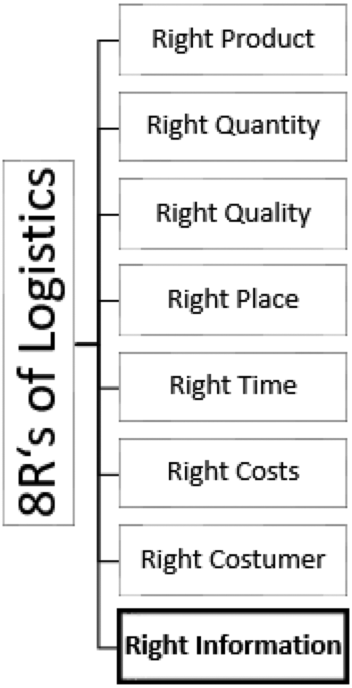

Fig. 3. The 8R's of logistics in the information age [9]

Thus it is relevant to know both sides – the production logistics as well as the information logistics aspects – to make use of the advantages of data management for the production.

2.2 Big Data and Smart Data

Big data is a comprehensive term for generally any collection of data set – structured or unstructured – that are so large and multifarious that processing them with conventional data processing systems is almost impossible. Therefore Provost and Fawcett define "Big Data as 'datasets that are too large for traditional data-processing systems and that therefore require new technologies" [11]. Big data is mainly produced by machines and thus often represented as machine data, too. According to Cooper and Mell 'Big data is where the data volume, acquisition velocity, or data representation limits the ability to perform effective analysis using traditional relational approaches or requires the use of significant horizontal scaling for efficient processing." [7] Concerning the scalability IBM describes Big Data in terms of four dimensions: (1) volume, (2) velocity, (3) variety and (4) veracity as shown in Fig. 4.

These information assets demand cost-effective, innovative forms of information processing for enhanced insight and decision-making. And this is the direct connection to production planning and supply chain issues nowadays. Here methods and approaches have to be found and implemented to get the most out of the big data and make smart data for the corresponding context. Data Analytics and Data Algorithms are here the

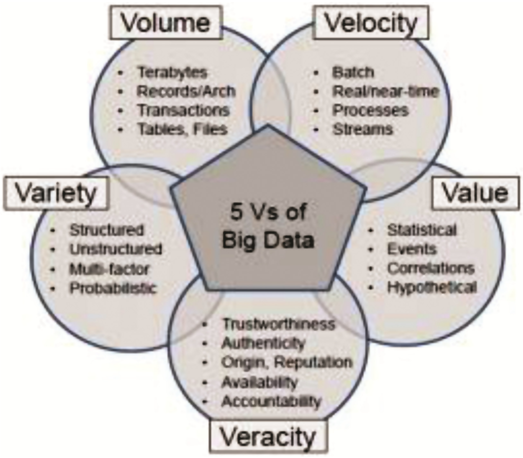

Fig. 4. 5 V's of big data

keys. Thus making smart data out of big data, as Fig. 5 schematically illustrates. "Smart Data" means information that actually makes sense. Algorithms turn meaningless numbers into actionable insights. Smart data is data from which signals and patterns have been extracted by intelligent algorithms. Collecting large amounts of statistics and numbers bring little benefit if there is no layer of added intelligence.

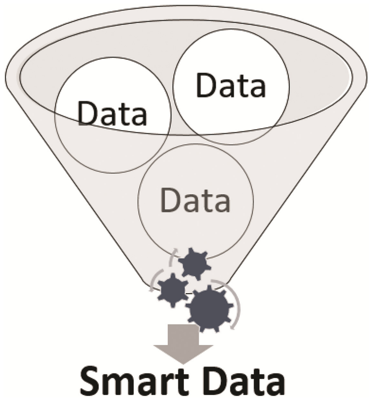

Fig. 5. Turning big data into smart data

3 Impact on Production and Logistics

Coyle et al. stated that information flow has become an extremely important factor for success in supply chain management. Traditionally information was viewed as flowing in the opposite direction of products, it means, from the market or customer back to the wholesalers, manufacturers, and vendors. The information was primarily demand on sales data, which were the trigger for replenishment and the basis for forecasting. If there were long time intervals between orders, the members of the supply chain were faced with much uncertainty about the level and pattern of the demand, which usually resulted in higher inventory or stock-out costs, a phenome-non known as the bullwhip effect [8].

All above mentioned aspects of data and information management mainly focus on the data domain and are therefore insufficient to cover all topics faced in managing production logistics processes, as for example complexity or analyzing the data gathered is not covered in the definitions above. In order to connect the different characteristics of Big Data to Production logistics the mentioned aspects need to be expanded further creating an integrated view of the topic, which includes dependencies of characteristics, Business intelligence, statistics and characteristics clustering [13].

Due to all these aspects the focus has to combine production, information technology and internet in order to be beneficial for classical industrial processes – in production and logistics. In the whole production life cycle, the mechanism and approaches of data management, big data and smart data are merged inseparably throughout, which will lead to advantages for all involved parties. More functionalities and customization options are gained for the client and more flexibility, transparency and accuracy for the whole production. Using information more effectively is one of the most important sources of competitive advantage for business firms today. The key to business success is information: accurate information, delivered at the right time, to the people who need it and can quickly make the best use of it. Nevertheless, this means the industry to introduce new types of production strategies.

Here a research programme is currently starting to investigate on the benefits on production in details: different logistic production processes – and in the long run supply chain processes - will be analysed and in a next step it will be researched on finding combinations for approaches from information logistics including data management and production management. Thus the logistic processes in production and also for the supply chain can be improved by means of big data analytics.

4 Future Work and Conclusion

If information is not well managed, it may lead to disruptions in the supply chain, thus endangering the overall performance of the supply network. However, when information is managed appropriate, accurate, timely, and complete, the companies will be able to make good decisions for their own operation, and also maximize the profitability of the entire supply chain. In the research project it is the main goal to develop a roadmap for data science in the logistics area and to develop a big data analytics architecture for logistics, comparable to the research of [13]. With this architecture it should be possible for companies to gain business value out of using big and smart data.

Therefore, this paper gives a rough overview of information management and addresses big data and smart data aspects. A currently starting research project is investigating on the process benefits due to big data and smart data. (It is estimated that first findings can be presented at the conference and can be mentioned in the final paper version!)

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Multi-Disciplinary Collaboration in the Development of Smart Product-Service Solutions

Identifying Key Aspects of Success for Product Service Systems

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Abstract. As companies struggle with the various challenges of their PSS, identification and elimination of possible errors and potential challenges early in the design phase is crucial. This paper aims to identify the universal key aspects of success for a PSS; thus, providing a general foundation for many companies within the industry to focus their initial efforts. Utilizing historical and contemporary literature within the PSS field, one central aspect was identified with three additional aspects serving to support the core aspect that all PSS are centered around – creating customer value. Standardization, product usage information (PUI), and environmental sustainability all support the goal of ultimately adding customer value. While there is a potentially unlimited number of additional individual supporting aspects that are important and contribute to this objective, these do not apply to all PSS universally. As a combinational effort, the three supporting aspects help to ensure that value is added to the customer in different, but related routes. These aspects involved may be utilized to allow companies to examine and analyze their current PSS and implement these aspects into their PSS operations and/or, ideally, reflecting on them during the PSS design phase. A limitation of this study is, that the universal nature of the 4 identified key aspects reflects only the PSS cases within the literature reviewed.

Keywords: Product service systems · Servitization · PSS · IPSS · Smart services

1 Introduction

Companies historically focus primarily on their manufacturing processes and optimizing the design of their products. A large portion of their revenue is often still generated from the initial sale. However, a growing part of their total lifecycle revenue can be generated during the after-sale phase (Middle of Life – MOL) (Mahut et al. 2016). Entering service agreements and contracts can allow a company, e.g., to perform preventative maintenance, scheduled diagnostics, and other advanced services for the users of their products (customers). These service agreements can block out other competitors, reduce costs for the manufacturer and customer, and add value to the customer.

A Product Service System (PSS) is a relatively new strategy where companies focus on both products and services with the goal of adding value to the customer/user. For

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example, a jet engine manufacturer will sell thrust, not the engines themselves any longer. A printing company will sell printed pages, not physical printers. This mindset is quite different from the traditional manufacturing avenue. Companies such as these, focus on the result, the value, and experience provided to the customer. Benefits from these PSS are found to include: reduced costs, reduced environmental footprint, lower overhead costs, more technology-driven systems, and ultimately more revenue.

Problem Scope: While many PSS are generally considered successful, they are not immune to various challenges and difficulties. Companies face these challenges on a daily basis and are confronted with mishaps in their current PSS. Some aspects of a PSS may be strong, but at the same time other areas may prove problematic. It is suggested to identify, understand, reduce and eliminate the possibility of errors and potential challenges early in the design phase while increasing the capabilities and flexibility of a PSS.

Main Objective: The main objective of the paper is to identify the key success aspects that are universal to all PSS. The main question to be answered is whether there is a set of common aspects that successful PSS have in common and whether they can be identified and potentially utilized to improve current product service systems or assist in developing an upcoming PSS. Furthermore, utilizing resources from outside one's industry or obtaining new successful concepts may help to build a stronger and more resilient process. Analyzing these lessons learned and companies' successful PSS as well as their operations, allow for a business to learn and strengthen their own (current or future) PSS if adapted and implemented carefully.

Methodology: In the following section, four aspects of PSS operations have been identified that characterize successful PSS through a comprehensive review of current literature. The literary review covered mostly journal articles that were published within the last five years while others were within the last ten years. This selection process served as a method of obtaining contemporary information regarding today's industries. A few articles provided a historical foundation of PSS principles that were beneficial to the support of this paper's claims (Blumberg 1994). Utilizing these historical principals allowed for a basis to help build upon other claims through more recent literature. Various databases were searched through to determine the paper selection. The *Services Industries Journal* and *Journal of Cleaner Production* were two of the major journals used for the literary review. Both journals have provided historical articles as well as recent literature that entails current technology-driven applications.

Selection of the articles was completed through evaluating studies of successful PSS. Based on the various articles' studies of current PSS, many articles identified how those PSS operated, interactions they had with their customer, and what the company valued overall. First, a set of literature was reviewed to help form this model of successful key aspects. Pulling from historical and recent literature, case studies were examined for the core values that ensured success of the PSS. Next, supporting literature was reviewed and integrated to validate the model through a deeper evaluation. This resulted in most of the PSS key success aspects to become apparent.

Extracting each of these successful aspects into a summary and compiling the similar aspects together allowed for the main aspects to emerge. Completing this literary review revealed two interesting discoveries. First, each of the successful PSS reviewed consisted of these four main aspects that ensured the advancement and success of the individual PSS. Second, these four main aspects were also highly related and integrated together. Implementing one aspect would ease the ability to implement another aspect. Furthermore, impacting just one aspect would have a considerable effect on other aspects. Derivation into the details of the aspects were completed to see how closely dependent they are.

2 Identifying Key Aspects

The first aspect, "Center Around Customer Value" is the overarching goal and 'raison d′être' of what encompasses a PSS by definition (Blumberg 1994; Boehm and Thomas 2013). Li also discusses the framework of value co-creation in PSS through digital technology and connectivity in his paper (Li and Found 2017). With value co-creation (customer value) at the center of the framework, other stakeholders stem off from this main aspect.

In this paper, three additional aspects serve to support the overall goal of adding customer value; which were identified as being universally applicable across all successful PSS studied in this research. These include, standardization, product usage information (PUI), and environmental sustainability. As each of these aspects are individually sound on their own, customer value is supported by these additional aspects. This development is supported by Li's value co-creation framework where stakeholders serve to provide each of the key aspects identified (Li and Found 2017).

Understanding how each of the key aspects are connected ensures for a more transparent and strategic implementation. This is illustrated in Fig. 1 with the four key aspects highlighted in a darker shade. From the research, these three aspects are universal to nearly all PSS reviewed in the literature. Regarding Fig. 1, the left tiers are given to show that there are other key aspects in other varieties of PSS, but this was not the scope of the paper. The three main tiers are universal to nearly all PSS. Each of the universal aspects has interaction and dependency with one another. However, the scope of the

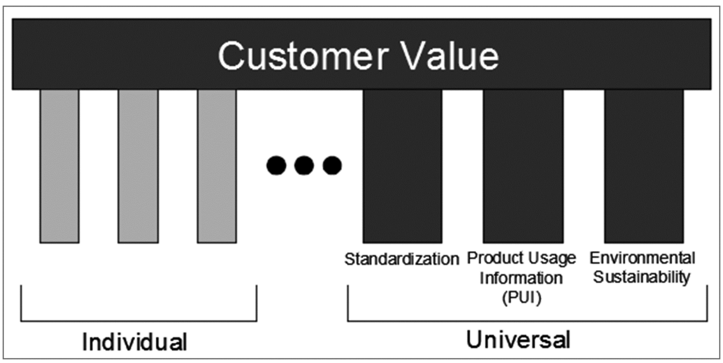

Fig. 1. PSS key supporting aspects to customer value

paper was to identify these aspects and their combinational effort to support customer value for a PSS.

2.1 Center Around Customer Value

The PSS operations should be centered around customer value (Colen and Lambrecht 2013; Mont 2002). A trusting relationship between the customer and manufacturer is formed through the continued use of a PSS and the value it delivers. Continued interaction and effective communication will strengthen business relationships and ensure that the customer is obtaining added value. Due to increased servicing, higher quality parts and services are implanted to ensure that the product is operating correctly and efficiently. A company's product is able to last longer and ensure for a longer life cycle. This generally benefits both the customer and the company providing the PSS. For the customer, a PSS can provide value through higher quality products and broad customization (Baines et al. 2007).

Overall, monitoring, maintenance, and administrative tasks are completely hands-off to the customer as it is transferred to the manufacturer. For the manufacturer, a PSS allows for a great competitive edge and market opportunities. Companies can serve their customers with more value through increasing service elements (Baines et al. 2007). To maintain customer loyalty, manufacturers and customers enter into a service agreement. These agreements allow for manufacturers to serve the customer by using their innovative and proprietary processes and products for their customers – creating customer value. This also helps hinder competitors from offering similar systems to customers. Enhancing the manufacturer's overall PSS will correlate to a stronger bond between the company and their customers (Wuest and Wellsandt 2016).

In turn, utilizing a PSS to provide extensive services could potentially be a threat to the manufacturing efforts. One department pushes for manufacturing more units while the PSS efforts support less manufacturing through increased service – a contradiction. A company must surpass these functional barriers by working together as one synchronized unit (Colen and Lambrecht 2013). Adopting a product-service culture, implementing internal processes and capabilities presents its own challenges (Wuest and Wellsandt 2016). A company should be able to stimulate both manufacturing and PSS efforts simultaneously. As a core promise of PSS, it is no wonder that an emphasis on the customer value is a key aspect that successful PSS have in common. In addition, the following key aspects support this customer value endeavor.

2.2 Standardization

Overall, a successful PSS must limit uncertainty and complexity (Colen and Lambrecht 2013). This statement means that standardization of purchasing options and additional services is crucial to the success of the company. However, a balance must be reached between standardization and customization (Colen and Lambrecht 2013), especially with PSS. Marketing too many options can confuse a customer as well as increase costs (Blumberg 1994). Modules, packages, and bundles should be utilized to help combat this issue. Standard service elements can be combined into a menu for a customer to choose. Furthermore, customers perceive these solidified options as higher service and value by receiving maximum value for each package (Blumberg 1994). If a customer desires a few extra features that is in another package, the manufacturer may be able to upsell the customer to purchase the more expensive package. In selling to a customer, only a certain amount of customer input should be accepted. Companies can agree to this only if a customer recognizes this added value and is willing to pay for the customization (Visintin 2012). Otherwise, this only adds variability and additional costs for the company. It is best to avoid customer customization input so that the company can focus on the standardized packages that they offer (Visintin 2012). In addition to adding customer value, this can also increase control for the manufacturer's revenue as well as reduce costs overall. There is no longer a need to have several different configurations varying in dimensions and various components. The customer feels that they are able to customize their services while the manufacturer is still keeping the options standardized. Overall, it was found that limiting uncertainty and complexity of PSS as much as possible without jeopardizing the defining value-added characteristics is a common trait of successful PSS.

2.3 Product Usage Information (PUI)

A PSS should fully benefit from an installed base of information on their customers/users (Blumberg 1994). This "base" contains a variety of data about the customer, service history, usage parameters and several other data. A company may forecast demand, diagnose, and perform various analyses based on this data. Moreover, this can help schedule maintenance, diagnose problems, and serve as a great indicator for future developments. Product Usage Information (PUI) can also be key in developing future products as they assist in the development of PSS directly from customer feedback (Lutzenberger et al. 2016). Knowing how a customer uses its product, service, or PSS allows to understand the true, often implicit, requirements better. Thus, the development of targeted solutions in form of additional services or product redesign can deliver more value to the customer/user. Applying sensors and data collection devices can be a tremendous asset to both the operation and design of a PSS. The concept of analyzing this data that is collected and implementing it into future product and/or service design can be crucial to the success of the PSS. Although research on this concept is relatively new and scarce, it proves that opportunity is still available to gain a competitive edge in the marketplace. Not only will the sensor data benefit future product design, but also maintenance of the existing products. A manufacturer can gather this PUI from their various customers, which will provide the ability to schedule preventive maintenance for the components.

Regarding additional services to the main customer base and PUI, this can be enhanced through the use of a web-based PSS for maintenance, repair, and overhaul (Zhu et al. 2012). This type of web-based system allows for real-time access of customers, maintenance schedules, and an up-to-date view of product usage information. In addition to gathering data, PSS visualization using dashboards are available to display the flow and process of customer activities, state of products, and various partners (Lim et al. 2012). PUI data may be able to be implemented into this visualization to provide an overall view of the PSS process.

2.4 Environmental Sustainability

An indirect benefit to the company and the customer is the environmental impact. Utilizing a PSS system through cleaner production, sustainability, and more thorough eco-design, can allow for a system to have a factor of 4–20 times the environmental impact reduction than a normal production system – while maintaining the same quality of service (Roy 2000). By switching to PSS, manufacturers can sustain the products that currently exist through upgradable components and eco-design. Furthermore, hybrid systems are also being introduced that are called "Upgradable Product Service Systems (Up-PSS)" (Pialot et al. 2017). These systems are based on upgradability, optimized maintenance, and adding customer value.

A study conducted in France, Germany, and Spain showed that many consumers dispose of 50% of vacuum cleaners, expresso machines, and other electrical household appliances even if they still work (Pialot et al. 2017). Furthermore, nearly 50% of products accumulate three problems or more (Pialot et al. 2017). Yet, only a small portion of these consumers have considered fixing these problems instead of buying another. Rather than simply dispose of a product, consumers would rather purchase a new one. This is a call-to-action for many manufacturers worldwide.

For PSS, upgradable products and servicing can allow companies to be able to upgrade the products easily and install longer life cycle parts. Applying the product life cycle (PLC), upgrades can be easily scheduled along the timeline of the product and its related components for easy maintenance scheduling. After introducing product usage information into the PSS, a company is able to collect data on these upgradable parts. Recycling the old parts to be remanufactured is a goal that could benefit the environment tremendously. Continual developments in recyclable components that have a longer PLC is critical. Environmental impact is a continual issue that each company strives to improve upon. While not being directly connected to economic KPIs for the PSS provider, successful PSS are common in the fact that they benefit the environment in one way or another.

3 Discussion

Although there are several factors that might be associated with the success of a PSS, four main aspects were repeatedly identified as relevant in case studies published in recent literature. Many papers discuss different PSS operations in depth, while implementation is not as thoroughly focused (Baines et al. 2016). There is little research about how a company should implement this into one's current system – a large knowledge gap. Without this, a company may blindly upgrade their systems with faulty database integration and/or skewed data. And in the end, no data is better than "wrong" data, as the availability of wrong data leads to dangerous consequences. Research must be completed for the implementation phase of new upgrades as well as applying these concepts in the design phase.

A PSS serves to provide value to the customer and to ensure its company's products are working efficiently for their customer. Thus, **customer value** is the overall goal of a PSS. Supporting customer value are three additional aspects that all correlate strongly. First, **standardization** allows for ease of choice with predetermined packages or modules for the customer. However, customization is also balanced with these standardized modules. This adds to the customer's perceived value with providing a set of options that is still allowed to be customized, yet is kept standardized. Next, **Product Usage Information (PUI)** can be obtained from the customer utilizing data collection and analytics technology, e.g., IoT. This information assists in providing a basis for future product design and development, maintenance, and possible future sustainability efforts. Data collection devices can flag when certain components fail, their overall average PLC, and analyze the utilization of the company's products. In turn, the company will collect this feedback to improve their future development in their products and shift their focus to their customers' needs. Finally, **environmental sustainability** totalizes these efforts to ensure for a positive impact on the environment. Up-PSS's products are upgradable along the PLC to ensure for recycling, reduced waste for the consumer and the manufacturer, and added-value to the customer.

4 Conclusions and Future Outlook

The purpose of the paper was to identify the key aspects that define successful PSS from published literature. Moving forward, companies should consider these four universal key aspects that successful PSS have in common and interpret them individually when developing an implementation plan for their own PSS business model. Though these aspects are separate, they are also dependent upon one another as shown in Fig. 1 to some extent. As a first step, companies should analyze their own business to determine how to integrate these aspects to add customer value. In turn, the other aspects will be positively impacted based on the implementation approach. More research, including the collection of a larger sample based on primary research data, is required and might lead to identifying additional aspects that commonly define successful PSS. Another area that needs to be explored is the impact that different industries and PSS business models (e.g., B2B vs. P2C) have on the identification of defining aspects. In a next step, the findings presented in this paper will be validated through primary data collection. Additional key aspects for certain industries may be identified to supplement the four universal aspects identified here.

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Prerequisites for the Successful Launch of Enterprise Social Networks

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Abstract. The importance of social networks and, in particular, enterprise social networks in business contexts is increasing significantly. Regarding the prerequisites for a successful implementation of an enterprise social network, exclusively providing the technical infrastructure is insufficient. A holistic view that considers and integrates different perspectives is crucial for success. This includes technological, organisational and human aspects as equally important parts of the network. This paper identifies prerequisites for a successful launch of enterprise social networks and groups them along these three dimensions.

Keywords: Social network · Social software · Enterprise Social Network · Socio-technical system · Human-Technology-Organisation concept

1 Introduction

Technological developments have changed the way humans interact with each other. Replacing bilateral communication, e.g. on the phone, information is increasingly shared via social networks. Such networks have become a permanent feature in most of our private daily lives. Facebook counts 1.6 billion accounts, and 1 billion people use the instant messaging service WhatsApp. YouTube, Instagram, Twitter and Skype are also used by millions of people [1]. In 2015, a total of 2.14 billion people were active in social networks [2]. With some delay, social networks have also become more important in a business context: Companies like Microsoft, IBM or Deloitte have established enterprise social networks (ESN) to increase their ability to innovate as well as their employees' productivity [3].

Regarding future developments, the significance of enterprise social networks will keep increasing as more business leaders recognize their potentials to improve company internal communication, collaboration and innovation processes [4]. Those potentials include the following: ESNs allow to connect employees with each other according to specific needs. They help to reduce hierarchical barriers between employees and thereby improve knowledge transfer within the company [5]. All employees can be involved in the innovation process regardless of barriers of time or location. For these reasons, new solutions can be developed faster and with a higher chance of success [5]. Another aspect is that ESNs enable companies to uncover possibilities and risks earlier than is possible within traditional hierarchical structures [5]. In addition, person-specific knowledge can

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be shared more easily [6]. In conclusion, ESNs have the potential to enhance the capability of companies to innovate and to increase work efficiency.

In order to exploit all existing potentials, the challenges associated with the launch of an ESN have to be addressed and overcome. This includes aspects such as data security [7], internal conflicts (e.g. conflicts with the works council or the company's management) [8], or unsuitable or lack of staff responsible for the operative management of the network [9]. The assumption that the only necessary step is the implementation of a suitable information and communications technology infrastructure and that employees will use the network without any further steps is considered untenable nowadays [10]. Many authors emphasize the importance of a structured network management which must be planned long before the IT infrastructure is implemented [9]. This leads to the central research question to be answered in this paper: What are the relevant prerequisites a company has to meet to successfully launch an Enterprise Social Network?

To answer this question, a short overview of the relevant definitions and the state of the art in related research is given, followed by a description of the applied methodology. Thereafter the research results are pointed out and thematically clustered. The paper concludes with a summary including some examples of how the relevant prerequisites can actually be met and an outlook on possible future research.

2 Definitions and State of the Art

In a business context, ESNs can be distinguished by both their purpose and target group. Regarding their purpose, ESNs can be differentiated by whether they focus on cooperation/collaboration or on innovation processes. In terms of target groups, ESN can be aligned with either company-internal or external users. Although the ESN typically has one of the above-named focuses, these are not necessarily exclusive, e.g. networks that focus on collaborative processes can also, as a side effect, foster innovation [11]. The application of ESNs mainly targeted at company-external stakeholders, e.g. to support customer relations, is increasingly important. This paper, however, focuses on ESNs essentially designed for company-internal users whose main purpose is to support processes of cooperation and collaboration [12].

The above categorization results from a socio-scientific and organisational perspective on the topic. Focussing on the technological aspect, the term 'social software' is used for web-based solutions that enable communication, cooperation, coordination and collaboration in the context of networking of people [13].

Both perspectives have to be considered as equally important. Consequently, ESNs can be interpreted as socio-technical systems which can be defined as systems that neither exclusively consist of technical (plant, machinery) nor of social (work and process organisation) sub-systems but rather of a combination of both system types [14].

The current state of the art in research on ESNs is shaped by different approaches that have a particular focus on either socio-scientific, organisational or technological perspectives concerning their implementation and utilization in companies. This paper, in addition, provides a holistic view of the topic that integrates and expands the results of existing research. Moreover, this paper can also be used as a guideline for companies seeking to implement an ESN.

3 Methodology

For the introduction of an ESN, a number of different challenges have to be met. Therefore a suitable reference framework has to be selected in which the factors for a successful launch can be structured and classified.

Following an extensive literature review, a holistic analytical approach to networks was chosen, based on the view of ESNs as socio-technical systems and, additionally, including the human element as a crucial factor. This approach, known as Human-Technology-Organisation Analysis, considers technology, organisational aspects and human individuals to be equally important parts of a well-functioning system. It places emphasis on the interactions between the individual elements and foregrounds the distribution of tasks between humans and technology (human-machine interface) [15].

Applying Human-Technology-Organisation Analysis to the research of prerequisites required for a successful launch of an ESN, an in-depth literature research was carried out as a first step to gain a profound theoretical understanding. The results were discussed with experts from several companies of different sizes and business sectors that are very experienced in the application of ESNs. In discussions and workshops including structured interviews, using predefined questionnaires, it was tested whether the results represent actual company practices. As a next step, the results were further elaborated. The identified prerequisites were categorized along three dimensions and subsequently grouped into topic-specific clusters. This provides a systematic overview of the central aspects to be considered, which should be helpful to users later on. In order to ensure the correctness of the results, they were finally validated by experts. The entire process can be illustrated as follows [16] (Fig. 1):

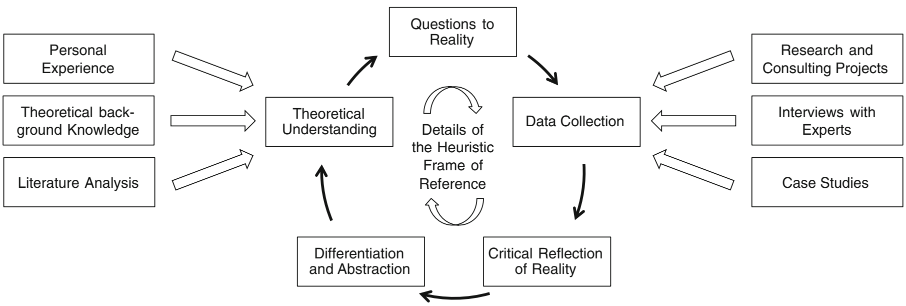

Fig. 1. Explorative research process [16]

4 Results

Following a Human-Technology-Organisation Analysis approach, the identified prerequisites for a successful launch of the ESN can be categorized along the dimensions of human, technology and organisation. The results, which are described in detail below, can be illustrated as follows (Fig. 2):

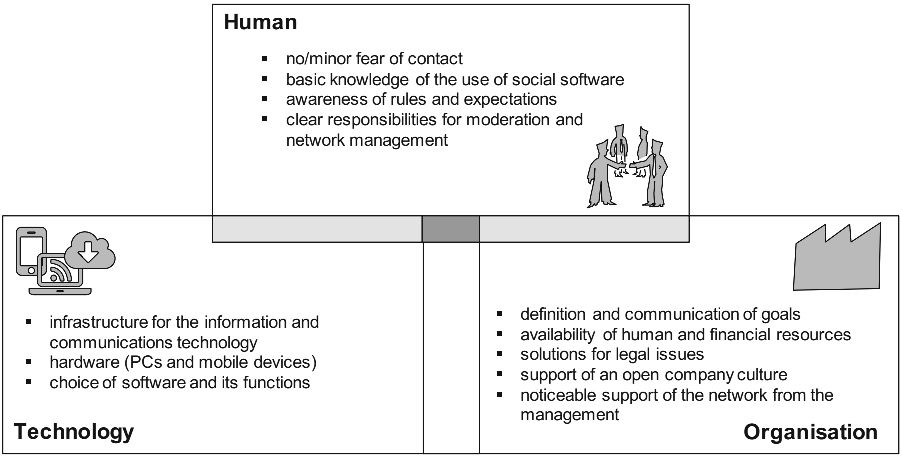

Fig. 2. Prerequisites for a successful implementation of enterprise social networks, clustered following a human-technology-organisation analysis approach

4.1 Human Dimension

Within the human dimension, the prerequisites companies have to meet can be grouped into four thematic clusters.

First, employees should not be afraid of using the new ESN [7]. Reservations and anxieties about using the network may be due to various reasons: Possibly, they result from insecurity about new working methods which require sharing of non-finalised work results [17]. In addition, it is unusual for employees to comment publicly on their colleagues' or supervisor's work or to criticize it openly [8]. To overcome this, a positive and open error management must be established [13]. Employees may also be worried of losing control of their knowledge or of surveillance [8]. To prevent any complications, the company needs to alleviate worries that employees might have from the very beginning by establishing transparent work routines and structured communication [8]. Another prerequisite resulting from this is explained by Murschall [8]: "Members of staff should be prepared to let their sovereignty of information go and share their knowledge with others. If the employees participate actively in the network, its overall benefit increases and the network is more likely to be accepted by its users."

Another crucial requirement for success is that all affected employees have the basic knowledge needed to operate the new medium [8]. They need to know which functions offer what kind of benefits and what kind of content is useful to share. Additionally, it is important to make decisions regarding the length, frequency and visibility of specific information that is shared via the ESN. At the same time, users also need to be aware of the benefits as well as the limits of the network [18]. It is important to know when a traditional telephone call or face-to-face meeting might be a better choice.

A further requirement for successful implementation is that there is fundamental clarity about and awareness of rules for members of staff [19]. Every employee needs to know how much time he/she should spend on using the ESN and what kind of information is to be shared to what extent [8]. In order to fulfil these prerequisites, companies should clearly define what they expect from the use of the network and communicate to the team the goals they want to achieve. This can be realized through participation, content, or code of conduct guidelines [20]. In addition, the benefits for employees must be clear to them, otherwise the ESN will not be used [21].

The network's success also requires that responsibilities for network management and moderation are defined early on [9]. There is now a consensus that the establishment and development of an ESN is a process that must be moderated and guided.

4.2 Technical Dimension

The technical prerequisites can be grouped in three thematic clusters. First, for the successful launch of an ESN, an appropriate infrastructure must be in place [6]. This includes the availability of a high data transmission rate and data storage capacity [21]. The ESN must be technically stable and react fast, if needed [9].

In terms of hardware, personal computers and/or mobile devices [22] will be required as well as servers [8]. Because of the increasing use of mobile devices such as smartphones or tablets, data can be saved on cloud-based servers [22]. Sensitive data or company secrets should, however, be saved on an extra server and have a unique decoding system for additional protection [8]. The firewall settings have to be adjusted so that mobile access is possible from outside the company's network.

Furthermore, the choice of software and software functions is an equally important prerequisite for the success of an ESN [20]. Companies may choose to use standard software, which is generally cheaper to acquire and offers basic but stable functions [6]. They may, however, also decide to develop their own software. This comes with a higher workload and effort but enables the company to implement specific functions according to their needs and to use company-specific vocabulary, if desired [6]. Regarding the design of the user interface of the network, it needs to make sure that important topics are highlighted and that a useful content structure exists [21]. All in all, the software should be easy and intuitive to use [13]. Moreover, it must be possible to extend the software and add functions, if necessary. This is crucial as the goals of the network may change over time [21]. From a technological point of view, it is also important to integrate the ESN into already existing websites and systems [23].

4.3 Organisational Dimension

Regarding the organisational foundations that need to be laid, five thematic clusters can be identified.

It is of utmost importance that the company sets specific goals for the use of the network [20]. This should hold a strategic value and benefit for the company [24]. It is important to communicate the business objectives with the help of participation, content, or code of conduct guidelines, for example [20].

An additional prerequisite is to make sure that human and financial resources are available when needed [20]. Among other expenses, costs will arise for managers and moderators of the network, IT managers, and for the purchase of hard- and software [10]. Furthermore, expenses for business trips, additional trainings or events that cover network-related topics may be necessary [24].

It is also mandatory to consider legal issues beforehand. One of the most important aspects in this context is the question of copyright. Additionally, industrial law and data security rights need to be considered [7]. The works council needs to confirm the appropriateness and agree to the use of the ESN [8]. Apart from this it is crucial that no company secrets are passed on to third parties [25].

In addition, a relevant factor for the success of an ESN is an open company culture [19]. To establish such a culture, organisational barriers need to be reduced. This means that hierarchical structures need to be transformed into connected network structures [18]. Members of staff need to be ready to trust each other and exchange ideas instead of keeping them to themselves to strengthen their own position [26]. An open work culture also means that employees are allowed to communicate constructive criticism across all hierarchy levels [8].

Eventually it is important for the participation of employees that the company's management exemplifies the use of the network [26]. Therefore, the visible support from executives is another factor for success [20].

5 Conclusion

In this paper, prerequisites for the successful launch of an ESN were identified. In order to illustrate them and to facilitate their use in practice, Human-Technology-Organisation Analysis was used as a frame of reference. The essential advantage of this approach is that related social, technical and organisational challenges are integrated and considered simultaneously. For each of the three dimensions, a number of prerequisites were identified and subsequently grouped into thematic clusters.

Within the human dimension, it is important to allay employees' fears of using the ESN and to enable them to use it by preparing them sufficiently, e.g. in personal talks with network managers, who should also serve as contacts if users need further support. In addition, the rules and requirements of the network need to be made transparent, e.g. by providing trainings or short marketing videos. Furthermore, persons responsible for the management and networking of members of staff are to be appointed. On top of that, one of the most crucial factors is to clarify the benefits of using the ESN for the users' everyday work.

Focusing on technological aspects, companies need to provide a suitable network infrastructure and hardware and select an appropriate software solution. In this context it is most relevant to ensure the usability of the software, especially if the age structure of the employees is heterogeneous.

Regarding the organisational dimension, the following aspects should be considered: The objectives that are to be achieved by using the network need to be defined and communicated to all those involved. It is necessary that personnel and financial resources are available and potential legal issues are clarified in advance. As a final and most relevant prerequisite for the successful launch of an ESN, the management has to support an open business culture and promote the use of the network, including actively using the network itself.

This paper can serve as a guide for enterprises willing to foster intra-organisational collaboration via ESNs, as it provides a structured overview of relevant prerequisites for a successful implementation. As the paper does not focus on the description and analysis of best-practice approaches of companies that have already successfully launched an ESN, this could be a topic for future research.

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Getting Ready for the Fourth Industrial Revolution: Innovation in Small and Medium Sized Companies

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Abstract. Companies are currently preparing for the fourth industrial revolution, which is envisioned to radically change manufacturing processes, logistics and business models in global manufacturing networks. Previous research have emphasized the need to respond to the changing landscape of the digital economy in dynamic and innovative ways. This study aims at exploring how small and medium-sized companies are prepared to meet this opportunity and challenge. In order to do this we have applied insights from innovation theories and empirical findings from eight companies that are part of two industrial clusters. The findings in this study indicate that even though most of the case companies have ambitions to position themselves in a new digital landscape, they prepare themselves differently. We see that organizations that has progressed furthest in implementing Industry 4.0 related concepts are the ones that make actively use of their external network in cooperation and sharing knowledge. These companies also have managed the balance between exploration and exploitation internally, where employees are both engaged in efficient manufacturing of existing products and product development. Consequently, we claim that both openness and organizational ambidexterity is vital for successful implementation of Industry 4.0.

Keywords: Innovation · Networks · Organizational ambidexterity · Implementation · Industry 4.0 · Digitization

1 Introduction

The term "Industrie 4.0" originates from a governmental high-tech strategy in Germany, promoting the computerization of manufacturing [1]. This strategy which is referred to as the fourth industrial revolution, includes initiatives termed the Industrial Internet, Factories of The Future, and Cyber Physical Systems (CPS). The accelerated use of Internet of Things (IoT)-technologies is a driving force for this development [2]. Industry 4.0 encompasses a broad range of technologies and concepts, and is generally referred to as digitization. In the context of manufacturing, Industry 4.0 focuses on intelligent products and production processes [3]. In the envisioned factory of the future, or smart factory, CPS will enable communication between machines, products and humans. The products are intelligent and customized, to accommodate for the increased

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need for rapid product development, flexible production and increasingly complex environments [4]. According to Brettel et al., this development leads to an increased importance of collaborative manufacturing and collaborative development environments, especially for Small and Medium Enterprises (SME) [3].

A challenge for manufacturers is their ability to keeping up with escalating technological change [5]. This applies not only the purely technical aspects, but involves the socio-technological systems, as intelligently networked objects in manufacturing is expected to constitute tasks distributed in time, space and content, and thereby change the content of work [6]. This will require new competence as well as increased worker flexibility, and the design of systems in the age of Industry 4.0 needs to be human centered in all parts of the manufacturing network [1], as the fourth industrial revolution aims at creating synergetic collaboration between humans and machines [7]. Hence, implementing Industry 4.0-concepts, requires not only implementing new technology and infrastructure, but also to adopt a completely different organizational setup, and a set of processes that are different from those found in traditional manufacturing [8]. This will lead to the development of innovative communication, different competence requirements, and interdisciplinary collaboration [7]. Moreover, the introduction of digital technology is expected to create unseen and unexpected fault lines, and also accelerate the pace of innovation [9].

With this as a point of departure, we may consider the implementation of concepts from the fourth industrial revolution as an open process that requires innovation capabilities inside the organization, as well as an openness for collaboration with other companies in a network, e.g. other cluster companies. Hence, in the following we will present theories addressing innovation internally to organizations, and innovation in the digital age with intensified networking.

2 Literature Review

2.1 Innovation in Organization

March claimed that for long-time survival, firms need to configure organizational resources to exploit existing assets and positions in a profit-producing way, while simultaneously explore new technologies and markets [10]. In this lies a fundamental tension between what he terms exploitation and exploration. Furthermore, firms are confronted with the basic problem of having sufficient exploitation to secure its current viability while engaging in enough exploration to ensure future viability. Several streams of literature have sought to address this fundamental problem. One of them is the literature on dynamic capabilities that is concerned about companies' "ability to sense, seize and reconfigure organizational assets to adapt to changed environmental conditions" [11].

According to O'Reilly and Tushman [12], the ability to balance exploitation and exploration, that is being ambidextrous, is at the core of dynamic capabilities. Managers must sense changes in the organization's environment, including potential changes in technology, market and regulation, and be able to act on the opportunities and threats by reconfiguring the organization's assets [13].

How do firms manage to balance this tension between exploration and exploitation? O' Reilly and Tushman [11] claim that ambidexterity requires commitment of resources to exploratory projects and establishing separate but aligned organizational units for exploitation and exploration, and these should have aligned organizational architectures. Here, leadership is essential in resolving the tensions arising from the two separate units and architectures. O'Reilly and Tushman stress that the organization's strategy needs to reflect an importance of both exploration and exploitation that is articulated through shared vision and provide a common identity. Furthermore, they suggest building senior teams that are committed to the ambidextrous strategy, which had incentives to both explore and exploit. Based on the above, we see that the strategic choices by the leaders of an organization are essential for facilitating innovation for future competitiveness, while exploiting existing assets to secure running profit. This comprise the dynamic capabilities of a company [14], which is necessary to survive in the long run [15]. However, a criticism to the literature on dynamic capabilities and organizational ambidexterity, is that it views the organization in isolation, and does not take into account that innovativeness and organizational survival is dependent on the organization being a part of a larger network of companies [16]. This view of innovation is challenged by the network view of innovation, as the concept of open innovation, which will be addressed in the following.

2.2 Innovation in the Age of Digitization

Digitalization can be referred to as generation of new knowledge that could not be possible without digital technologies [17] Yoo et al. [18] defines digital innovation as "the carrying out of new combinations of digital and physical components to produce novel products" (p. 725), which reflect a product centered view of digitization. Furthermore, they claim that adoption of pervasive digital technology is fundamentally reshaping organizations, and change the very nature of innovation in organizations. Yoo et al. [9] claim that this happens in three ways: The importance of digital technology platforms, the emergence of distributed innovations, and the prevalence of combinatorial innovations (p. 1400). In this study, we focus on the second; distributed innovations.

Distributed innovations mean that innovation activities are spread across multiple organizations, as opposed to the view that innovation processes takes place internally in organizations. This is in line with the concept of open innovation, which Chesbrough define as "the use of purposive inflows and outflows of knowledge to accelerate internal innovation and expand the markets for external use of innovation" [19]. When introduced, this represented a paradigm shift from the closed view where innovative process was confined within the company's borders, where internal innovation activities led to internally developed products and services that subsequently were distributed by the firm. In contrast, in the open innovation model, companies use external as well as internal ideas and knowledge to advance their technology and combine ideas into architectures and systems in order to create value [19]. According to Yoo et al. [9], digital technology intensifies the aspect of innovation emphasized by the open innovation model, in that heterogeneity as well as the need for dynamically balancing and integrating of knowledge resources, becomes even more important. However, their arguments are strongly based on technology and use of digital tools. Moreover, the recent examples of innovation associated with concepts from digitization and Industry 4.0 is largely based on companies that are parts of a networks with a large number of companies and are delivering products and services to a mass market. There is a lack of knowledge shedding light on how small and medium sized companies being part of a regional innovation networks, are approaching the fourth industrial revolution. Moreover, there are few studies exploring what role the innovation processes plays in the implementing of concepts and technology related to Industry 4.0. This study aims at filling this gap.

3 Methodology

In this study, we aim at contributing to filling the gaps in the literature by adopting a multiple case study design [20, 21]. We have carried out case studies in order to gain insight into how small and medium-sized companies in regional clusters are prepared to meet opportunities and challenges represented by the fourth industrial revolution, from an innovation perspective. Data was collected through semi-structured interviews with top managers in eight manufacturing companies, representing two regional clusters based in North-West Norway. Additional data was collected in workshops and meetings with cluster companies.

The data collection aimed at revealing how the companies looked upon Industry 4.0 and related concepts, their strategy for meeting this challenge and opportunity, and their thoughts about how far they had come in implementing Industry 4.0-related concepts internally in their organization. Moreover, we wanted to map their innovation process internally, as well as how they involved other companies external to their organization. Finally, the respondents were asked to reflect upon the possible challenges for moving into the next digital age.

4 Case Companies

The case companies were selected from two industrial clusters in the North West part of Norway, representing a high-cost manufacturing context. Both clusters are part of the Norwegian cluster program, where both are at first out of three levels, being clusters at an early stage of development. The establishment of both clusters have created important arenas for networking and competence building. The cluster projects were established in a situation with little cooperation between companies, and have quickly shifted into a new way of working characterized by openness, trust and cooperation.

Cluster A is a cluster covering 38 companies within several industries, as manufacturers of equipment and services to the offshore and maritime industry, plastic component manufacturers, process industry, electronics companies, consultants, logistics companies, among others. Cluster B is an industry cluster including 12 companies manufacturing finished goods, mainly furniture. The companies delivers the products mostly to wholesalers, and the end-market covers private customers and contract customers nationally as well as globally.

Both clusters focus on Industry 4.0 as a part of their cluster strategies, although in slightly different ways. Cluster A has named the concept "Industrial Internet" as the main strategy of the cluster, and have facilitated several initiatives involving cluster companies that aims at building competence in this field. This involves IoT (Internet of Things), Big Data, sensory, 3D printing, VR (Virtual Reality), AR (augment reality), AI (Artificial Intelligence), robotics and automation. Lately, they have focused mainly on how digital insights on these new technologies may represent new sustainability business models, products and services.

Cluster B builds on a common desire to build stronger international competitiveness based on strong brands among their members. They have oriented themselves towards digital business models, and are currently organizing an educational program for their members, focusing on this issue. Both clusters are involved as industry partners in competence building projects addressing issues associated with Industry 4.0, and aim at establishing new projects with research groups nationally as well as internationally.

5 Findings

5.1 The Concept of Industry 4.0

The concept "Industry 4.0" itself was well known among all the case companies, which should be expected based on the increased attention surrounding this topic the last years, especially from the two cluster organizations. The companies views Industry 4.0 and related topics as being described as both an opportunity but also a necessity in order to stay competitive. Six of the companies describes Industry 4.0 as a part of their strategies and ambitions for the future. However, at this point the implementation of new technology in manufacturing and digital integration with external actors, is relatively limited in the majority of the companies.

Although our case companies describes Industry 4.0 as an opportunity, it is also considered as a fuzzy concept for SMEs. Several of the companies were uncertain what the implications of the recent development in digitalization would be, which is reflected in one of the CEOs reflection: "*Industry 4.0 technologies is first and foremost relevant as a mean [towards a goal]*", and another one pointed out that "*we are not there [industry 4.0] yet*". These respondents were not clear about how to position themselves in relation to Industry 4.0, which reveals a gap between the expressed ambition and their current situation.

Furthermore, the findings revealed that companies perceived Industry 4.0 and the associated technology differently, and put different emphasize on their internal manufacturing processes or the product itself. Here, we could observe differences between the two clusters. Firms from cluster B gave more attention to key enabling technologies associated with their products, as the integration of sensors giving the opportunity to collect user data. Companies from cluster A focused more on the use of new technologies that could improve the efficiency of their manufacturing processes.

5.2 Innovation

Exploration and Exploitation

Based on the theory presented above, we assessed the case companies' innovation strategy. It varied significantly how companies carried out their product development processes related to existing and new products, while carrying out their daily business. On the most explorative side, the founder and manager of one of the companies expressed their strategy in these words:

> *"Our success and focus has been not to only sell the original [basic] product, but to sell the complete product. Our main motive has been to develop new technology that is adapted to the market."*

The company is continuously working with development of new business models and the implementation of new technologies. This strategy turned out to be important when they experienced that their main product lost market shares the recent years. Then they could turn to their new and innovative products, which they had worked with "on the side". In this company, employees were heavily involved in the innovation processes: "*It has been important to develop a culture in the company were people want to develop themselves*". In addition to this company, three other companies in the study could be characterized as being explorative in the sense that they seek new opportunities, and are able to develop new products while attending to their existing business.

In contrast, the CEO of another regional company reported that their innovation processes mainly took place outside of the company, from where they purchased new designs and concepts. This company also reported low level of technology use: "*there is not much technology around here*", and was mainly concerned about upgrading the existing ERP system. Another case company in the same cluster and producing relatively similar products to the same market, had a different ambition and strategy regarding technology use, and was currently investing in new data driven manufacturing equipment. This illustrate that there are other factors than the characteristics of the product, market or manufacturing context that are governing how a company prepare for implementing new technology.

Networks

Being members of two clusters organizations, the companies has opportunities to participate in arenas where knowledge is being shared. However, we found that the use of these arenas varied considerably among the case companies, and the general impression was that the companies that were oriented towards internal innovation, also were the ones most actively drawing on external networks. Not only within the clusters, but also between the two clusters and through other networks. One respondent from cluster A illustrated this by the statement: "*If you are going to be innovative, you have to work with other companies*". This company had recently developed an innovative product that was a result of cooperation with internal personnel, a company from another industry (cluster A), and an external actor. Another respondent claimed that "*a network have two sides: both the social responsibility and contacts in the network are important.*"

Furthermore, both clusters aim at increasing the member's knowledge within the field of digitization, new business models, and innovation. The clusters have established educational programs in cooperation with universities and university colleges within this field. Several respondents reported that they were part of these programs, and for one of the companies, this was the only arena for cluster participation.

6 Discussion and Conclusions

This study has examined how eight manufacturing SMEs in two clusters in North-West Norway prepare themselves for the future of Industry 4.0. Contrary to the recent literature addressing Industry 4.0, we have based our study on innovation literature. In this literature, the terms exploration and exploitation are terms that are mostly used as terms inside the companies, and innovation in network has been regarded as an alternative approach. In our study we have seen that this goes hand in hand; the companies that handle the ambidexterity of innovation, that means being able to explore new business opportunities as well as attending to and improving their current activities, also are the ones that draw heavily on external networks in their innovation processes. This is illustrated by a quote from one of the managers; "*you have to attend to the daily activities, but you have to be able to look forward at the same time*". O'Reilly and Tushman [11] claim that companies need to carry out the explorative activities in a separate organizational unit, which is done in two of our case companies. However, our findings from these small and medium-sized companies indicate that several of them were able to combine both exploration and exploitation, without having a separate organizational unit for exploration activities, and in fact were the ones that were most innovative and had come furthest in implementing new technology in their products.

Moreover, we see that companies that have managed the balance between exploration and exploitation internally also are the ones that make actively use of their external network in cooperation and sharing knowledge, and that has progressed furthest in implementing Industry 4.0 related concepts. This demonstrate and confirms the claims made by Yoo et al. [9], that the implementation of digital technology intensifies the need of open innovation model. Hence, both openness and organizational ambidexterity seems to be important for implementation of Industry 4.0 for small and medium sized companies, which are challenged by limited resources for explorative activities.

The implications of our findings is that the first step of implementing/orienting towards Industry 4.0 is to create a culture for innovation in the organization with employee involvement, while establishing collaboration with other companies in networks. Moreover, the company needs an explicit strategy and ambitions towards implementing enabling technology. Eventually, our findings emphasize the importance of being part of clusters and extra cluster networks when preparing for the fourth industrial revolution.

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Effects of Environmental Dynamicity on Requirements Engineering for Complex Systems

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Abstract. With customers demanding more and more holistic answers to their problems, solution providers respond with complex systems, integrating product, service and ICT elements into their offer. These solutions need to be aligned to a high number of requirements, coming not only from the individual customer but also from an environment of network partners, technology providers and other stakeholders. Especially for Product-Service Systems, where the solution provider takes responsibility in the operational phase, this environment is dynamic over the system life cycle. Stakeholders may enter or leave, as well as changing needs and technological capabilities. This makes the requirements towards the solution volatile, demanding a suitable Requirements Engineering approach. In this paper, it is discussed how environmental dynamicity can be monitored for its effect on requirements, with a special focus on organizational issues. Through a literature review and industrial case studies it is analysed, how it can be ensured that environmental changes can be taken into account in Requirements Engineering, leading to an optimal system configuration to address the customer problem.

Keywords: Requirements Engineering · Dynamic environment · Product-Service System · InnoScore Service · Focus Activity Model

1 Introduction

Within the last decades customers increasingly demand holistic solutions for their individual problems, and their procurement is driven by the expected benefits from using the solution rather than sales price only [1]. Consequently, solutions are becoming

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complex systems that have to be aligned to an environment of stakeholders, technology and constraints. In the case of Product-Service Systems (PSS), where the solution provider is responsible for the whole life cycle of the system, including operation and evolution [2], this environment is dynamic. Stakeholders, application scenario and available technologies will change over time.

Following these developments, the main prerequisite for a high quality solution is understanding the underlying needs, and thus the requirements for the system throughout its entire life cycle [3]. The effects of environmental dynamicity on the requirements for the system have to be taken into account for Requirements Engineering (RE); i.e. constantly monitoring the changes of stakeholders, needs or newly available technologies and adapting the requirements accordingly. The need for developing models, modelling methods and tools supporting RE for complex systems, such as PSS, has been claimed by several authors [4–7].

The objective of this paper is to discuss the effects of environmental dynamicity on RE for complex systems like PSS. How can it be monitored, and how can the influence of changing stakeholders and technology on the requirements for the solution be managed? After defining the research question and methodology in the next chapter, a literature review on the challenges of RE for complex systems in dynamic environments is presented in the third chapter. Based on this, Sect. 4 presents two approaches to monitor environmental dynamicity, which are applied in industrial use cases. Finally a summary and research outlook is given.

2 Methodology

The main research question to be addressed in this paper is how to monitor dynamicity in the stakeholder and technological environments of for complex systems, such as PSS, and feed the results back into the RE process?

In order to answer this question, the authors have conducted a literature review to understand the research gaps and challenges. To perform this state-of-the art investigation, the authors have performed a search through the scientific databases "Google Scholar", "Scopus" and "Research Gate", using key words combinations to address the specific topic of interest: "RE AND Systems Engineering", "Product Service Systems Requirements Engineering", "Requirements Engineering for complex systems", and "Requirements Engineering + PSS". The search has been targeting specifically the Title, Abstract and Key Words of the documents. Papers collected were then screened and selected by the analysis of their abstract.

Furthermore, the researchers have been involved in the specification and development of PSS scenarios in several industrial use cases during the last two years. More specifically, action research was applied [8], conducting multiple on-site workshops with representatives from different departments. During this work, two approaches were developed and tested to monitor changing environments: Innoscore Service and Focus-Activity Model.

3 Requirements Engineering for Complex Systems in Dynamic Environments

This chapter presents the outcome of the literature review, first showing the shift of complex system RE preferences in general before deriving the challenges for RE in dynamic environments more specifically.

3.1 Shift of Requirements Engineering Preferences

RE for complex systems in dynamic environments has to be able to coordinate effectively among stakeholders, while envisioning future needs and technological opportunities in the process. Svetinovic [4] has called such an approach "Strategic RE" and highlights four conceptual shifts of RE preferences in the system perspective by analysing the characteristics of complex sustainable systems and the challenges in their design process and combining them with the mechanisms of RE (see Fig. 1).

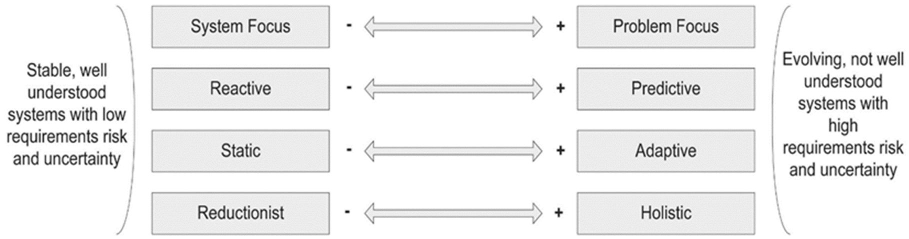

Fig. 1. Strategic shift of RE preferences for complex systems [4]

As can be seen, first it is important to focus on the problem, instead of the system functionality. As the problems are initially not well defined, it is imperative to define clearly all the requirements aligned with the system environment. Furthermore, as the system environment will change, RE methods have to predict future requirements arising from the system's interaction with the environment. Connected to this, the system has to be adaptive to unforeseen changes through feedback during system operation without the necessity for costly re-development and prototyping. Finally, RE must follow a holistic perspective of the system and its environment. Moreover, the author highlights the necessity to analyse the interactions and to adapt the requirements within the context [4].

A suitable RE methodology has to support the management of unstable and unknowable requirements, taking into account information from all system life cycle phases [9]. This is in line with the openness to change and attention to uncertainty management for complex systems. Regarding a long-term perspective, no specific approach is provided within RE methodologies. Such considerations e.g. for future PSS are not strongly addressed or allowed by specific tools enabling, for instance, to contemplate future requirements rising beyond the current ones.

3.2 Implications of Dynamic Environments for Requirements Engineering

Berkovich [7] and Aurum and Wohlin [6] have focused on the importance of the assessment and management of requirement changes during the RE process and the necessary engagement of customers and stakeholders for the effectiveness of tailored solutions. Wiesner et al. [9] have defined collaboration and interoperability between stakeholders and PSS components from different domains, especially products, services and software, and the management of unstable and unknowable requirements, taking into account information from all PSS life cycle phases as key challenges for RE. These works show that RE for complex systems in dynamic environments has to take into account several issues. Three main challenges can be identified:

- All internal, external, primary, secondary **stakeholders** have to be identified for RE, considering possible future scenarios.
- Impacts and effects to and from the environment should be considered for RE, such as newly available **technologies**.
- **Future requirements** should be proactively predicted for RE, with a long-term view on the suitability of the system.

4 Approaches to Monitor Environmental Dynamicity in Requirements Engineering for Complex Systems

Following the shift of RE preferences for complex systems and the implications of dynamic environments, in a first step solution providers must be enabled to monitor the stakeholder and technological environment to be able to predict future requirements. Jarke et al. [10] propose to consider the relationship between requirements and their business context, also during their implementation process, concluding that only systems embedding an adequate, flexible, and evolvable world-model are likely to survive. Nemoto et al. [11] also recognise the value of context in system design in a framework which allows to draft a macro environment around the customers from the long term-global environmental context elements. Consequently, strategic tools are needed that allow providing a more complete and deeper consideration of all meaningful influences provided by external elements on the development of a complex system. Two different approaches to monitor a dynamic stakeholder and technological environment of complex systems have been tested by the researchers in industrial use cases: the Innoscore Service and the Focus Activity model. These instruments can give system developers a guideline for including environmental effects into the set of requirements to develop a complex system, as described below.

4.1 Innoscore Service

An approach to consider the environmental situation against the organizational capabilities of the system provider is the "InnoScore® Service" tool which is based on the EFQM-model [12–14]. It is an online tool for measuring, evaluating and improving strategic innovation in manufacturing firms to offer complex Product-Service Systems against their competitive environment [15–18]. The tool is currently available in German for various types of manufacturing companies and takes between 15 and 20 min to complete. Nine different aspects are analyzed and compared to an environmental benchmark based on 126 companies from the plant and engineering sector in Germany. The detailed evaluation of these environmental aspects enables the company to adapt its innovation strategy and derive additional requirements for the development of Product-Service Systems [19, 20]. The individual aspects are discussed in more detail below.

By assessing the "Structure and Network", "Skills and Knowledge", as well as "Innovative Culture" of the environment, it can be determined if all relevant stakeholders are considered for PSS development. Observing the "Technology", and "Market" aspect helps to define the technological context of the solution, thus taking into account changes that might happen in this environment. The aspects "Product and Service", "Strategy" and "Process" examine processes, such as RE, that must be built up and further developed in a targeted way [21–23]. Figure 2 shows an exemplary evaluation of a company, where the aspect "Technology" is very good in comparison to the benchmark, while the aspect "Skills & Knowledge" should be improved. This might indicate to re-assess the stakeholder environment to derive requirements from additional actors for system development.

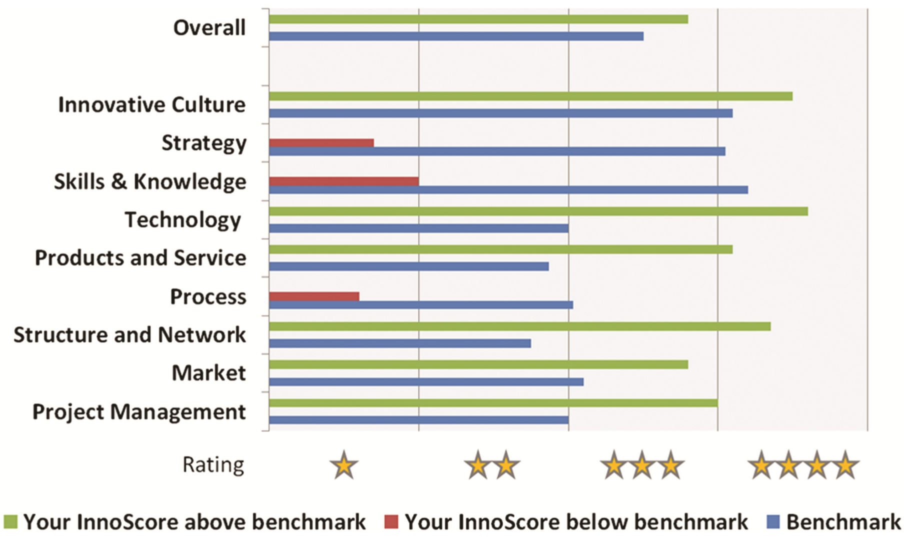

Fig. 2. Screenshot of the evaluation of an example company [18]

While the Innoscore Service is not able to provide changing requirements automatically to the RE process, it helps to understand the relationship between the environment and the innovation strategy. A periodic application of the tool helps to identify new stakeholders and technology and derive new requirements accordingly.

4.2 Focus-Activity Model

The Focus Activity model has been proposed within the PSYMBIOSYS European project as a mean for mapping innovation needs for implementing PSS in a company. It enables a company to position its product and service business separately along a structural and a cooperation dimension. The "Structural Focus" indicates how much a company is oriented on product or on service business, based on factors such as strategy, network or capabilities. "Cooperation Activity" refers to the level of proactive collaboration during PSS design, with the appropriate interfaces, information and roles [24].

Between the high and low values for both dimensions, four types are distinguished in Fig. 3 below. This figure illustrates a company increasing its service focus, while at the same time improving cooperation in product and in service (Type III → Type I).

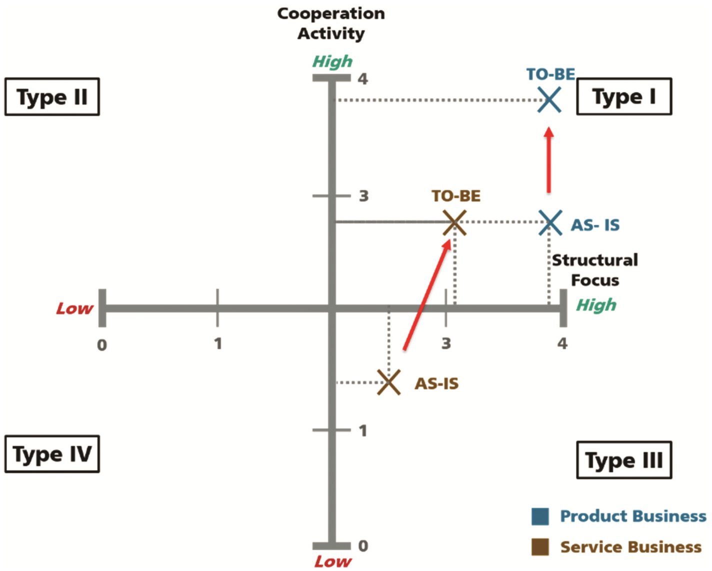

Fig. 3. Example of Focus Activity Model

The movement of the product or service business along the axes and between the different types illustrates intended or actual changes in the organizational environment of a complex system. Thus, it can provide a simple vision of different future scenarios for deriving changing requirements in the RE process. By including the product and service related stakeholders ("Network"), inconsistent requirements and trade-offs can be identified for PSS development. Furthermore, new technological capabilities or interfaces might lead to new requirements to be considered for system design. Like the Innoscore Service, the Focus Activity model cannot automatically provide requirements to RE. However, it helps to develop future PSS scenarios as a basis to discover new requirements.

5 Conclusions and Future Work

Engineering of complex systems is evolving from a temporal development process for individual solutions towards a permanent orchestration of distributed product, service and ICT elements adapted to a dynamic environment, which has to be observed by RE. Based on a literature review, a predictive, adaptive and holistic approach with a problem focus has been identified as the new preference for RE. Three environmental aspects have been identified as important: changing stakeholders from different application scenarios, constant feedback on new technologies or capabilities, and prediction of future requirements for the system.

Two high-level approaches to monitor these aspects have been tested with industrial use cases. While not being specifically designed to support RE, results from the use cases indicate that useful conclusions can be drawn from their application. The Innoscore Service approach provides a feedback on the industrial benchmark for several environmental aspects to derive requirements accordingly. The Focus Activity model helps to develop future PSS scenarios and discover related requirements.

Both approaches are limited to an organizational level and do not automatically provide requirements to RE. Thus, in future research, the authors aim to formalize their application, so that they can be included into a RE methodology for complex systems in dynamic environments. In addition, the inclusion of sensors and communication capabilities into systems could provide the opportunity to monitor directly the environment. Big data analysis of operational data or the users' sentiments would help to automatically detect changing requirements and adapt the PSS accordingly.

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Sustainable Human Integration in Cyber-Physical Systems: The Operator 4.0

Social Factory Architecture: Social Networking Services and Production Scenarios Through the Social Internet of Things, Services and People for the Social Operator 4.0

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Abstract. The prevailing industrial digitalisation flagship initiative, Industrie 4.0, gathers a substantial part of its functionality from the human in the system. This will drive a need for focus on both human and social dimensions of technology. The paper explores the roles of the Social Operator 4.0 in smart and social factory environments, where humans, machines and software systems will cooperate (socialise) in real-time to support manufacturing and services operations. A Social Factory Architecture based on adaptive, collaborative and intelligent multi-agent system is proposed for enabling such cooperation. Further, production scenarios are proposed, to show how social operators, social machines, and social software systems will communicate and cooperate via enterprise social networking services to accomplish production goals in the Social Internet of Things, Services and People.

Keywords: Industry 4.0 · Operator 4.0 · Social Internet of Things · Services and People · Smart wearables · Smart machines · Social assets · Enterprise social networking services

1 Introduction

Industry 4.0 will allow new forms of interaction between humans, machines and software systems. Such phenomenon are known as the industrial *Internet of Things, Services and People (IoTSP),* where interconnecting things, services and people via the Internet will improve data analysis, optimise operations, boost productivity and flexibility, enhance reliability, save energy and costs, and generate innovative e-services for smart factory environments [1].

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Smart devices and smart wearables, such as data goggles or tablets, will increasingly make it possible for humans to interact with so-called "social machines", and powerful social (assistance) software systems (e.g. artificial intelligence, virtual assistants, and chatbots) will guide operators in increasingly complex cyber-physical systems (CPSs), including smart machines and supply chains, as temporarily equal partners at the shop-floor [2].

Moreover, with the emergence of the *Social Internet of Industrial Things (SIoIT),* manifested as smart machines with social properties (context awareness and cooperative initiates), namely "social assets", such will share their status information (e.g. location, condition, and availability) and cooperate via *enterprise social networks* to achieve a common goal, an optimal smart factory production system [3].

This paper explores the role of the *Social Operator 4.0* in the context of smart and social factory environments, where humans, machines and software systems will cooperate (socialise) in real-time to support manufacturing and services operations. Furthermore, a high-level *Social Factory Architecture* based on an 'adaptive, collaborative and intelligent multi-agent system' will be introduced in this paper as a proposal to enable such cooperation, as well as, some production scenarios envisioning how social operators, social machines and social software systems will communicate and cooperate with each other via enterprise social networking services to accomplish production goals in the *Social Internet of Things, Services and People*.

2 The Social Operator 4.0 and Its Social Companions

An *Operator 4.0* is defined as "a smart and skilled operator who performs not only 'cooperative work' with robots, but also 'work aided' by machines as and if needed, by means of human cyber-physical systems, advanced human-machine interaction technologies and adaptive automation towards 'human-automation symbiosis work systems' " [4]. Moreover, a *Social Operator 4.0* is a type of Operator 4.0 [4] that uses smart wearable solutions together with advanced human-machine interaction (HMI) technologies to cooperate with other 'social operators', 'social machines' and 'social software systems' in order to communicate and exchange information for mutual benefit and align/alter activities as well as share resources so that more efficient results can be achieved at the smart and social factory of Industry 4.0.

With the emergence of smarter factory environments and the Social Operator 4.0, smart wearable solutions [5], HMI technologies [6], and adaptive automation strategies [7] will play a significant role when combining different interaction mechanisms and sharing and trading control strategies between social operators, social machines and social software systems towards a 'social factory' [8].

A *Social Factory* is a live enterprise social network with powerful middleware and analytics backend to improve the connection between social operators, social machines and social software systems working together in a smart production environment, and the data created within the networking process [8] towards a sustainable 'learning factory' [9, 10].

According to [8], a *social factory* should be able to (a) provide the right information and the right time and place (anywhere and anytime) to the right person, machine and/or software, (b) support humans under any working conditions, (c) engage humans to contribute to new knowledge creation, (d) treat humans, machines and software as equal partners, and (e) learn from all this socialization of knowledge by explicitising it.

In this context, the faithful social companions of the Social Operator 4.0 will be other social operators, social machines and social software systems. The Social Operator will be able to interact with these other social entities, communicate and exchange information, align or alter activities, share resources, and work together on joint tasks.

3 Social Factory Architecture: Components and Technologies

The *Next Generation Balanced Automated Production Systems* [11, 12] consist of 'hardware' (e.g. machine tools and robots), 'software' (e.g. enterprise information systems) and 'humanware' (e.g. blue-collar and white-collar workers) components coexisting with mechanical and human autonomy as well as with human-machine collaboration capabilities where autonomy and synergies between human, machines and systems create a social sustainable and competitive factory. The next subsections will detail selected areas of relevance.

3.1 Hardware: Smart Wearable Solutions and the Internet of Things (IoT)

Several *smart wearable solutions,* part of the IoTSP paradigm, have been designed for a variety of purposes as well as for wear on a variety of parts of the body, such as head, eyes, wrist, waist, hands, fingers, legs, or embedded into different elements of attire [5] in order to tech-augment operators physical, sensorial and cognitive capabilities [12].

Similarly, a diversity of 'things' has been embedded with electronics, software, sensors, actuators and network connectivity in order to augment their capabilities. Such is the case of *smart machines,* now capable of operating autonomously (intelligence), avoid and correct processing errors (security), learn and anticipate future events (management), and interact with other machines and systems (connectivity) [13].

3.2 Software: Actively Adaptive Agents for Human-Automation Symbiosis

The essence of *Agent Technology (AT)* is to mediate interaction between human beings and technological artefacts. Hence, AT has been considered an important approach for developing socially sustainable factories, where human agents can cooperate (socialise) with other human agents and artificial (machine) agents as hybrid agents and emerging agents to keep their *agenthood* [12], and therefore optimally leverage human skills and automation capabilities at the shop-floor in order to provide human inclusiveness and harness the strengths of human beings and machines to achieve new levels of efficiency and productivity that neither can achieve alone [14] and that not compromise production objectives [12].

Agents' Agenthood is defined by Wooldridge & Ciancarini [15], "as a system with the following properties: autonomy, reactivity, pro-activeness and social ability".

According to Yamasaki [16] in Xu et al. [17], an *Active Interface* is "a type of human-machine (agent) interface that does not only wait for users' explicit input but also tries to get information from users' implicit input, and external environment. Based on the gathered information, it acts spontaneously and keeps the system in advantageous conditions for its users", with users being human agents or artificial (machine) agents in this case. Furthermore, an (active) *Interface Agent* "can learn by continuously 'looking over the shoulder' of the user as he/she/it performs actions against other artefacts, and provide the users with 'adaptive aiding' as well as of alternating the activities instead of human" [18]. In this sense, a human or machine in the physical world will coexist with its associate human or artificial (machine) agent (a.k.a. digital 'agent' twin) in a cyber-physical environment, so that as an intelligent agent can evolve by itself as a human or machine user's proficient level improves [18]. For humans, such learning/evolution could be tracked by means of *Advanced Trained Classifiers (ATC)* [19, 20], while for machines the use of different *Machine Learning Techniques (MLT)* [21] might be considered.

The use of *intelligent* and *actively adaptive collaborative multi-agent system* to coordinate the support of manufacturing and services operations at the shop-floor is proposed to achieve *human-automation symbiosis* [11, 12] at the social factory and its smart production environment. In such a set-up, *active interfaces* within the social IoTSP of the factory, as *interface agents,* will allow to gather information from the social operators, social machines and social software systems *agenthood status* and send a request for cooperation (i.e. to create a hybrid or emergent agent) to other human or artificial (machine) agents in order to keep their agenthood, and therefore production running.

In this sense, the social factory should be considered as a 'collaborative environment of intelligent multi-agents' [22], where (real) humans and machines 'twin agents' use *interface agents* to facilitate communication between them and the cyber and physical

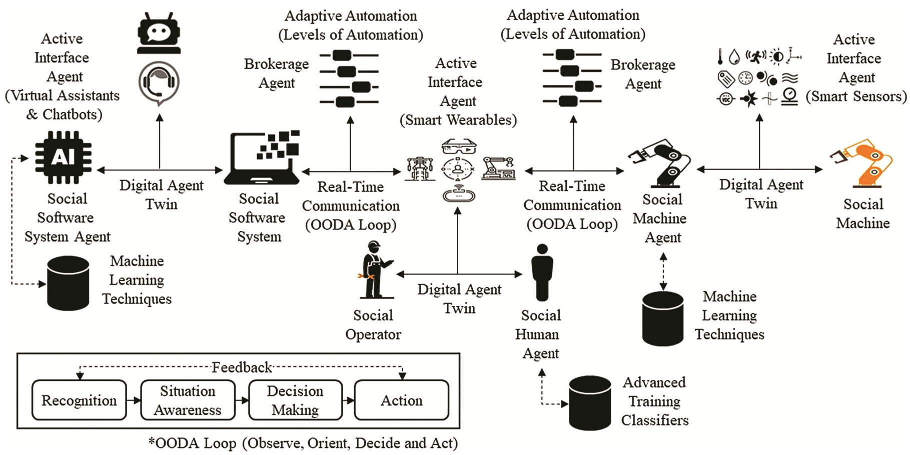

Fig. 1. High-level social factory architecture based on an ACI-MAS

worlds, and other agents such as *broker agents* support tasks allocation and control sharing & trading [23] in the cyber-physical production environment. Figure 1 presents a high-level *Social Factory Architecture* based on an Adaptive, Collaborative and Intelligent Multi-Agent System (ACI-MAS).

Such intelligent MAS architecture will aim to (a) facilitate communication between the social operators, social machines and social software systems, (b) assist them to distribute tasks (based on their competences) and share & trade control in collaborative tasks, (c) maintain as much as possible human inclusiveness without compromising production objectives, and (d) record and track humans and machines evolution as their proficient levels improve through learning and practice.

The following agents will operate in the social factory fulfilling different roles:

- *Human agents* - represent the humans and their capabilities in the system and are a duo consisting of human + interface agent, which allows a human to interface with the rest of the system.
- *Artificial (machine) agents* - represent the machines and their capabilities in the system and are a duo consisting of machine + interface agent, which allows a machine to interface with the rest of a system.
- *(active) Interface agents* - represent a set of interaction rules and conditions for supporting humans and machines interfacing with the rest of a system; their 'active' feature allows the interface agent to constantly learn and evolve its rules by being trained by observation, imitation, feedback and/or programming in order to be able to personalise the assistance to its user (viz. human or artificial (machine) agent) [24] and such assistance be provided in an adaptive and dynamic manner, and only when required, to help the human or machine in difficulty to main his/her/its 'agenthood' at the tasks at hand by different automation or mechanisation invocation strategies [11, 12] (e.g. critical-event, measurement-based and/or modelling-based strategies [23]).
- *Broker agents* - represent the (adaptive) levels of automation [25, 26] (viz. adaptive automation) available in the system and the rules for sharing and trading control in human-machine cooperation in order to efficiently allocate labour (cognitive and physical) and distribute tasks between the automated part and the humans at the workstations of an adaptive production system [11, 12, 27].

3.3 Humanware: The Human Factor in Adaptive Automation Systems

Humanware is defined as "a function of 'leadership', 'followership' and the reciprocal interaction between the two, where leadership is a leader's willingness to fulfil both task accomplishment and group maintenance and followership is followers' voluntary desire to follow their leader and to achieve their tasks" [28].

In the social factory, the Social Operator 4.0 will be empowered with technology (e.g. smart wereables and other devices) and thus encourage collaboration with other social operators, social machines and social software systems. At the same time, the Social Operator 4.0 will be monitored with the help of ATCs [19, 20] and other detecting and preventing error approaches like "digital poka-yokes" [4, 29] for 'poor humanware' (i.e. wilful transgression, risk-taking, peer acceptance of poor humanware [28]) in order to avoid human error (i.e. perception, judgment, action errors) and provide a virtual safety net.

In this context, the main goal of adaptive automation, based on active interface agents and brokerage agents, is to prevent errors and to reduce out-of-the-loop performance of the humanware by preserving an adequate level of situation awareness and mental workload [30], while providing a crucial perception of empowerment materialised into an appropriate level of freedom [31] for the social operator [4, 12].

4 Enterprise Social Networking Services and Production Scenarios

Enterprise Social Networking Services (E-SNS) focus on "the use of mobile and social collaborative and interface methods to connect the smart (social) operators at the shop-floor with the smart (social) factory resources, including other social operators, social machines and social software system. Such connections include 'social relations' among the workforce (*cf.* social network services) and between social operators and smart (social) things and services (*cf.* Social IoTSP [1]) to interact, share and create information for decision-making support and/or alignment or altering of activities and their related resources to achieve a compatible or common goal" [Extended from 4].

In this case, the social operator is considered the main focus and the following scenarios are always centred on the Social Operator 4.0. While there are many other scenarios (e.g. Social Machine to Social Machine) possible and worthwhile to be analysed, this is not the focus of this research work.

4.1 Social Operator Networking Scenarios

One of the possible collaboration scenarios is a Social Operator interacting with other social operators. In such, a Social Operator to (one or many) Social Operator scenario, the use of adapted *social network services* like a B2B Facebook or Twitter that are capable to facilitate, e.g., one-to-many communication, incorporate location based services and real-time sharing of media (viz. audio, picture, video) or allow for facilitating a dynamic community based capability matrix. Such E-SNS, supported by an intelligent and actively adaptive collaborative MAS, can enable opportunities and real-time multimedia communication (viz. images, holograms, video, audio and text) capabilities between social operators using smart wearables (viz. MS-HoloLens) that can empower the workforce to communicate and contribute with their expertise to different problem-solving scenarios at the shop-floor by bringing together the right people with the right information and the right time to address a situation without certain limitations (e.g. different location of expert and to be solved problem).

4.2 Social Machine Networking Scenarios

Enhancing the 'senses' of the Social Operator 4.0 through, e.g. smart wearable tech, enables her/him/it to engage in social interaction and communication with social machines within the E-SNS. SIoIT can connect, through 'interactive machine learning', smart (social) operators with smart (social) things (*cf.* intelligent assets) in social networks for sharing information and exchanging messages about their location, condition, operation status and availability for improving (for example) at machine level the asset reliability (e.g. intelligent maintenance) and at production line level the material flows and resources productivity (e.g. spotting bottle-necks) towards social problems-solving and optimisation of the production system.

4.3 Social Software Systems Networking Scenarios

Similarly to the Social Operator 4.0 interacting with social machines (*cf.* intelligent assets), being 'always-on' and connected enables the social operator to naturally engage in communication with social software systems. This can be envisioned as a 'virtual assistant' with an Artificial Intelligence (AI) backend, like IBM Watson, where the social operator can either actively ask questions that the system will answer based on available information/data or, passively, the social software system might monitor the environment and behaviour and provide pro-active information and/or decision making support through voice, video or holographic communication channels.

5 Conclusions

This paper is suggesting a *Social Operator 4.0* concept in the context of smart and social factory environments. Furthermore, a high-level *Social Factory Architecture* based on an adaptive, collaborative and intelligent multi-agent system was introduced taking advantage of a 'multi-agent approach' for interconnecting and interoperating multiple agents across an enterprise social network to provide solutions by means of temporary collaborations (viz. hybrid and emerging agents) in situations where expertise and capabilities are spatially distributed. Finally, some production scenarios envisioning how the Social Operator 4.0 will communicate and interact with other social operators, social machines and social software systems have been presented.

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Impact of Technology on Work: Technical Functionalities that Give Rise to New Job Designs in Industry 4.0

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Abstract. With rapid advancements in the application of Industry 4.0 technologies throughout industries, a collection of different views on its potential implications for workers are emerging. Various authors agree that these technologies and their application in manufacturing systems is structurally different compared to current methods of production. Consequently, it is expected that the impact on manufacturing jobs, specifically on the tasks, is profoundly different from what we already know from literature. However, authors often borrow from existing literature to describe changes in work, and are not explicit on how and why Industry 4.0 and the implications is conceptually different. Until now, little research has focused on defining the technical functionalities that give rise to new job designs. This paper therefore focuses on synthesizing the diverging views on the effect of Industry 4.0 on employees' jobs and specifically aims to understand how the technical changes of the transformation towards a Cyber Physical System in production relate to changes in job design. The central question this paper addresses is: How do the technical changes of the transformation towards a Cyber Physical System impact job design in industrial production? The contribution is an overview of the technical functionalities of Cyber-Physical Systems that are conjectured to change direct and indirect value-adding jobs in industrial production. This model will be used as a basis for further empirical inquiries. Moreover, it provides central points of interests for organizations involved with the design and implementation of Industry 4.0, focusing on job design.

Keywords: Industry 4.0 · Cyber Physical System · Technical functionalities · Job design

1 Introduction

Since the German government launched the Industry 4.0 initiative as one of the key high-tech strategies in 2011 [1], the term is being used as an umbrella term to describe the intensified application of an array of digital technologies in industrial production. They include a growing use of sensors, the expansion of wireless communication, growing computational power and storage capacity as well as growing data connectivity and AI applications [2]. Industry 4.0 is often described as the next industrial revolution following the digital revolution of information technologies and computers in production [3]. On the basis of this initial digitization, further technological developments

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defined in the concept of Industry 4.0 are projected to introduce a new paradigm shift [4] by allowing new methods of production [5]. This implies a drastic change for the design of jobs, specifically the quality of work, work organization and human-computer interaction [6]. These changes are described in two different development scenarios in literature, evolving around the potential of the new technologies to augment the worker in more complex tasks or to fully replace the worker and his skills [7]. Similar changes in work have also been discussed earlier in the context of computer-integrated manufacturing (CIM) and evolve around the up- and deskilling potential of new technologies. Despite the fact that changes are forecasted, we still know little on specifically the technical functionalities that give rise to new job designs in the context of Industry 4.0. This is because the term is relatively new and lacks a strong conceptual foundation. Moreover, the level of technological sophistication in Industry 4.0 developments at organizations is still rather low. Hence, empirical insights into implications of developments are scarce and we still have to rely on forecasts. To further develop this understanding, this paper synthesizes the different perspectives of the effect of manufacturing technologies on work, specifically in the context of Industry 4.0. We then aim to define the technical functionalities of the transformation towards a Cyber Physical System (CPS) as a core concept of Industry 4.0, and discuss how these relate to changes in job design.

2 Impact of Technology on Work

2.1 The Deskilling vs. Upskilling Perspective

Throughout the last decades, two main schools of thought were represented referring to the changes in skills originating from technological change [8]. The adoption of these perspectives by scholars changed periodically and many rejected the deterministic relationship it implies. In terms of a structural perspective, as brought forward in Giddens structuration theory, human agency and structure are mutually constitutive, meaning there is a mutual influence of social processes and the structural features of the new technology [9]. On the one side, the de-skilling perspective describes the simplification of jobs and the reduction in skills of more highly skilled craft workers [10]. This perspective first appeared during the first industrial revolution of mechanization as a result of the replacement of craft skilled labor through machines [11]. It was reestablished during the introduction of computers into the manufacturing environments in the 1970's as the concept of the automated factory, or lightless factory emerged. This viewpoint has also been referred among others as the degradation of work or polarization of skills approach [12]. In general, a capitalist management focuses on automation technologies with the goal to gain greater control over their production workers, thereby simplifying and routinizing work processes, reducing the need for individual skills and knowledge of the process, materials or quality issues involved. Consequently, management is less dependent on the individual skilled craft worker whose special knowledge, insights and skills will be transferred from the production worker to technical professionals. The work is organized so that the production worker often has to follow routines and procedures on simple tasks determined by others, diminishing the need to conceptually understand one owns work or to take decisions. The tasks are then polarized into jobs with routine tasks and highly complex tasks, respectively. On the other hand, the upskilling perspective identifies technological change as making work more demanding in terms of skills required for the job [12–15]. This perspective appeared in the mid of the 20th century when the first computers entered the production environments. Fearing that computerized work settings and potentials for automation could affect workers, various researchers started examining the impact of automation on the tasks and skills of the workers [16, 17]. The upskilling perspective contrasts the de-skilling perspective, stating that rather than automating complex and skilled tasks, simple and routine jobs are automated, resulting in jobs that focus on the more challenging and complex aspects of tasks posing higher cognitive demands [13]. Workers are freed to take up new tasks such as monitoring and controlling equipment and become troubleshooters for automated processes [e.g. 13, 17]. Both views have received much criticism throughout the years as they tend to oversimplify and generalize matters and assume a unidirectional effect of technology on work. However, this effect often differs per type of technology [17] due to different functionalities made available with that technology. Moreover, studies indicate that the impact of technology on job design depend on a variety of other various organizational factors [18], such as management choice, their vision and goals [19].

2.2 Industry 4.0 – Human Centered or Intelligently Replaced?

There are two main positions taken in literature focusing on different implications of Industry 4.0 technologies for work [20]. These development scenarios include on the one hand the enabling scenario closely resembling the up-skilling perspective. On the other hand, the replacing scenario mirrors the deskilling perspective. Enabling technologies often provide means to increase the performance or the capabilities of a user or process. As opposed to the workerless facilities as proclaimed by CIM in the 70's, the Industry 4.0 movement often emphasizes the importance of the people in the system as an integral factor of the production environment [7, 21]. Humans are forecasted to keep a high level of autonomy and are highly skilled. Technological support should be provided in such a way that the full potential of these skills and talents can be realized [22]. As such, people are charged with a new role of strategic decision makers and flexible problem-solvers. Routine, simple execution and control tasks are then automated [23]. The nature of tasks will shift towards a higher degree of complexity. Employees will have to interact, monitor and control more complex technical systems, increasing the need for knowledge on e.g. software architecture, automation and IT. Furthermore, tasks can become more unstructured and diverse. This is what Koelmel [24] refers to as increased technical and contextual complexity. This changes their work towards more mental work as information processing, abstraction and problem solving requirements will increase [7, 25]. The human will become the central decision maker, augmented by technology. Windelband et al. [26] refer to this perspective on change as the tooling scenario. The information available and the analysis done by computer systems are geared towards augmenting the knowledge and expertise of the employee. Therefore, by assisting workers better in their jobs, they can take over more complex tasks [27]. On the contrary, new technology in Industry 4.0 is perceived by others as a possible constraining factor, thereby replacing human insights and technically enabling controlling and monitoring possibilities. This scenario is also referred to as digital

Taylorism referring to Taylors principles of work simplification and control [28] and resulting in a strong deskilling effect. Edwards & Ramirez [29] refer to the paradox that Industry 4.0 is a fully configured system linked by information technology resulting in a reduced ability to shape the wide contours of the system. In accordance with this is the expectation that especially low skilled jobs will have to follow a pre-determined sequence of steps and will have less possibilities to intervene in the working process [25]. In line with that thought is the potential of technologies to fully replace the human skill and expertise as autonomous human decisions can increasingly be taken over by the computer or the application system that control the processes. In the digital factory, increasing autonomy of IT systems and corresponding integrated manufacturing equipment can potentially lead to human workers being pushed to the background [30], only intervening as a troubleshooter. The question then is to what extend the decoupled worker is still able to intervene and react to problems if he is taken out of the loop. Moreover, as systems are becoming smarter, they have the potential to further emit the worker and take on the formerly human based control decisions. Thereby potentially they are becoming less dependent on the skills and control of the worker. The two development scenarios presented represent two very different implications for the design of jobs and it is expected that depending on local application conditions and other factors, different job designs will emerge. The changes through CPS are expected to be dependent on the organizations choice of design of technology and the corresponding provided functionality as well as how they organize work around it [23]. To obtain a better understanding into the functionality provided by Industry 4.0 technologies and how it relates to work, in the next section we propose distinct functionalities that are provided through a combination of technologies that transform production into a cyber-physical production system. Subsequently, we shortly discuss what this means for the design of jobs in direct and indirect value adding tasks.

3 Technical Functionalities of Industry 4.0 and Job Design

The interconnected cyber-physical production system. A central element of Industry 4.0 in industrial production is the creation of a factory wide information network integrating data, models, machines, processes and software tools vertically and horizontally [2]. In its essence, CPS are physical production components that are represented in a cyber-counterpart, a logical layer that processes pre-specified information and that, depending on its capabilities, can communicate, negotiate and interact with other actors in the information network [31]. Embedded computers such as Programmable Logic Controller (PLC) or embedded systems can monitor and control the physical processes [32] and can share the information horizontally across the process or vertically up to higher level information systems. This is projected to result in interconnectedness, information transparency and increasing autonomous behavior of production components [33]. However, the transformation towards a CPS is not a turn-key project, but we expect that different stages will emerge. We characterize these states by a passive or active role of production components and the level of intelligence of production components, respectively. First, we distinguish between a passive and an active role of production components. A passive role means that production components will obtain an identification technology, such as a RFID chip, and as such will be able to respond to inquiries concerning location, environmental conditions or states. This so called passive role of a component mainly provides real-time data capture and as such, promotes the further digitization of manufacturing processes as real-time data can be collected and distributed within the information network of systems, machines, products and processes. Hence, this system is characterized by passive actors that can communicate pre-specified data when initiated by other active actor, most likely humans that take the initiative. The active role of production components refers to physical objects such as products or machines being capable to use their processing power to not only collect data but also to communicate, to negotiate and take autonomous actions to meet pre-specified design objectives. A key characteristic here is the ability to act autonomously without the intervention of human beings. The production system increasingly becomes an active actor that takes autonomous decisions. Second, we distinguish between different levels of intelligence that can be present in a CPS system. The level of intelligence refers to production components and other embedded systems having increasing processing power to convert data to useful information based on pre-specified design objectives. If production components solely collect and communicate data, they are characterized by a low level of intelligence. However, if they are capable of converting this data into useful information and use this information to fulfill a pre-specified purpose, they are characterized by a high level of intelligence. This translates into the phases as specified by Fig. 1. First, production components receive a cyber identify and the capabilities to be identifiable and communicate passively. Subsequently, the production components are increasingly interconnected with each other and within the information network, and they begin to exchange information and communicate and negotiate with each other [1]. To do so, they need processing power, which also increasingly allows them to process the data into information that they can share. In subsequent phases, production systems then move towards intelligent automation, in which active production components increasingly take autonomous actions without human intervention.

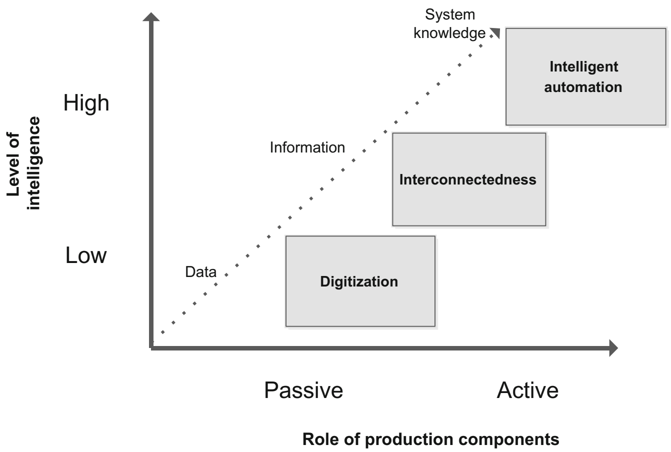

Fig. 1. CPS typology

Implications for job design: It is expected that the transformation towards a CPS does not only radically change existing manufacturing practices, but will change the design of jobs too, currently described in two diverging development. Based on the functionalities described, we expect that during digitization, the human worker will remain the key information processor and decision maker. Workers, especially supporting functions such as planning, control or maintenance workers will then be required to work with and process larger amounts of digital information, possibly resulting in higher cognitive demands and need for information processing. Simple, repetitive work related to the collection and administration of data will increasingly be automated, promoting a shift of the human workers towards tasks related to the control, coordination and improvement of production based on the improved information transparency. These changes will potentially mostly be felt by supporting functions. Also, certain aspects of jobs might be simplified or also enhanced, as new ways to interact and present information will increasingly augment the human in his work. At the same time, manual work might be simplified and constrained as detailed and standardized digital work instructions can be provided that allow little room for deviation and job autonomy. As production components move from passive to active actors and are becoming more intelligent, these interconnected systems can increasingly aggregate and visualize information comprehensively so that it can provide tailored information that augments the human in the decision making process. For example, to provide information on certain possible product routings or alert him of changes. Finally, in the last stage of intelligent automation, the technology can increasingly be empowered to take over certain control and production management tasks, potentially eliminating or decreasing human tasks. In this case, human knowledge and skills might increasingly be substituted by intelligent control algorithms and computer programs. Based on these development perspectives, we expect that the total share of human work in industrial production will decrease due to the transformation towards a CPS. Moreover, the composition of human tasks in production will change due to the reduction of repetitive, manual and simple work, for example simple administrative tasks and the increase in cognitive, mental work posing increasing skill requirements. As such, this can lead to a growth of supporting work related to the control and improvement of processes and less manual work. Ultimately, the implications for the human worker depend on how the technology is designed and how work is organized around it. As such, management has significant over the technology selection, design and implementation process. The role of the human worker in CPS hence is not determined by the technology itself, but a variety of other factors.

4 Conclusion

Throughout the history of industrial production, two development perspectives on the implications of new technology for work have been discussed. The possibilities to up- and deskill employees are also central in the discussion on changes in work in the context of Industry 4.0. As such, the adoption of either perspective depends on a variety of factors, among which the technological functionalities that provide opportunities and constraints for the design of jobs. This paper aims to increase our understanding on these technical changes in the transformation towards a CPS that give rise to changes in the design of jobs, and we presented two key dimensions. These two dimension include the level of intelligence of production components and their active or passive role, respectively. In the long term, the transformation towards a CPS will reduce human work in industrial production. Moreover, human work will focus on cognitive and mental tasks. Ultimately, this impact will not solely be determined by the technology itself. Management often has significant discretion on how new technologies are configured and the way that work is organized around it.

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Jobs and Skills in Industry 4.0: An Exploratory Research

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Abstract. Industry 4.0 is at the center of the current debate among manufacturing leaders, industrial practitioners, policy makers and researchers. Despite the increasing attention paid to changes in jobs and skills generated by Industry 4.0, research in this domain is still scarce. Our study focuses on the evolution of technical skills in the context of Industry 4.0 and it provides qualitative insights gained from an on-going collaborative research project involving a variety of manufacturing stakeholders in Northern Italy (e.g., manufacturing companies, industrial associations, academic and education experts, recruiting companies, IT providers, consultants, etc.). Our findings contributes to shed light on manufacturing skill needs linked to Industry 4.0, setting the stage for future research on the topic and providing companies, policy makers and education stakeholders with first indications to detect skill gaps and initiate competence development.

Keywords: Industry 4.0 · Jobs · Skills · Competence

1 Introduction

The evolution of jobs and skills for the successful implementation of Industry 4.0 is of significant contemporary interest and importance to both researchers [1], policy makers [2] and practicing managers [3].

The introduction of the latest automation and digital technologies in manufacturing - such as Cyber-Physical Systems, the Internet of Things, cloud computing and Big Data - is envisaged to significantly affect work processes and the work environment [4]. Employee jobs are expected to change in terms of content and new types of job are also being created. As a consequence, novel skill requirements are foreseen [2, 5].

Notwithstanding the increasing attention paid to the topic, research on the changes in the jobs and skills required by Industry 4.0 is still emerging. So far, research (e.g., [1, 6]) were mostly theoretical and provided a generic overview on Industry 4.0-related competencies, without articulating them according the specificities of the different organizational areas where technologies are being introduced.

Consequently, significant gaps remain on how job profiles will evolve and what types of skills will be relevant and in demand in Industry 4.0 [7].

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In this paper, we aim at contributing to fill the above-mentioned gaps by providing a fine-grained set of technical skills related to 5 organizational areas affected by Industry 4.0 – i.e. operations management, supply chain management, product-service innovation management, data science management and IT-OT integration management.

We focus on technical skills as they are crucial to the understanding of and participation in the new Industry 4.0 workplaces.

In doing so, we make two main contributions to our knowledge. First, our study advance current research shedding further light on technical skills for Industry 4.0. Second, our study goes beyond previous research, since it combines findings from the literature with the expert knowledge of different manufacturing stakeholders.

Our results also contributes to practice by providing business, government and education with new relevant insights for the identification of re-skilling, up-skilling needs and the development of the future industrial human capital.

The rest of the paper is structured as follows. In the next section, we provide an overview of extant models and research on skills for Industry 4.0. Subsequently, we describe the methodology adopted. We then present the set of technical skills coming from our exploratory research. Finally, we outline our contributions, the limitations of our study and propose some suggestions for future research.

2 Related Work

Competency models refer to collections of knowledge, skills, abilities, and other characteristics that are needed for effective performance in the jobs, job families or functional areas [8, 9]. During last years, several works were carried out in order to define competency models for manufacturing, ICT and Industry 4.0. The most significant ones for the scope of our study are summarised in the followings.

The U.S. Employment and Training Administration (ETA) developed a competency model framework depicted in a pyramid graphic with nine tiers. Each tier is comprised of blocks representing the skills, knowledge, and abilities essential for successful performance. The general framework was then tailored – among others - to the U.S. Advanced Manufacturing, Automation, Aerospace and Mechatronics industries [10]. Linked to the ETA framework is the O*NET program, which provides a description of the mix of knowledge, skills, and abilities, as well as the tasks, tools and technologies required by different occupations in the U.S. [11].

With regard to ICT-related competences, the European "e-Competence Framework" provides 40 competences, including skills and knowledge requirements, which can be used across Europe [12]. Similarly, the EDISON project is working on the development of a "Data Science Competences Framework" that includes: competence groups, big data and analytics tools and programming languages [13].

It is worth noting that the above-mentioned frameworks were not developed with a specific focus on Industry 4.0 but they represent a useful starting point for the identification of relevant skills and the analysis of their evolution in Industry 4.0.

Regarding Industry 4.0, [1] proposed a skillset for the production worker of the future. The identified competences were clustered into two categories: technical and personal qualifications and skills. Among the technical ones, IT knowledge and abilities, organizational and processual understanding, ability to interact with modern interfaces (human-machine /human-robot) were identified as a "must have" in the future Industry 4.0 scenario. Additionally, [6] presented the development of a generic competence model for Industry 4.0, including technical, methodological, social and personal competencies. The technical skills reported in the study are: state-of-the-art knowledge, technical skills, process understanding, media skills, coding skills, understanding IT security.

Despite the important insights generated by the two papers, they addressed skills in a generic way, without articulating and differentiating them for different organizational areas or job families.

3 Method

The study used a three-steps process based on: literature review, focus groups and in-depth interviews. First, the literature review aimed at identifying existing organiza-tional areas of advanced manufacturing and the technical skills related to each of them. Then, technical skills classifications for the manufacturing field were analyzed. Different sources were used, namely scientific papers as well as reports and classifications provided by national and international bodies (e.g. the O*NET-SOC 2010 Taxonomy [9] sponsored by the US Department of Labor/Employment and Training Administration and the European e-Competence Framework [10] sponsored by the European Commission).

The organizational areas and technical skills identified through the literature review were, then, used as an input for two subsequent focus groups [12]. The two focus groups aimed at refining and further specifying the initial list of skills by collecting new insights and ideas from recognized manufacturing experts. In particular, the first focus group involved 20 participants, with representatives from Industry 4.0-related technology providers, academia, research centers and national institutions, while the second one, involving 50 participants, specifically addressed manufacturing companies moving to Industry 4.0. All the stakeholders involved were from Northern Italy. During the focus groups, all participants' ideas were first collected on post-its and posters, and then categorized by means of an Affinity Diagramming approach [14]. The focus group discussions were managed by the authors of the paper by following the principles identified by Axelrod [15].

Finally, based on the results of the two focus groups, in-depth interviews with further relevant stakeholders from both technology providers and manufacturing companies were carried out to check and refine the technical skills in each of the five organizational areas. The results obtained after the interviews are reported in the following paragraph.

4 Results

The following sub-sections summarize the final sets of technical skills for Industry 4.0 in each of the 5 organizational areas under investigation: 1) Operations Management,

2) Supply Chain Management, 3) Product-Service Innovation Management, 4) Data Science Management, 5) IT-OT Integration Management.

4.1 Operations Management

- Defining a roadmap to the adoption of Industry 4.0 technologies aiming to continuous improvement;
- Analysis, modelling and simulation of production based on big data from sensors and devices;
- Use of digital devices (e.g. tablets, smartphones, smartwatches) for production monitoring and control;
- Programming and use of collaborative robots;
- Use of additive manufacturing technologies;
- Management of human resources, interconnected through digital devices;
- Design of predictive maintenance systems (sensors, data flows and analytics);
- Remote system monitoring and supervision of maintenance interventions;
- Use of virtual and augmented reality for instruction and support of maintenance interventions on-field;
- Defining systems for monitoring maintenance services to support the definition (e.g. service level agreements) and management of maintenance service contracts, by using big data from the sensors.

4.2 Supply Chain Management

- Design and building Digital Supply Networks;
- Management of Concurrent Digital Supply Networks;
- Use virtual design for business process;
- Analysis of big data (e.g. sentiment analysis) to predict market behaviour and other phenomena impacting the supply chain;
- Development of IT strategies to support Supply chain Management (e.g. collaboration platforms on the cloud and Internet of Things);
- Real time management leveraging monitoring and tracking technologies;

4.3 Product-Service Innovation Management

- Research, analysis and use of innovative materials (e.g., shape-memory materials, composites) and/or production processes (e.g., additive manufacturing);
- Design of smart products (integration of sensors, antennas, chips and other components);
- Design of the service model (functionalities, interactions) based on the product-service platform;
- Joint design of product and service, integration with the enterprise IT systems.

4.4 Data Science Management

- Design and implementation of Big Data architectures and software platforms (e.g. e Hadoop o Data Lake);
- Design of data and workflow models;
- Big Data management, use of cloud computing and data storage;
- Development of applications and tools for Big Data analytics (e.g. R, Python);
- Big Data analytics (e.g. machine learning, Bayesian classifiers, deep learning);
- Info-graphics for intuitive and engaging interpretation of data analytics (e.g. maps, charts, diagrams);
- User experience design.

4.5 IT-OT Integration Management

- Development of a strategic roadmap for the integration of information technologies (IT) and operations technologies of industrial automation (OT), in alignment with business needs;
- Implementation of IT architectures, platforms and components oriented towards Industry 4.0;
- Selection, specification and integration of embedded devices, cyber-physical systems and advanced Human-Computer-Interfaces (e.g. interface for mobile applications, Virtual and Augmented Reality)
- Implementation of IT networks enabling real-time connection of robot, machines, products and people;
- Selection and application of data communication protocols (IIoT, cloud, cybersecurity, Big Data) and Industry 4.0-related standards;
- Use of modelling tools to generate digital twins of manufacturing systems and simulate"what if scenarios";
- Use of graphic modelling tools to specify, analyse, design and verification of complex systems, including hardware and software components;
- Design of structured strategies for and management of cybersecurity, data privacy and safety.

5 Discussion and Conclusions

Even though manufacturing is rapidly moving towards Industry 4.0, there is still a lack of knowledge about the consequent evolution of job profiles and skills, and how manufacturing companies should deal with the skills gap that is being created.

For this reason, the current paper presented the results of one of the first exploratory studies aimed at outlining the new set of Industry 4.0 skills required for the successful implementation of the approach. In particular, the work aimed at reaching a twofold objective. On one hand, the identification of the latest needs of manufacturing in terms of Industry 4.0 skills. On the other hand, an attempt to anticipate the needs of companies in the near future. Therefore, the results obtained can constitute a sound basis for a wide range of different actions, e.g. recruitment and training of workers, organizational design, business process improvement.

Three main limitations can be identified for the current study. First, the research was based on a qualitative methodology, which allowed to develop a structured list of technical skills for Industry 4.0. To strengthen the proposed model, a survey should be used in order to further validate the list by means of a quantitative approach. In addition, the survey will be able to provide further information about the maturity level of companies in terms of skill levels for Industry 4.0, and about the potential differences between small, medium and large enterprises. Second, given its exploratory nature, the study was based on the contributions of Northern Italy representatives. The findings should be expanded through the access to a wider European audience, in order to identify the possible cultural, systemic and industrial divergences in the perception and solution of the Industry 4.0 skills issue. Finally, the present study is focused on skills, while future research could expand the scope of the analysis by investigating knowledge, abilities and attitudes in order to create a thorough Industry 4.0 competency model.

In conclusion, despite the limitations this study has, it advances both research and practice by providing a fine-grained set of Industry 4.0-related technical skills for 5 organizational areas.

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Skills and Education for Additive Manufacturing: A Review of Emerging Issues

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Abstract. The recent advances in digital technologies and in additive manufacturing (AM) in particular are revolutionising our industrial landscape. These changes require new engineering and management skills to exploit fully and sustainably the benefits offered by these advanced technologies. The current talent shortage calls for new education programmes to deliver a skilled, capable and adaptable workforce. Existing courses on design, engineering and management related to production and manufacturing do not systematically deliver the necessary skills and knowledge for an effective deployment of AM technologies. Based on a literature review and evidence collected from multi-stakeholder workshops, this paper presents the key themes for education programmes to address the current skill gap and barriers to AM adoption and exploitation.

Keywords: Additive manufacturing · 3D printing · Education · Skills

1 Introduction

1.1 Background

Additive Manufacturing (AM), also commonly referred to as 3D printing, was first developed in the 1980s [1, 2]. Early AM technologies were mainly used for rapid prototyping and tooling [1]. Recent advances in AM have enabled its use for direct manufacture of components and end-products for a broad range of applications.

AM builds artefacts from CAD models by adding material layer by layer [3], as opposed to conventional machining techniques which are 'subtractive' as they cut material away to obtain the shape desired. The direct use of digital files for manufacturing simplifies the process from design to production, enables the potential for mass customization and can significantly reduce lead times [4, 5]. This 'digitalisation' trend in the manufacturing industry is a game changer as (i) current limitations are progressively being removed (e.g. design constraints, centralised manufacturing to achieve economies of scale) and (ii) new limitations emerge (e.g. resource scarcity, cap on waste and emissions).

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A new mindset is required for product and process design, manufacturing system configurations and business models more broadly. These new rules of how, where and when products are manufactured, distributed and used are still evolving. Accordingly, education programmes need to be adapted [6] and shift towards systems-oriented solutions integrating science, engineering and management principles [7].

1.2 Current Additive Manufacturing Applications

The growth of AM utilisation has impacted all sectors of the economy:

Primary sector – raw and intermediate materials for AM. Currently, there are limited options for standard AM materials. In metal powder manufacturing, the powders used for AM are the same standard powders as for other manufacturing techniques such as powder forging, spray deposition, metal injection moulding or hot isostatic pressing. Although it is difficult to tailor materials for AM [8], it is possible and in fact required for some high-value AM produced parts. In addition, powder reclamation for reuse and recycling is a growing sector with particular promises in contributing to a more efficient use of material at systems level.

Secondary sector – additively manufactured products. The most direct impact of AM adoption is on the manufacturing sector, and especially for:

Aerospace. AM is particularly appropriate in aerospace applications as parts are complex, need to be lightweight, high performance, produced in relatively small quantities, and made from advanced, expensive materials. New applications and level of performance present challenges for current (and future) designers and engineers, e.g. new design rules, new materials, new technology, etc.

Automotive. The automotive industry has used AM technologies since the late 80s for rapid prototyping, tooling and custom parts in small production volumes [1], with a recent focus on lightweight materials to improve vehicle fuel efficiency [9].

Medical. AM has been widely used for hearing aids, dental implants and prosthetics. Further applications include with bio-printing to additively manufacture skin tissue and human organs [9]. In the pharmaceutical industry, the technology shows potential to produce custom-made pills to adapt to the patient specific needs, simplifying medication, improving compliance to prescription and reducing risk of medication errors.

Tertiary and quaternary sector – services for AM or services using AM. The service sector has also been impacted by the adoption of AM. Example of AM services include AM machinery sales, leasing, maintenance, upgrade and training; design, manufacturing and delivery as services [4]; development of design libraries providing CAD templates, customized designs; certification, etc.

2 Research Method

This research addresses the general need to explore how to make the best out of AM technologies, while avoiding lock-in or unsustainable and irresponsible use of the technology. The work was carried out as part of the 'Bit by Bit' project[1] and the activities leading to the development of the UK National Strategy for AM[2]. As part of the AM national strategy process, the main evidence was collected over the period March-October 2015 [10] with additional data gathered during a series of working group sessions in the period November 2015-December 2016, supplemented by desk-based research drawing on secondary sources. The data revealed seven key themes (barriers and opportunities) for AM adoption from a UK perspective [11]. The seven themes identified are highly interconnected and overlap, with a repeated emphasis on the need for skills, education and professional training across almost all the other themes. Thus the skills and education theme was identified as a core issue for the development of the national strategy. Prior to the finalisation of the UK National Strategy itself, an event on 'Identifying and Developing Additive Manufacturing Skills for UK Industry' was held in March 2017 to specifically focus on skills and education, drawing together 80 representatives of a wide range of AM relevant stakeholder organisations.

The next section presents the education and training issues identified to enable the effective deployment of AM technologies in the short to long-term. It does so in three steps: (1) first the barriers and industry needs (skills) for AM were reviewed from the literature and the industry data available, (2) then a review of existing AM courses was conducted, (3) finally, a gap analysis was performed to highlight the key topics that need to be integrated into new education and training programmes.

3 Results

3.1 Review of Skills and Industry Needs for AM

There is a growing body of literature reviewing the barriers and enablers for AM adoption and exploitation [e.g. 8–17]. Some of the work particularly focuses on skills [6, 12–16]. In addition, a synthesis of the findings from various workshops and surveys [6, 10, 11] is included to provide a broader view of the issues from industry, government and academic perspectives. A summary of current industry needs is provided in Table 1. It is important to note that the themes often overlap.

[1] '*Bit by Bit: Capturing the Value from the Digital Fabrication Revolution*', UK Engineering and Physical Sciences Research Council (EPSRC) award number EP/K039598/1.

[2] http://www.amnationalstrategy.uk/.

Table 1. Themes and perceived barriers to the adoption and exploitation of AM.

Issues/themes	Summary of industry needs and common perceived barriers
Design & modelling software	Need for design guidelines, modelling software, 3D scanning, education programmes on design for AM, better understanding of new freedoms and constraints, new focus on functionality, availability of AM-skilled designers, security of design data
Materials, processes & machines	Understanding properties of different processes, machines, applications, size, costs, availability (e.g. intellectual property (IP), independent suppliers). Use of mixed materials with implications for recyclability and biocompatibility. AM-skilled operators, and importance of post-processing
Skills & education	Lack of appropriate skills preventing adoption, up-skilling current workforce vs. training next generation. Public awareness and education. 3DP in schools, "teaching the teacher". Balance the provision of generalist and specialist skills through "mix-and-match" modular programmes. Industry mentoring schemes, more hands-on teaching methods. Access to open-source learning material
Quality, standards & testing	Metrology, in-process inspection and controls. Need for data libraries (designs). Lack of standards for processes, materials, software, products, tests, etc. General vs. sector-specific standards. Tests for higher volumes, non-destructive testing. Quality assurance, certification and liability
Partnerships & networks	Regional and national hubs or platforms, collaborative and community-oriented networks (such as maker spaces) to raise awareness and provide alternative educational pathways to learn about AM. Ensure that knowledge and emerging industry needs are captured to teach industry-relevant and up-to-date topics
Creativity & innovation	Cross-functional teamwork, ideation techniques and new teaching methods to foster creativity. Use of 3DP in schools to engage and inspire the next generation of students
Energy & sustainability	Increase the use of AM for green solutions, i.e. renewable and clean energy such as AM-based materials and components to enhance fuel cell performance. Need to reduce dependency on fossil resources and the environmental burden of human activities. Need for life-cycle considerations to assess social and environmental impact
Cost & financing	Realistic estimate of costs compared to scale of opportunity to allow for viable business cases. Funding to increase awareness and reduce risk of adoption (e.g. scale-up, machine purchase) especially for SMEs Understanding of full costs, including materials, post-processing and testing
IP & security	Balance need for openness to share knowledge with need for commercial protection to capture value from investments, enforcement of IP rights. Current security, IP and legal systems not appropriate for digital networks. Global IP leakage. Cyber security concerns preventing rapid AM adoption

3.2 Review of Education and Training Programmes

A non-exhaustive, exploratory review of existing education programmes – both Continuous Professional Development (CPD) and Higher Education (HE) – was conducted. A total of 45 sources were identified. These include university undergraduate and post-graduate courses, from full programmes to short modules, professional training courses, massive open online courses and downloadable packages. They allowed the key topics being taught in existing programmes to be identified. Table 2 lists these topics along with a description of typical course content and activities.

Table 2. Topics and activities in current AM education and training programmes.

Topic	Description of typical courses and activities
AM fundamentals	Lectures about advances in AM and production engineering. Learning about a range of technologies, compatibilities between AM and traditional techniques (pros & cons)
AM industry applications	Case studies on current industrial applications. Examples of best practices. Prototyping, tooling, direct manufacturing, mass customization
Advanced process engineering	Physical sciences, applied mathematical, advanced engineering design, material science. Hands-on experience with a variety of AM equipment. More in-depth understanding of material characteristics, process parameters, and machine designs. Advanced controls and parts testing. Process optimization. Experiments to explore technology limitations
Design and modelling	Reverse engineering and 3D laser scanning for direct digital fabrication purposes. Hands-on labs to design parts on CAD. Design for manufacture, material-specific design principles and qualification approaches. Design software options for designers. Ergonomics in design
Production economics & business management	Method to improve productivity and reduce manufacturing costs. Ensure products and services delivered to industry at the quality and time required. Inventory management
Management and communication	Teamwork, problem-solving skills, critical and analytical skills, communication and management skills
Research & development	Lab-based R&D in measurement methods, models, instrumentation, sensors and data. Improve scientific understanding of AM. Advances in process controls, equipment and material properties. Industry-focused research project with novel processes, materials and simulation

3.3 Summary of Skills for AM and Suggestions for Education Programmes

The list of topics taught in programmes available (Sect. 3.2) was compared to needs collected from the literature and industry (Sect. 3.1) to identify the gaps in current programmes available. The first observation was that there is still a relatively low number of AM programmes available. It shows that (1) AM is not systematically taught in design and engineering curricula within universities, and (2) few institutions are proposing specialised courses for AM. The second observation was that, while most courses focused on technical aspect, some topics around softer issues are poorly covered (if at all); e.g. IP, liability, quality assurance, sustainability and business models specially as they relate to AM.

In summary, the following recommendations are made to enhance the AM skills for designers, engineers and managers:

- Recognise AM as a family of technologies. Appreciate the value of AM as tool for manufacturing along more traditional techniques, and as an enabler of innovation (see design considerations below).
  - Know when to use AM (and when not) by considering other manufacturing techniques and their respective strengths and limitations. AM may not be the best solution: other traditional or mixed/hybrid methods could work better, be cheaper, more efficient, result in better quality products, etc.
  - Need to understand the appropriateness of various manufacturing techniques for different materials and applications.
  - Need for new process controls and quality assurance methods.
- Effectively design products for AM by shifting focus and using new tools.
  - New levels of performance achieved through AM with innovative solutions based on new design thinking (focus on functionality, performance, quality).
  - Designing for AM requires new design approaches and modelling software, e.g. 3D scanning, new design freedoms and structures.
  - New design guidelines should include considerations for emerging constraints, e.g. limited availability of AM materials, resource scarcity for rare metals, design for modularity, upgradability, disassembly, recycling, etc. (principles of design for the environment).
- Understand AM processes and materials and their broader implications on the value chain and business model.
  - Economics of AM go beyond basic machine and material cost.
  - Need for basic understanding of legal (e.g. IP, cyber security) and liability issues (e.g. quality assurance and insurance) surrounding AM utilisation.
  - Need for more responsible models of production and consumption (sustainable products and services) through innovative business models.
  - Need to consider the full impacts of AM from a life cycle perspective. It is currently challenging to assess the sustainability of AM technology due to the lack of tools and methods to do so.
- Acknowledge that AM technology is evolving quickly so the limitations we see today may very well be removed the next year.
  - AM creates new opportunities, new business models, new jobs, etc.
  - Need to prepare current and next generation to respond effectively and keep an open-mind as the rate of technological change is accelerating.
  - Need to quickly adapt and update programmes to technology progress.
  - Need to “teach the teachers” to avoid spreading misunderstanding and misperception of AM technologies and capabilities.

- Balance the provision of generalist skills and knowledge as well as more advanced courses for specialists.
  - Promote distributed and modular models for all educational levels.
  - Need for open-access, free, online resources.
  - Need for regional and national platforms and community-oriented networks (such as maker spaces) to raise awareness and provide alternative educational pathways to learn about AM.
- Prepare students for jobs in industry and support incumbent workers by ensuring that AM courses and programmes are up-to-date and easy access.
  - Raise awareness among the public and provide easy access to training programs for workers and students by establishing collaborative and community-oriented networks for AM awareness and education (i.e. above-mentioned alternative ways to learn about AM).
  - Support educational programs in STEAM (STEM + arts) and across a wide range of learning environments to provide industry-relevant knowledge and experience, e.g. tutoring, industry-based projects, lab-based activities.
  - Need for new partnerships and innovation centres bringing industry and academic institutions to keep education and research relevant and closely linked to industry needs.

4 Conclusions

Research is still on-going to better understand the business opportunities created by AM as well as barriers to realise the full benefits of AM. The challenges encountered by industry in effectively using the technology are not fully understood. This paper attempts to capture the current state of these industry challenges and barriers to AM adoption which should be addressed by education programmes. Industry needs and challenges were categorised and linked to specific sets of skills for AM. We then reviewed existing education programmes and compared their content to the industry needs to characterise the skills gap for AM adoption and exploitation. Finally, we made some initial recommendations for developing new education and training programmes to support the provision of AM-skilled designers, engineers and managers.

The review of education programmes revealed that there are some courses available providing AM content covering a broad range of issues as identified in the review of industry needs. However the number of programmes available is low compared to today's high demand for AM skills. In addition, there are increasing concerns about the content of these courses: Do they provide the necessary skills and knowledge to realise the full potential of the technology? There is an urgent need to develop university and other training programmes to increase awareness and educate the next generation of workers and students in productive utilisation of AM technologies and generate some societal "pull" for AM technologies [17].

Some of the most commonly mentioned barriers are lack of AM-specific design skills, limited working materials, uncertainties in part qualification, lack of metrology and production standards. Besides these technical barriers to AM adoption reported mainly in the literature, there is a clear need to better educate future engineers as unfamiliarity with AM technologies is recognised as a major barrier for industrial adoption. Finally, some of the issues poorly covered as highlighted in bold in Fig. 1. Further work is still needed to consolidate the findings and recommendations made in this paper.

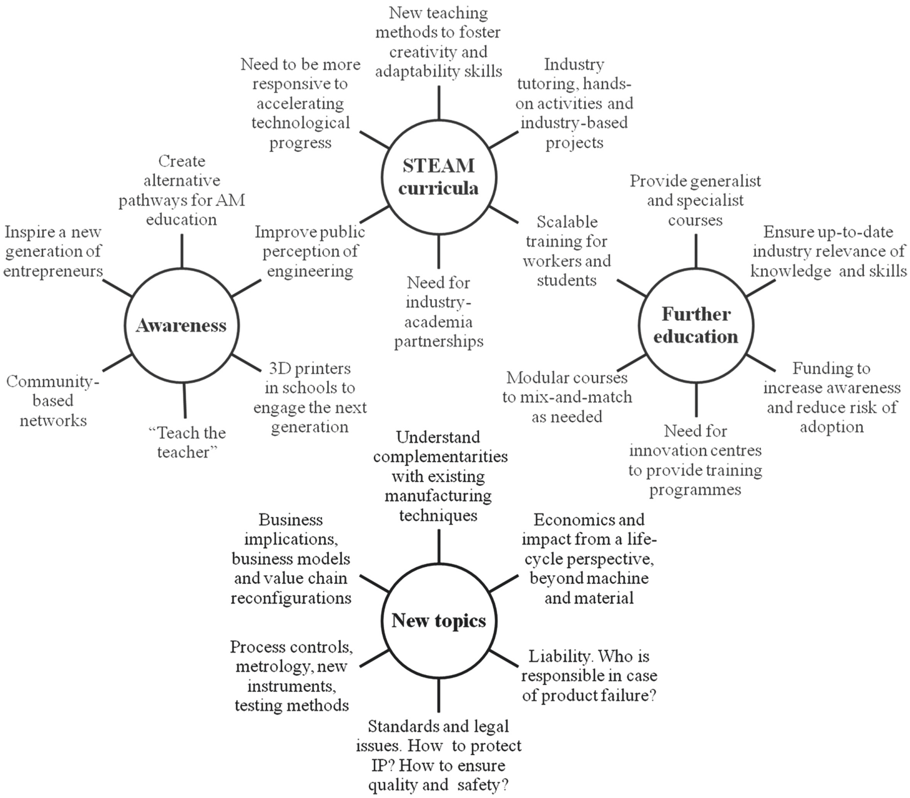

Fig. 1. Mindmap of recommendations for AM education and training.

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The Effect of Industry 4.0 Concepts and E-learning on Manufacturing Firm Performance: Evidence from Transitional Economy

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Abstract. With the application of smart technology concepts, the fourth stage of industrialization, referred to as Industry 4.0, is believed to be approaching. This paper analyzes the extent to which smart factory concepts and e-learning have already deeply affected manufacturing industries in terms of performances in transitional economy. Empirical results indicate that manufacturing companies that have introduce both e-learning and selected smart factory technology concepts differ significantly. E-learning is mainly applied on graduates in production. Results reveal that two smart factory concepts are significantly and positively related to the firm performance when e-learning is applied.

Keywords: Industry 4.0 · E-learning · Smart factory · European Manufacturing Survey

1 Introduction

Industry 4.0, a new fundamental paradigm shift in industrial production [1] is a result of the basis of an advanced digitalization within factories, the combination of Internet technologies and future-oriented technologies in the field of “smart” objects (machines and products) [2]. “Industry 4.0 represents a smart manufacturing networking concept where machines and products interact with each other without human control” [3]. This concept does not consider less employees in production, the contrary, human resources are acknowledged as the most flexible parts in the production system being maximally adaptive to the more and more challenging work environment [4].

The success of manufacturing enterprises depends on their capability to quickly adapt in more and more complex environments [4]. The implementation of adequate qualification measures is required comprising both the organizational and technological concepts [4] in order to enable the employees at all levels (i.e. unskilled, technicians, graduates) to fulfil their tasks efficiently. The company will succeed only if the rate of acquisition of knowledge is greater than the rate of change of environment and

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discontinuous, unforeseen impacts [5]. The purpose of this paper is to analyze and understand the extent to which smart factory concepts and computer-aided technologies for training purposes have already deeply affected manufacturing industries in terms of performances in transitional economy.

2 Background and Related Work

2.1 Industry 4.0

The term Industry 4.0 was firstly introduced in Germany at the Hanover Fair in 2011 [6]. This concept has emerged as a popular catchphrase in German industry to cover functional areas such as efficient, individual production at lot size 1 under the condition of highly flexible mass production by the emergence of cyber-physical systems and internet of things technologies in the production domain [4]. The similar terms were also introduced in other main industrial countries – "Industrial Internet" in the USA and "Internet +" in the PRC [7].

One of the fundamental concepts of Industry 4.0 is "smart factory" [2]. This concept assumes that all manufacturing is completely equipped with sensors, actors, and autonomous systems. Smart factory exists when manufacturing site is using "smart technology" related to holistically digitalized models of products and factories (digital factory) [8]. Work in progress products, components and production machines are collecting and sharing data in real time [9]. This type of a factory is autonomously controlled and includes following technological concepts:

- Software for production planning and scheduling (e.g. ERP) [10],
- Systems for automation and management of internal logistics (e.g. RFID) [2],
- New systems in the development of products and services [8],
- Product-Lifecycle-Management-Systems (PLM) [11],
- Mobile/wireless devices for programming and operation of equipment and machinery [1],
- Digital solutions in production (e.g. tablets, smartphones) [1].

With the use of technological concepts, companies are reaching higher targets. Russmann et al. [12] found that smart factory Industry 4.0 concepts will make production systems as much as 30 percent faster and 25 percent more efficient. Manufacturing companies that have introduced and fully utilized smart factory technologies are continuously upgrading their performance [13]. 82 percent of organizations that claim to have implemented smart manufacturing say that they have experienced increased efficiency, 49 percent experienced fewer product defects and 45 percent experienced increased customer satisfaction [9].

2.2 Computer-Aided Technologies for Training Purposes

With the implementation and usage of smart factory concepts the manufacturing site is facing with new boundary conditions. Workers are facing on the shop floor increased product complexity, shortened product development cycles and quickly changing production processes [4]. To achieve consistent high performance, company needs to have skilled workforce in production adaptable to innovative environments. To bypass the limitations of traditional training, computer-aided technologies for training purposes need to be developed and deployed in the existing IT and organizational infrastructures of the manufacturers. Hence, automated learning systems are vital to smart factory [6]. In this context, computer-based training is a solution.

With the popularization of e-learning systems, many companies have developed computer-based training programs for their employees [14]. The use of technology allows some advantages over traditional learning methods [4]. Firstly, worker in production can independently read material posted on the computer and then test the acquired knowledge [14]. Secondly, during the learning process, worker can interact with other participants, such as the instructor or other employees [15]. Thirdly, employees have greater control over learning, which makes learning self-paced. Compared to the traditional learning process, where workers usually learn in a group by sitting in the same room with the instructor or other employees, the e-learning process is usually designed for studying by sitting in front of the computer and the workers are given control over learning elements [16]. Finally, e-learning in the workplace is cost efficient [17]. Costs can be reduced if the training is targeted to manufacturing goals that can effectively provide employees with the kind of training that will increase their knowledge and skills to enable the employees in production (i.e. unskilled, semiskilled, technicians, graduates) to fulfil their tasks efficiently [18].

2.3 Research Questions

Based on literature review, the following research questions were proposed in attempt to identify the effect of smart factory industry 4.0 concepts and e-learning on performance of manufacturing products:

- *RQ1: Since Republic of Serbia is considered as developing economy* [19]*, the question is whether companies from manufacturing sector that utilize some of the technology concepts related to Industry 4.0 are deploying e-learning?*
- *RQ2: If yes, for which employees in production those companies use e-learning (semiskilled/unskilled, technicians, graduates)?*
- *RQ3: How smart factory concepts, along with the use of computer-aided technologies for training purposes, are affecting organizational performances (e.g. time-to-market, product defects, revenue-per-employee)?*

3 Data and Methodology

Our analysis used the Serbian dataset from the European Manufacturing Survey [20], a survey on the manufacturing strategies, the application of innovative organizational and technological concepts in production, and questions of personnel deployment and qualifications in European manufacturing industry [21]. The written survey set has been carried out by the Fraunhofer Institute for Systems and Innovation Research (ISI) since 1995 [22]. The current Serbian dataset of 2015 includes 302 observations of Serbian firms of all manufacturing industries. The survey was conducted among manufacturing firms (NACE Rev 2 codes from 10 to 33) having at least 20 employees. About 41.4% of the firms in the sample are small firms between 20 and 49 employees, another 48.0% of the firms have between 50 and 249 employees, and 10.6% of the firms have more than 250 employees. The largest industry in the sample is the manufacture of food products (NACE 10; 18.2%), followed by manufacture of fabricated metal products, except machinery and equipment (NACE 25; 13.6%) and the manufacture of rubber and plastic products (NACE 22; 8.3%). To analyze the relationships between smart factory concepts, e-learning offerings, and organizational performances we employed a multivariate data analyzes.

4 Results and Discussion

Descriptive statistics for smart factory technological concepts use are shown in Table 1. Companies were asked which of the selected technological concepts related to smart factory Industry 4.0 were they using. Software for production planning and scheduling was considered as the most widespread "smart technology", as more than 33% of Serbian manufacturing companies used it. It is worth mentioning two more concepts, which are implemented in at least 20% of Serbian manufacturing companies namely the technology concept of near real-time production control system (27.2%) and digital exchange of product/process data (22.4%).

Table 1. Usage of Industry 4.0 technology concepts in Serbian manufacturing companies

Industry 4.0 technology concepts	Share (%)	Rank
Software for production planning and scheduling	33.8	1
Near real-time production control system	27.2	2
Digital exchange of product/process data	22.4	3
Systems for automation and management of internal logistics	19.5	4
Devices for programming and handling of machines	8.1	8
Product lifecycle management systems	9.2	7
Technologies for safe human-machine interaction	11.8	6
Digital visualization	13.3	5

The results for our research question 1, "*whether companies from manufacturing sector that utilize some of the technology concepts related to Industry 4.0 are deploying computer-aided technologies for training purposes (e-learning)?*" indicate that 48% of the manufacturers in Serbia with more than 20 employees, that have introduced at least one smart factory concept, have deployed IT-based self-learning programs (e-learning) for their employees in production. In addition, results show that manufacturing companies that have introduce both e-learning and selected smart factory technology concepts differ significantly. Results indicate that highest percent of companies from manufacturing sector that utilize the technology concept software for production planning and scheduling are deploying computer-aided technologies for training purposes (40.9%).

On the other hand, only 12 per cent of Serbian manufacturers declared that they used e-learning and utilized technologies for safe human-machine interaction. Table 2 depicts the data in detail.

Table 2. Share of e-learning related to Industry 4.0 technology concepts

Industry 4.0 technology concepts	e-learning (%)	
	Yes	No
Software for production planning and scheduling	40.9*	27.3*
Near real-time production control system	34.6*	20.3*
Digital exchange of product/process data	25.4	19.7
Systems for automation and management of internal logistics	22.6	16.7
Devices for programming and handling of machines	12.5*	3.9*
Product lifecycle management systems	12.8	5.9
Technologies for safe human-machine interaction	12.0	11.7
Digital visualization	18.9*	7.9*

*Note: * statistical significance Chi-Square test, at < .05*

The results for our research question 1, "*whether companies from manufacturing sector that utilize some of the technology concepts related to Industry 4.0 are deploying computer-aided technologies for training purposes (e-learning)?*" indicate that 48% of the manufacturers in Serbia with more than 20 employees, that have introduced at least one smart factory concept, have deployed IT-based self-learning programs (e-learning) for their employees in production. In addition, results show that manufacturing companies that have introduce both e-learning and selected smart factory technology concepts differ significantly. Results indicate that highest percent of companies from manufacturing sector that utilize the technology concept software for production planning and scheduling are deploying computer-aided technologies for training purposes (40.9%). On the other hand, only 12 per cent of Serbian manufacturers declared that they used e-learning and utilized technologies for safe human-machine interaction. Table 2 depicts the data in detail.

For which employees in production companies use e-learning (research question 2)? The results are presented in Table 3. These data indicate that manufacturing companies in Serbia that are deploying e-learning are applying it on all employees in production. We found that IT-based self-learning programs are mainly applied on graduates in production (77.3%). On the contrary, only 6% of manufacturers are using e-learning programs for their unskilled/semiskilled employees.

Table 3. Share of companies with deployment of e-learning and its application

	Eligible employees in production		
	Semiskilled/unskilled	Technicians	Graduates
Application of e-learning	6.0%	43.9%	77.3%

Figure 1 depicts the results for our research question 3, "How smart factory concepts, along with the use of computer-aided technologies for training purposes (e-learning), are affecting organizational performances" which we gained by analyzing EMS data.

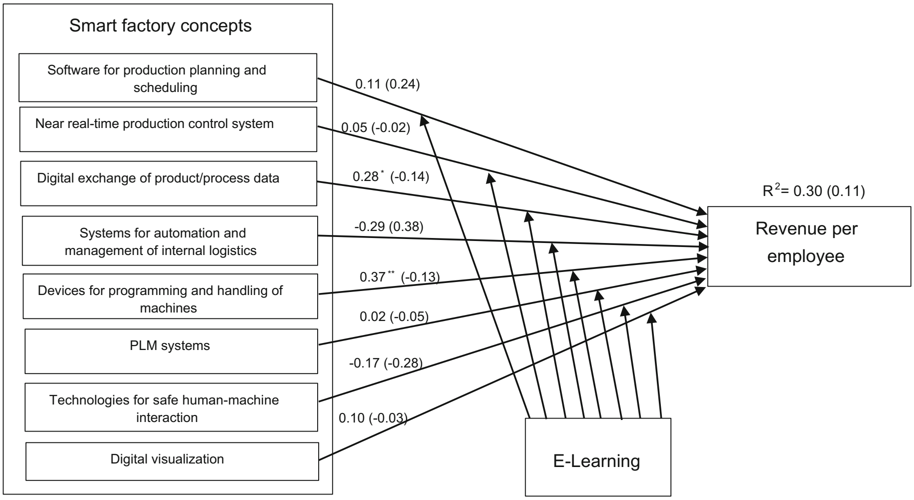

Fig. 1. Linear regression model. *Note.* Values w/e-learning (w/o e-learning); $^{*}p < .05$, $^{**}p < 0.01$.

To identify relevant smart factory concepts on different organizational performances (i.e. time-to-market, product defects, revenue-per-employee) we tested the two models (1) with the application of e-learning and (2) without application of e-learning. For organizational performances time-to-market and product defects no statistically significance of the model is found. In the model estimating the revenue-per-employee with moderating role of e-learning (without application of e-learning), none of the smart factory concept is significantly related to the probability to organizational performance indicator. The change of the variable e-learning to manufacturing companies that applied it, model shows the expected significant and positive impact, providing support to research question 3. The R^2 improves significantly from 0.11 (without application of e-learning) to 0.30 (with the application of e-learning). The results for the model with the application of e-learning within company show that two smart factory concepts (i.e. digital exchange of product/process data, devices for programming and handling of machines) are significantly and positively related to the revenue-per-employee. Once again, the change of e-learning significantly sharpens the differences between the models. This is in line with the previous research [9, 14, 15].

5 Conclusion

Using large-scale survey data, this paper provides a representative picture of smart factory concepts and e-learning in manufacturing industries and related causal relationships in transitional economy. To conclude, we found that 48% of the manufacturers in

Serbia with more than 20 employees, that have introduced at least one smart factory concept, have deployed e-learning for their employees in production. Furthermore, IT-based self-learning programs are mainly applied on graduates in production. Finally, manufacturing companies in Serbia that are utilizing industry 4.0 concepts and are deploying computer-aided technologies for training purposes are showing higher performances through revenue-per-employee.

This research has also practical and managerial implications. Our results show that the use of specific smart factory concepts, along with computer-aided technologies for training, clearly positively affects the ability to manufacture with higher performances (i.e. revenue-per-employee). This is a clear message to managers in developing countries that deployment of digital exchange of product/process data, and devices for programming and handling of machines along with the application of e-learning on technicians and graduates in manufacturing will produce greater results.

The sample was drawn from a single developing country, probably lacking the diversity that can be expected from a comparable sample chosen from across different economies, both developed and developing. Further research should test the model and relationships in the manufacturing companies within developed economies. Another limitation is within the industry specificities. We selected the manufacturing companies from different industries not taking into consideration the specificity of each sector. Thus, the primary focus in future research will be on the comparative analysis of the different manufacturing sectors. In our research, we did not examine the content of e-learning. Attention to various types of e-learning (e.g. video, audio, training simulations, interactive scenarios, gamification, virtual reality) should be paid in future studies to investigate the relationships more thoroughly.

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Towards a Semantically-Enriched Framework for Human Resource Management

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Abstract. Human resources are one of the most important assets of an organization. The setup of a proper Human Resource Management system undoubtedly represents one of the pillars upon which any organization should be built. Many effective standards and solutions have been proposed in the past decades. However, the ever changing environment and the emerging technologies, such as ontologies and linked data, lead to adapt them and consider new approaches. The solution proposed in this document aims to combine existing standards for manufacturing information and ontology modelling. As a result, the development of an ontology model enhancing the HR information flow with semantics, on the one hand, enables the use of common data formats and exchange protocols promoted by the world Wide Web Consortium (W3C) and exploitable on the Sematic Web. On the other hand, it lays the foundations for an automated decision making process based on inference rules and smart data management. A study has been performed in a real-life industry revealing highly notable results.

Keywords: Human resources · B2MML · Ontology · Semantic interoperability

1 Introduction

Today more than ever, companies are seriously considering to adopt strong and effective Human Resource Management (HRM) solutions in terms of HR analysis capabilities and smart information management. Factories are moving towards the future, but the HRM solutions need more effort to keep up. In a changing manufacturing and operating environment with human-machine interactions, using the possibilities offered by the Internet of Things and real-time or near real-time data, that result to big data, things are getting more and more complicated. More advanced HRM products, compared to more

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conventional ones, such as Customer Relationship Management (CRM) and Enterprise Resource Planning (ERP) systems, appear nowadays in the market. The big players, like SAP or IFS, offer solutions, along with medium range ones, such as JAMS, Automic, Street Smart, Smart Factory and more. This is a living proof of a concise need of the market. However, it should be noted that most of the products are oriented towards a specific niche market or they are focused on interconnections and integrations with specific Manufacturing Execution Systems (MES). Hence, there is a need for a data exchange model based on existing standards and emerging technologies that can translate business procedures and manufacturing operations to information that can be exploited for dynamic HRM solutions. In this work, elements from the Business To Manufacturing Markup Language schema (B2MML) have been translated into elements of an owl ontology to provide a framework aiming to enrich the semantics of the B2MML-based data flow, enabling knowledge sharing and semantic interoperability through the Semantic Web [1].

2 B2MML

HRM can be considered as one of the most complex tasks, especially in industrial environments, when dealing with resource management, due to the highly dynamic attributes that present themselves in real-time operation, such as machine failures, the advent of urgent jobs, etc. To facilitate the information exchange at environments that host a vast heterogeneous network of distributed information sources that constantly produce data in various formats and intervals, a Common Information Data Exchange Model (CIDEM) has been introduced [2], with one of the core components being the B2MML schema.

The B2MML, as published by the Manufacturing Enterprise Solutions Association (MESA [3]), is an open XML representation of the Enterprise-Control System Integration standard(s) (ANSI/ISA-95 [4]), and it is used to specify and constrain the content of the information flow between Enterprise and Control systems [5], and specifically describes XML schemas for four information categories: (a) Capability & Capacity Definition, (b) Product Definition, (c) Production Schedule, and (d) Production Performance, as well as four resource categories: (i) Personnel, (ii) Equipment, (iii) Material and Energy, and (iv) Process Segments.

As depicted in Fig. 1, the use of B2MML schemas can offer an open, interoperable, vendor independent and straight forward data exchange at production lines, optimally linking ERP and supply chain management systems with manufacturing systems such as Industrial Control Systems and MES. As such, and within the scope of the presented work, the B2MML schema was used as the foundation on which the information exchange was based upon; delivering a B2MML ontology that enables the formation of the semantically-enriched framework that enhances human resource management at production lines.

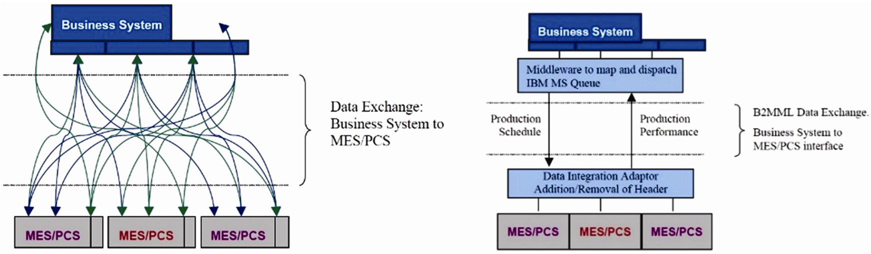

Fig. 1. Shop floor information exchange architecture before and after the deployment of the ISA-95 standard and B2MML schemas

3 Semantic Modelling

Industrial assets - in particular human resources - management is gaining from the use of semantic technologies and, in particular, knowledge base development [6–8]. Semantics structures, such as ontology models, provide a formal and ubiquitous information artefact aiming to make all the elements of a domain and their links explicit. Indeed, ontologies play an important role for many knowledge-intensive applications since they provide formal representations of domain knowledge, leveraging many of the properties discussed in [9].

According to the proposed approach, elements (e.g. classes and properties) from the B2MML xml schema have been, therefore, translated into elements of the B2MML owl ontology. Semantics is initially extracted from the B2MML xml schema and used as a basic taxonomy describing the former's classes. Relations among such classes have been defined in a way that each triplet appears as follows:

([DomainClassName]; has[RangeClassName]; [RangeName])

Three more (enumerated) classes have been, then, further characterized to meet the requirements specification set by the specific domain of analysis. In particular, *PriorityLevel {Non_Critical, Basic, Critical}, ActorGroup {MaintenanceSupervisor, Process, Operator, FloorManager, AutomationTechnician, ProcessSupervisor, ProcessTechnician, MaintenaceManager, ElectricalTechnician}, Experiencelevel {Experienced, Novice, Trainee}*. Eventually, a thorough analysis of the domain, in particular of the actor group mentioned above, allowed the extraction of 26 standard skills that can describe the requirements of each specific worker (actor) group. The results of this analysis were embedded in the ontology model. In fact, a further extension of basic semantic structure and subsequent alignment has been carried out by adding the enumerated class S*kill {Skill1, Skill2, …, Skill26}* (Fig. 2).

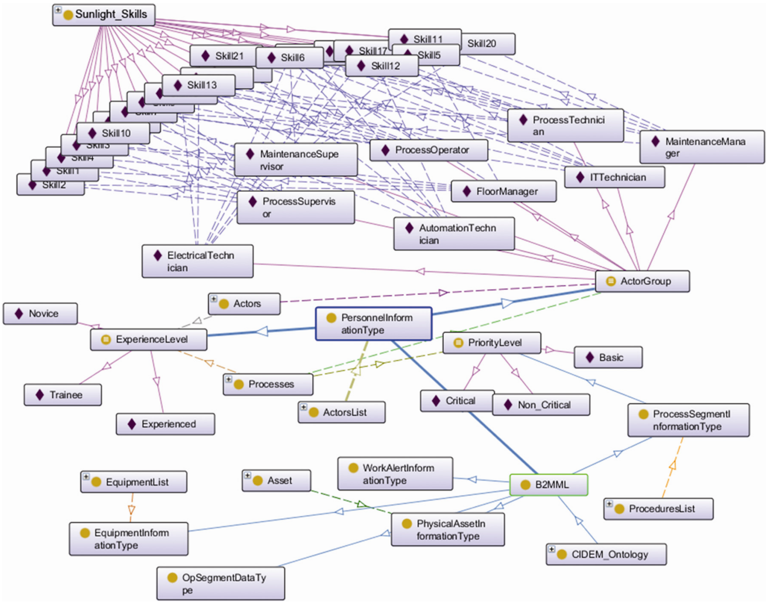

Fig. 2. Extension of the basic semantics with “skill” concept & instances

The semantically-enriched skills-based description of the worker groups enables the creation of inference rules to correlate worker skills to groups for each worker’s profile. Moreover, it provides an enriched structure that may continuously grow and discover new knowledge.

hasSkill some Skill and hasSkill only (Skill [1], …, Skill[n]) →
hasActorGroup (Actor, [ActorGroup])

4 Semantics-Based HR Information Management

In order to be able to utilise information stored in CIDEM, B2MML based static and dynamic data has to be transformed into RDF/XML (Resource Description Framework) [10] triplets by employing EXtensible Stylesheet Language Transformation (XSLT) as a means to map XML and OWL elements and execute the actual data transformation (Fig. 3), according to the W3C Recommendation for defining XML data transformation and presentation. The RDF standard was also developed by the W3C and helps to create metadata for describing web resources, enabling their sharing through the Semantic Web [11].

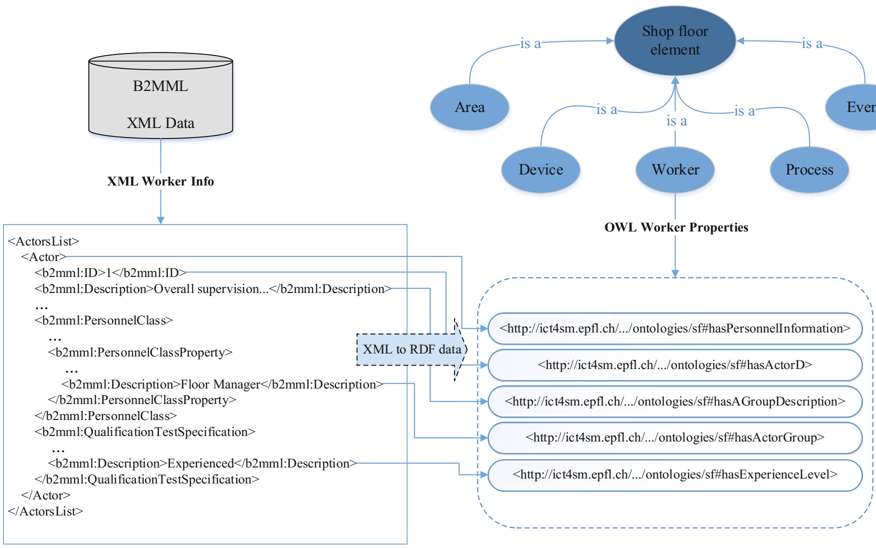

Fig. 3. From XML to RDF

SPARQL (SPARQL Protocol and RDF Query Language) [12] can be therefore exploited to express queries across the obtained RDF data sources, enabling a semantics-enhanced HR information browsing and knowledge management.

In particular, the efficient management of human resources and the optimization of the allocation of workers according to the needs of an organization are extremely important in fulfilling both the organization's objectives and the workers' feeling of satisfaction. The semantically-enriched information produced by the proposed framework can be exploited in different application scenarios. For instance, the suitability level of a worker to perform a specific task, which is described according to the model applied, can be evaluated using the semantic information. Assigning a task to the suitable worker according to his/her skills can result in the total task execution makespan. Furthermore, the availability of the automatically generated semantic information about HR and tasks paves the way towards automated or suggestions for actions regarding the assignments of tasks. This benefit can be important in highly dynamic environments, where for example, new maintenance operations can occur due to unexpected critical machine failures, and immediate response to handle the malfunction by the appropriate personnel is required. Another practical application of the produced semantically-enriched information is its presentation to the HR supervisor in a user-friendly human-readable format, in order to provide useful insights about the performance of workers, their skills, and their progress.

Regarding the utilisation of semantic information to perform automated actions, a decision-making engine could perform the following indicative operations:

a. Propose the most suitable worker to perform a new arriving task;
b. Use the semantic information as one of various parameters in order to make real-time intelligent decisions and schedule new tasks based on multiple criteria; and

c. Balance the workload among workers efficiently by taking into account their skills and the characteristics of the scheduled tasks.

5 Use Case

This approach has been applied to a real industrial shop floor environment at Systems Sunlight S.A. in the framework of the H2020 funded SatisFactory project. Sunlight is a global player in the field of integrated energy solutions, specializing in the development, production and marketing of batteries and energy storage systems for industrial, advanced technology and consumer applications. The challenge was to integrate data from multiple production cells and/or lines, to account for different types of actors and operators (also in terms of skills and organizational level), to consider different levels of expertise of employees, to combine information from the localization system of the employees in the shop floor and to integrate with the solution package suitable for the execution of a certain task. Here, the ontology framework is used to infer the time for each worker to perform a desired job. Based on the evaluation step, for all next steps the outcome is evaluated by the Decision Support System (DSS) through an HR optimisation process that leads to an improved workload balancing as can be seen in Fig. 4.

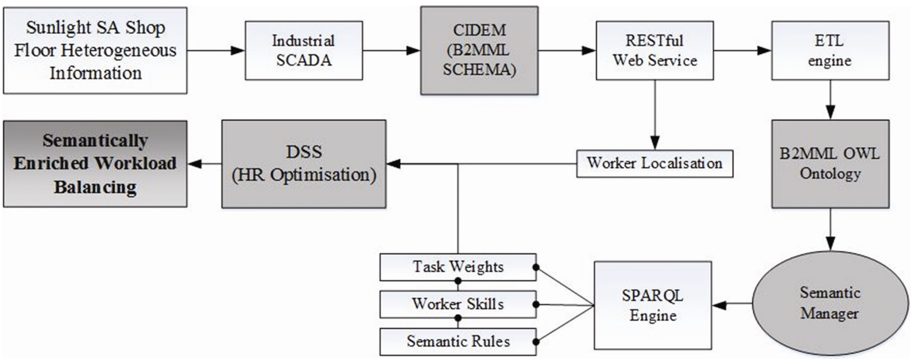

Fig. 4. Data exchange flow at sunlight SA shop floor

According to the given problem, the duration for each task may vary, depending on the type of tasks and the skills of the worker that is assigned to carry out that task. Therefore, semantic rules are used to infer the expected execution time for a certain task, taking into account both workers' skills and task's requirements. Eventually, the ontology framework produces a time estimation as shown in Fig. 5.

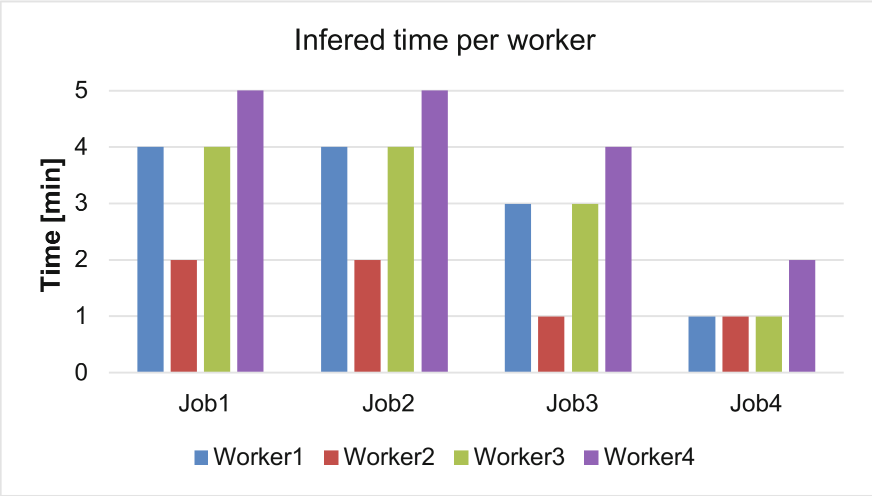

Fig. 5. Time estimation per worker

6 Conclusions

Elements of the B2MML schema have been translated into an approach of a vendor independent semantic model for efficient management of Human Resources and optimization of the assignment of tasks to workers according a set of parameters, including the needs of an organization. These semantically enhanced elements were used towards providing an improved balance in the workforce allocation at industrial shop floors. The concept has been successfully applied in the relevant of Systems Sunlight S.A., one of the global leaders in battery manufacturing company, which is located in Greece.

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An Ontology-Based Model for Training Evaluation and Skill Classification in an Industry 4.0 Environment

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Abstract. The recent advancements of manufacturing towards the Industry 4.0 paradigm should be supported by the effective training of industrial workers in order to align their skills to the new requirements of companies. Therefore, the evaluation of the training is becoming in this context increasingly important, given also the possibility of exploiting a huge amount of data from the shop floor about the workers' activities. These data – indeed – can be properly collected and analysed so as to provide real-time indications about the workers' performances and an evolving classification of their skills. In order to pursue this objective, a solution can be represented by the integration of semantic technologies with training evaluation models. For this reason, the paper aims at presenting a Training Data Evaluation Tool (TDET), which is based on the integration of a Training Evaluation Ontology (TEO) with a Training Analytics Model (TAM) for the definition of the skill levels of the workers. The main components and features of the TDET are provided in order to show its suitability towards the collection of data from the shop floor and their subsequent elaboration in summary indicators to be used by the management of the company. Finally, the implications and next steps of the research are discussed.

Keywords: Industry 4.0 · Ontologies · Training · Skill · Evaluation

1 Introduction

The introduction of the new Industry 4.0 paradigm has recently allowed the increasingly high dissemination of advanced technologies for the improvement of the industrial processes [1]. However, the technological advancements that are taking place should go hand in hand with a rapid effective training of the industrial workers so that this change can be supported by a proper alignment of the skills to the new needs of the companies [2]. In this context, the issue of the evaluation of the training provided to the workers is increasingly critical, since more and more complex data have to be collected and properly analyzed in order to define the skill level of the workers and introduce in case the necessary corrective actions [3]. For this reason, the identification and measurement of data directly from the shop floor becomes extremely important. In fact, this data can

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provide real-time indications about the workers' performances following training interventions implemented by the company. The problem is hence twofold. On one hand, it is necessary to understand the approach that is needed to collect and manage a potentially huge amount of data from the field, in order to make their elaboration automatic. On the other hand, the development of models that can provide a summary evaluation of the evolution over time of the worker skill levels on the basis of the available data is certainly a non-trivial task.

An answer to this problem can be represented by the integration of the so-called semantic technologies with training evaluation models. The former are in their turn one of the most relevant enabler of the Industry 4.0 paradigm and can provide the structure that is necessary to model, enrich and make interoperable the data collected from the shop floor, while the latter can address the concurrent creation and elaboration of summary indications on the skill levels that can be easily interpreted and used by the managers of the company. In the light of this final objective, the paper aims at presenting the Training Data Evaluation Tool (TDET), i.e. an extension of the previously developed SatisFactory Ontology (SFO) with an analytical model for the definition of the skill levels of the workers. In particular, in Sect. 2 the SFO is briefly introduced, as well as a literature review about semantic technologies and the models for training evaluation. In Sect. 3.1, the extension of the SFO, i.e. the Training Evaluation Ontology (TEO), is presented. In Sect. 3.2, the Training Analytics Model (TAM) for the evaluation of training and skills is introduced. Finally, in Sect. 4, the conclusions and the next steps of the research are reported.

2 Relation to Existing Theories and Work

2.1 Semantic Technologies and the SFO

Nowadays, the areas of knowledge representation (KR) and knowledge management (KM) are gaining from the use of semantic technologies over conventional approaches. Semantic models, such as ontologies, play an important role for many knowledge-intensive applications since they provide a formal representations of domain knowledge [4]. Organizations that use the languages and standards of the semantic Web, i.e. RDF, RDFS, OWL, SPARQL/RIF, aim to integrate existing information assets, using the best practices of linked data and the open world assumption, aiming to enhance their knowledge management system. However, despite the common belief that semantic technologies might be limited to cloud computing and big data, they are equivalently useful to private or proprietary data. Ontologies provide, indeed, a formal and ubiquitous information artefact aiming to make all the elements of a domain and their relations explicit [5].

The SatisFactory Ontology (SFO) presented in this work has been developed in the framework of the H2020 funded SatisFactory project. The SFO has an upper structure developed to gather and manage manufacturing knowledge, mainly focused on processes and assets at shop floor level. Therefore, the model is specialized in two different directions (clepsydra-like shape, see Fig. 1): (i) the *data structure-oriented* level that enhances with semantics the xml schemas used to exchange data within the

SatisFactory ecosystem; (ii) the *shop floor-oriented* level that models the elements and terms characterizing the specific manufacturing environment.

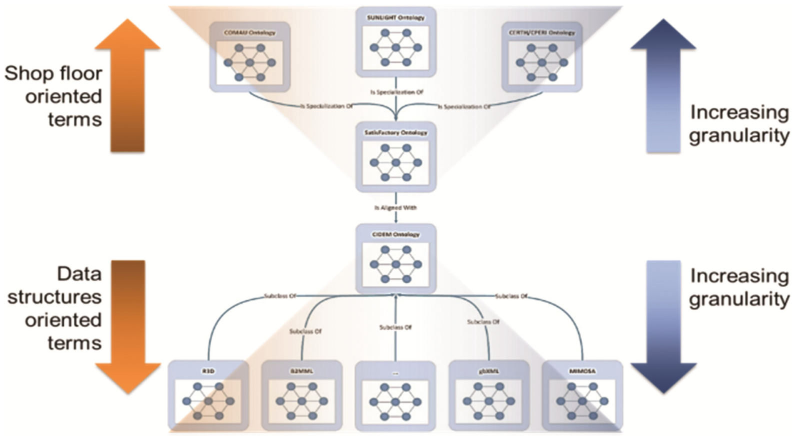

Fig. 1. SatisFactory network of ontologies

Lastly, the use of semantic technologies, and in particular the exploitation of the presented model, is not meant to be a replacement for existing information technologies, but rather an added layer that can leverage those assets for semantic interoperability.

2.2 Models for Training Evaluation

Different models for training evaluation have been developed and used so far. The most widespread and commonly accepted is the Kirkpatrick's [6] four-levels model [7]. The four levels of the model are Reaction, Learning, Employee Behaviour and Organizational Results. The first level evaluates the reaction of the trainees on the training activity. The second level evaluates the knowledge and skills acquired by the trainees. The third level evaluates the transfer of the knowledge and skills on the job. The fourth level evaluates the overall impact on the company/business unit in terms of economic and/or organizational performances. In particular, the two last levels should be considered as the most important for a company/business unit [8].

Over time, various changes to the Kirkpatrick's model have been proposed. For example, Hamblin [9] proposed five levels, by splitting the two last levels of Kirkpatrick's model in Organization and Ultimate value. Guskey [10] also presented a five levels model where the first two levels correspond to Kirkpatrick's ones, while the other three are Organizational support and Learning, Participant use of knowledge and skills, and Participant learning outcomes. The Nine outcomes model [11] presented a list of nine items (Reaction, Satisfaction, Knowledge, Skills, Attitude, Behaviour, Results, Return on investment, Psychological capital) to be checked in order to evaluate the overall impact of training activities, where all the concepts of Kirkpatrick's model are included.

The Kirkpatrick's model, together with the variations described above, represent conceptual approaches to be followed in a general training evaluation. From an analytical perspective, the few contributions available are focused on the estimation of the ROI as in the case of Phillips [12], therefore leaving to the single intervention/company the specific measurement of the impact, which is usually unstructured and targeting only the first two levels of Kirkpatrick's model. For this reason, the TDET described in the following section aims at providing a mechanism to collect and reuse the data from the shop floor in order to provide analytical indications about the impact of the training and the skill level reached by the trainees involved in the program.

3 Training Data Evaluation Tool (TDET)

The TEO should be perceived as a further enrichment of the actual SatisFactory ontology. In particular, the lowest level (or data structure-oriented) semantic model is extended with concepts that support the management and analysis of training data. This is due to the need of enriching with semantics training data coming from the shop floor, which are collected from heterogeneous sources (Fig. 2)

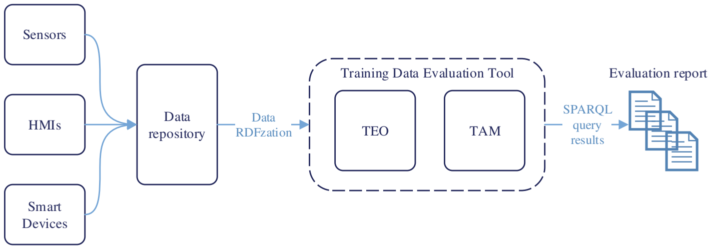

Fig. 2. Overall architecture

The TDET aims at producing a semantics-driven classification and evaluation of the trainees' expertise. As a first step, the so-called Training Evaluation Ontology (TEO) drives the semantic enrichment of the training activities and their evaluation data coming from the shop floor. Then, the model underpinning the quantitative evaluation is addressed by the Training Analytics Model (TAM) that exploits such semantically enriched data.

3.1 Training Evaluation Ontology (TEO)

The data structure-oriented ontology model, as conceived in the SFO, has been extended with the following concepts: (i) Training activity; (ii) KPI, (iii) KPI_Category, (iv) KPI_Score; (v) KPI Type; (vi) KPI_Focus. These, together with the specification of their inter-links, represent the pillars of the trainee expertise evaluation (see Fig. 3).

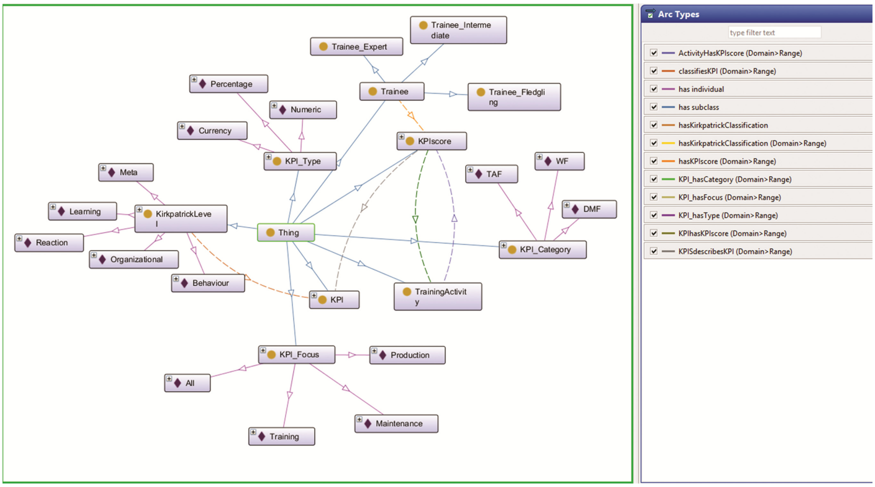

Fig. 3. Training Evaluation Ontology

The evaluation of the worker's expertise level exploits the semantic structure presented in Fig. 4, In particular each instance of the KIP_Score should be perceived according to the following statement: *One trainer may have several KPI scores. The latter ubiquitously describes (refers to) one kind of KPI and one specific activity. The KPI score has a (xsd:double) value.*

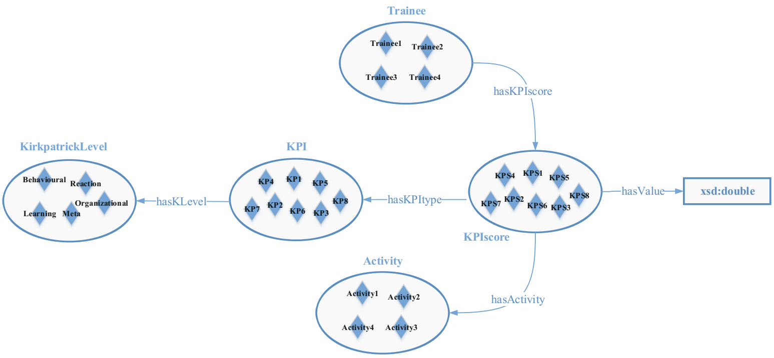

Fig. 4. Semantic structure of the KPI score

3.2 Training Analytics Model (TAM)

The quantitative evaluation of the training and the skill classification is addressed by the TAM, which partially stems from the work of Kiritsis *et al.* [13], who proposed the ActionPlanT Industrial Learning (IL) methodology for the implementation and evaluation of IL actions specifically addressing the last developments of ICT for manufacturing. It is in this framework that an evaluation approach based on Kirkpatrick's training evaluation model was presented. In particular, the first three levels were targeted, namely Reaction, Learning and Behaviour, and a weighted sum model (WSM) to quantify the impact of the training was proposed. However, the ActionPlanT IL WSM had some limitations:

- The performance indicators (KPIs) identified for each level were based only on answers to questionnaires and not on data retrieved from the shop floor
- The KPIs were only at the level of the single trainee, with no KPIs to evaluate the performances of the team (i.e. Organizational level)
- No mechanism to evaluate the skill level of the trainee according to a pre-defined target and the performances of the other trainees was provided

Therefore, on this basis a set of KPIs based on data to be retrieved automatically from the shop floor was developed for each level of the Kirkpatrick's training evaluation model (i.e. Reaction, Learning, Behaviour, and Organization). Furthermore, a mechanism able to assign each trainee to a given skill level (Low, Medium, and High) based on the comparison with both a target level and the performances of the other trainees was designed.

In particular, on the basis of the KPIs identified, a summary indicator summarizing the overall performance of the trainee i at time j for the KPI k was defined:

$$P_{ijk} = \left[\left(\frac{V_{ijk}}{AV_{jk}}\right) * WR_{jk} + \left(\frac{V_{ijk}}{TV_{jk}}\right) * WA_{jk}\right] * 100. \quad (1)$$

V_{ijk}/AV_{jk} is the ratio between the value of KPI k for employee i at time j (V_{ijk}) and the average of the values of KPI k of the n employees at time j (AV_{jk}). If this ratio is higher than 1 it means that the trainee i at time j for the KPI k is performing better than the average, if it is lower than 1 that is performing worse. V_{ijk}/TV_{jk} is the ratio between the value of KPI k for employee i at time j (V_{ijk}) and the target value of KPI k at time j (TV_{jk}) established by the management. If this ratio is higher than 1 it means that the trainee i at time j for the KPI k is performing better than the target value, if it is lower than 1 that is performing worse. WR_{jk} is the weight related to the Value/Average ratio while WA_{jk} is the weight related to the Value/Target ratio. These two weights can be balanced in order to give each time more importance to the performance of the single trainee compared with the average performance of the group or to the same performance compared with the pre-defined target value.

According to the value of P_{ijk}, each trainee i can be classified according to three different skill levels, namely Low, Medium and High. Considering as a reference all the values of KPI k of the n employees at time j, the trainee's skill level will be classified as Low if included between the zero and first quartile, as Medium if included between the first and third quartile and as High if included between the third and fourth quartile.

In order to aggregate the values of more KPIs for a given trainee i, standardized values of the single P_{ijk} should be used, in order to take into account different average and target values. As a consequence, for each P_{ijk} the following formula should be used:

$$Pstd_{ijk} = (P_{ijk} - AV_{jk})/SD_{jk}. \quad (2)$$

where SD_{jk} is the standard deviation of the values of KPI *k* of the *n* employees at time *j*. On this basis, the following aggregated performance of the trainee *i* at time *j* can be formulated:

$$AP_{ij} = \sum\nolimits_{kj} \alpha_{kj} * Pstd_{ijk}. \quad (3)$$

where α_k is the weight related to the KPI *k* at time *j*. This way it is possible to evaluate the overall skill level of the trainee *i* at time *j*, by using the same approach described above. Finally, the overall performances of the single team/group can be easily obtained by means of the averages previously calculated for the different evaluation and temporal levels.

4 Conclusions and Next Steps

With the introduction of the Industry 4.0 paradigm and of the related technologies, a huge effort is nowadays requested to manufacturing companies in order to continuously update the skill of the workers. For this reason, the relevance of training is increasing as well as the need to properly evaluate its effectiveness. In particular, thanks to the huge amount of data that can be retrieved from the shop floor through smart devices, sensors and HMIs, the evaluation of the training and skill levels can be now potentially made automatic with the provision of summary performance indicators to the management as an output. In order to pursue this final objective, the paper has presented the results of a preliminary work aiming at the integration of semantic technologies with training evaluation models in the Training Data Evaluation Tool (TDET), which put together the Training Evaluation Ontology (TEO) with the Training Analytics Model (TAM) for the summary evaluation of training and skills.

The TDET is suitable to the automatic elaboration of data retrieved from the shop floor and to the provision of a general evaluation of the given training activity by means of the aggregation of different KPIs developed *ad hoc*, which are related to all the four levels of the well-known Kirkpatrick’s model. In addition, the overall performance of a trainee can be computed, as well as his skill level (Low, Medium, High) according to a comparison with the performances of the other trainees. The overall performance and the skill level can be obtained for both a given time *j* or as a summary elaboration of the results over a longer time span.

The next steps of the research will include the deployment of the TDET through existing tools for ontologies and smart data management, and the evaluation of this framework on different industrial use cases in order to provide empirical evidence of the effectiveness of the presented approach.

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Towards Industry 4.0: Increased Need for Situational Awareness on the Shop Floor

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Abstract. Currently, much attention is given to the technological opportunities and challenges that "Industry 4.0" entails. However, though the change towards Industry 4.0 is driven by technology, this industrial revolution is not strictly technological. The human aspect of Industry 4.0 is still an emerging field, and must be further researched if modern manufacturers are to reach their full potential. While manufacturers have a high focus on modernizing production processes, the accelerating automation and consequent increasing complexity of tasks is not accompanied by the necessary support for the operator. This results in inefficiency and non-optimal use of workers' capabilities and potential. We argue that operators need technical support systems for increased situation awareness, to be able to efficiently handle an increased pace and complexity of tasks. Our empirical evidence shows that this is not only valid for high-tech manufacturing, but can also be seen in "traditional" manufacturing. We use case studies from three Norwegian manufacturers to illustrate how digitization is yet to reach the operator.

Keywords: Industry 4.0 · Situation awareness · Human-centred manufacturing

1 Introduction

"*In its scale, scope and complexity, what I consider to be the fourth industrial revolution is unlike anything humankind has experienced before*" [2].

Although the change towards Industry 4.0 is driven by technology, this industrial revolution is not strictly a technological one. Whenever the technical system changes in the workplace, it has an effect in the social (or human) system, and vice versa [3]. In fact, work organisation is said to be one of the largest challenges with implementing industry 4.0 [4]. Despite this, the human aspects of Industry 4.0 are largely under-researched. The change towards industry 4.0 will likely result in an increase in responsibility and authority of production for the operator, with a high degree of autonomy [4]. As machines become smarter, the operators will also become responsible for the production as a whole, and not just a single machine [5]. Operators are the manufacturing managers of the future, and will only delegate tasks to a higher level in case of exceptions [5]. This increased autonomy emphasizes the importance of operators ability to act on own initiative and organize own work [4]. Thus, we argue that operators need

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comprehensive knowledge about their production processes, knowledge that is typically found at a managerial level and not shop floor level today. In the area of maintenance there are some examples of systems providing information to shop-floor personnel [6, 7], but for support in daily operations little has been done. Regardless of the work task being maintenance, production or otherwise the overall challenge remains the same: The autonomous operator needs assistance systems that aggregate and visualize information comprehensibly, to make informed decisions and solve urgent problems effectively [5]. Operators should be provided with decision support to match their new decision authority.

As manufacturing becomes ever more high-tech, the work content and required skills for operators will change dramatically [8]. Industry 4.0 literature outlines how the new work of the operator in manufacturing is expected to change towards having more responsibility for production and complex decision-making. As automation eliminates repetitive, low skill work, the human role is changing from simpler manual tasks to more complex decision-making [9]. The operator will reorganize, reconfigure, and maintain the system, and will have a key role in quality assurance [4, 9].

With the increasing complexity and pace of production in the new manufacturing reality, increased situational awareness (SA) for the operator is essential. SA is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" [10]. SA is commonly divided into three levels of perception (see Fig. 1). In manufacturing, SA is necessary for the operators to deal with a complex and unexpected situation in an effective manner, namely to decide and act timely and appropriately [11].

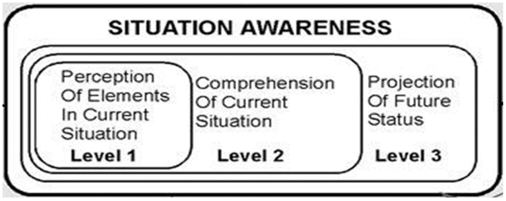

Fig. 1. The three levels of SA [1]

2 Method

As part of an on-going research project about highly automated and flexible manufacturing, the researchers have observed and participated in operators work in three case companies. The research has been conducted following the participative tradition of action research. In action research, the professional researcher and the stakeholders together define the problems to be examined, co-generate relevant knowledge about them, learn and execute social research techniques, take actions, and interpret the results [12].

To structure the case studies a topical framework for mapping was made, containing both methodological descriptions of how the researcher were to conduct the studies, and which topics to investigate. The topics covered a broad spectrum of issues, with the following headings: Production system, the team, quality, information and communication, management. Data collection methods have been qualitative, with a mix of observation, participation, unstructured and semi-structured interviews [13]. Results of the initial mappings were gathered in a report and sent back to the case companies for validation. When a set of problems were mapped and validated, further workshops were held with operators and production management to discuss the development and implementation of test cases of technical support systems for operators to solve some of the identified issues. The development of such test cases is still on going at the time of this paper.

3 Case Descriptions

All three case companies are Norwegian manufacturers, with several hundred employees and international markets. They have different levels of automation, from high to low, and so we have named them accordingly: *Robots In Line* (RIL), *Automated Machine Cells* (AMC) and *Pretty Manual Line* (PML).

3.1 Robots in Line (RIL)

RIL has a highly automated production line, with robots doing most of the work. In the department investigated, there are only two operators at the shop floor. Operators load/ unload parts to the line, do quality measurement, maintenance, re-configuration of the line, and solve errors. Even with advanced technology in production, the information flow to operators is still based on conversation, or manually written media such as paper, e-mail or whiteboards. Operators receive most information by conversations with factory managers. Whiteboards are used extensively in the factory, depicting a multitude of information including production and quality performance. However, operators claim that the only information they actually use from the whiteboards are production plans. Issues incurred during the shift is written by hand in a book, for the next shift leader to see, and for improvement work.

The case study revealed a multitude of issues relating to information flow at the shop floor. However, in this large line with few operators, what *the operators* wanted most was a tool to provide an overview in production. Signal lamps dispatched across the line are not visible from other parts of the line, and operators have to constantly move along the line or rely on their hearing to know if there is a problem – if it is too quiet, something is wrong. Operators want to be notified *immediately* if there is an error in a machine, regardless of where they are when the error occurs. They say this would reduce stress and unnecessary walking from having to “go and check”, and contribute to reduced downtime because of faster response to errors. To be better able to plan their work short term operators would also like to know if there is a low level in any of the feeders for input materials. This will eliminate downtime resulting from the operator not seeing that feeders need to be restocked. For simplicity with programming and installation, the company has chosen to display the information on screens first. This is a cheap and quick solution, which allows the company to test the usability of the information solution and re-design it to fit the operators' needs.

3.2 Automated Machine Cells (AMC)

AMC's production is organized as functional cells, with a complex production flow. Each machine is highly automated; once the program is started, machines perform operations without interference from the operator. The operators' main tasks are to load/unload items to the machine, start machines, change tools as needed, and monitor machines in case of malfunctions. Operators receive information mainly from other people in the factory, and from whiteboards and production notes.

Machine errors are an everyday issue at AMC. Signal lamps on the machines indicate errors, but these lamps can only be seen if you are nearby. With daily machine errors, the response time to errors significantly affect machine downtime. Thus, the operator needs to be nearby the machine in order to quickly detect and solve errors. With long processing times in most of the machines, monitoring accounts for a large part of operators' time, time that could be utilized better if the operator did not have to remain nearby the machine. In addition to the lamps, operators also depend on hearing to monitor machines. To increase operator mobility, operators need a mobile solution providing the same situational awareness as sitting by the machine. Such a mobile solution would allow the operator to move freely in the production facility, enabling the operators to handle several machines at once, or to work in teams. To achieve this, AMC has begun testing the use of smart watches for operators.

Due to numerous sources of variance, such as machine errors, each cell at AMC experiences large variations in production flow. Even the bottlenecks occasionally experience lack of work. To handle this, AMC has dedicated production coordinators working in the factory. These coordinators keep track of in-house inventory and progress in production. Although the coordinators do not have formal responsibility for production, they are key decision-makers – making decisions about what to produce and when. Operators receive the information they need about production flow from these coordinators, in addition to managers, and find the information from the coordinator useful and important. Without the coordinators chaos would rise. Although coordinators make decisions in production, their main function is to collect and analyse information. If operators were given appropriate information and decision support, coordinators would not be needed to organize flow. At a later stage, AMC might try to dispatch such information to the operators' smart watches. However, the issue with the machine alarms currently holds higher priority and AMC is experimenting with these now.

3.3 Pretty Manual Line (PML)

PML has a traditional production line. There is a low level of automation, with the machines performing simple, single tasks. The operators main work is to perform several manual tasks, such as to load products into the machines, run the machines, manually add materials/parts to the main products, and move products between different machines. The operators' main source of information is conversations with the manager and process engineer. Each operator team also has a whiteboard, to keep track of key information for their part of the production. Just as in the two cases above with more automated production, the flow of information at PML's shop floor is not automated or digital.

Operators at PML relate to the daily production target for their part of the line, and seemingly lack any information about the rest of production. PML's production area is divided into several buildings, and it is difficult to have a complete overview of production progress. It was only by chance we observed a key information channel for value chain information to the operator; namely the forklift driver. Because the forklift driver moves the products along the production line between buildings and storages, the forklift-driver attains an overview of production and inventory status across the whole production line. Thus, one can ask the forklift-driver about the status in other parts of production. Operators at PML have done so to the extent that it has become part of the driver's job to convey information between buildings. This was discovered during our observation of production, as the forklift-driver called out "8000" when entering the building – which turned out to be the number of items in an intermediate storage. The information conveyed by the forklift-driver helps operators to make decisions about when and where to dispatch batches.

Although the needed information might be available in the computer system, the operators prefer to ask the forklift driver. This is partly due to a cumbersome computer system and partly due to lack of knowledge about what information exists in the computer system. Asking the forklift-driver is the fastest option. Similar to RIL, PML will run tests with displaying information on screens for the operators. The operators are heavily involved in the design process. In addition to machine alarms, the screens will likely contain information that currently is written on whiteboards, and information about production in other buildings.

4 Analysis

Some common themes can be seen in the cases:

1. The operators need for information about the production
2. The inability of current computer systems to deliver information to the operators
3. The emergence of local solutions to get the needed information

First, in all three cases we can see clear evidence that operators in fact need more information than what is provided. Operators lack relevant, valid and updated information about the production system, and are completely dependent upon their managers and others who decide which information is relevant to convey. After a process of mapping what information the operators want most, the operators request support to increase their situational awareness (SA), a need that results from the increase in automation and reduction of the number of operators in the factory. To reduce downtime of machines, operators want to be notified immediately if there is an error in a machine, regardless of where they are when the error occurs. At AMC, a mobile SA support system can also facilitate the formation of operator teams because it will allow the operators to move away from their designated machine cells. It is likely that future operators will have to work in teams to solve complex problems.

Although the three cases are at different levels when it comes to production technology, they are similar when it comes to how the operator receives information. Even in the case of RIL with almost full automation, the information flow to operators is still based on conversation, or manually written media such as paper, e-mail or whiteboards. Although information is largely digitalized and somewhat automated at the managerial level, at operator level all three cases are in the "paper age". This is not unique; a large survey done in 2016 in the Norwegian industrial sector shows that in general digitalization is yet to reach the operator [14].

The second point is that although information systems exist with relevant information, operators do not use such systems to get information. In all three cases, the operators have some access to IT-systems. The operator's relation to these IT systems is to feed information into the system, so others can get information. All the case companies have various IT systems keeping track of production, with sensors measuring status in real time. However, this information is used by managers and process engineers, not operators. Most of the information that operators request, such as notifications about stops, errors, and low levels in feeders, already exists on some PLC system or a server, but is not available in real time to the operator. The lack of information systems for operators is contradictory to requirements described in Industry 4.0 literature. For instance, Herman et al. [5] argue that the autonomous operator will require assistance systems to aggregate and visualize information comprehensibly, in order to make informed decisions and solve urgent problems effectively.

The main reason that operators do not use IT systems is because the systems are made for managers. In addition, there are many different, disintegrated computer programs in each company, and managers spend a lot of their time wrestling with cumbersome user interfaces. To be useful, IT systems must be tailored to be people that are to use it. As operators are key decision makers in production, operators should be considered as the primary user of information systems in production [15]. In the case companies, the effect of involvement in information systems can be seen from how operators use the whiteboards. At RIL operators say that the only information they actually use from the numerous whiteboards are production plans. At PML the case is different – here the operators find the whiteboards very useful. They have designed their own whiteboards, and are free to change them as they want to, while at RIL the boards are company standard. In the same way that operators should be able to create their own whiteboards, they should get to configure visualisation of their own digital information systems.

Third, in all cases we observe that some workaround has emerged to deal with the lack of information. To convey information about production is not part of the forklift driver's job description, but a task that has emerged from an unsolicited need for information. At AMC, they have operators "baby sit" machines in case of errors, and the coordinator is manually collecting and analysing information to maintain production flow. At RIL, the operators solve their need for information simply by constantly moving around in the production facility to check that everything is running smoothly. In all cases humans have stepped up to keep the crucial information flow going in production.

However, these solutions have obvious weaknesses. If the coordinator at AMC or forklift driver at PML are absent, the operators are left “blind”, or have to spend time gathering information instead of maintaining productivity.

5 Conclusion

We see technical support systems that increase the situational awareness for operators as a first, important step towards optimized Industry 4.0 manufacturing, and a key to sustained competitive advantage in modern manufacturing. There is no doubt that operators in the case companies have an unsolicited need for information, and that the lack of such information is negatively affecting either productivity, or profits, or both. Existing IT-systems are not made for operators, and alternative information channels have emerged in production. There is a need for efficient managing of information, where information is displayed to the user according to the user’s current needs [15, 16], to help operators deal with the increased amount and richness of communication. The highly motivated operators currently lack the information they need to be able to maximize their own productivity (Table 1).

Table 1. Summary of elements that change with Industry 4.0

Element	Current	Future (Industry 4.0)
Operator role	Operator of machines	Manager of machines
Task complexity	Medium	High
Required level of SA	Level 1	Level 2
Pace	High	Higher
Autonomy/decision authority	Managed operators	Autonomous operators and teams
Responsibility	Single machine	Whole production
Information support	Made for managers	Real-time decision-support for operators

We have no indication that the three case companies are lagging behind the rest of the Norwegian (or to the degree we know it, European) industry. Rather, we believe this situation to be typical for all industry: Information systems are tailored to the needs of management, and ignores the need for situational awareness for the operators.

The information solutions we have designed together with the operators are merely at the first level of SA – the perception of element in current situation (see Fig. 1). Our experience is that it is difficult to envision a future state of your own work, and that is the reason for the low level of ambition in designing information systems. We find that in most people’s vision about the future factory, operators are mainly doing the same task, but then on more than one machine at the time. In Industry 4.0 operators will take on tasks that are currently performed by managers. This means operators will need the information managers currently have exclusive access to, but they will not have the same amount of time to find and analyse this information. The operator is the future manager in manufacturing.

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Virtual Reality for the Training of Operators in Industry 4.0

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Abstract. The time for maintenance operations is often restricted due to external circumstances. When conducted with inexperienced operators, additional uncertainties can arise and in case of a delay, high follow-up costs emerge. By using Virtual Reality (VR), operators may practice their skills in advance. This paper analyzes the training content and describes which parts of a generic operating cycle have the potential to be supported by VR as training technology. Furthermore, a training procedure and a resulting system architecture that allows to work efficiently with VR as a training technology are presented.

Keywords: Virtual Reality · Virtual Technologies · Training · Education · Industry 4.0 · Qualification · Flexibility · Individual Production · Smart Factory · On-the-Job Training

1 Introduction

As timeslots for complex maintenance tasks are often restricted, companies need experienced operators to fulfill these essential tasks in a short time. This is among others a characteristic of the machine industry, where operators may service an engine only during the planned maintenance time and in case of a delay, further loss-of-production costs or overtime payments can emerge. To avoid this, service operators usually rely on their experience or use paper based instructions for preparation. A problem with these utilities is that users cannot easily identify complex, three-dimensional subassemblies [1]. Neither can users train their motor skills. To gain experience when executing those operations for the first time or after a long period, a training method is needed, that enhances cognitive skills as well as motor skills – e.g. for movements in cramped areas. The training method shall enable the operator to interact with the prospective work object even without the training object being present, giving him the possibility to train at any place desired.

Virtual Reality (VR) imitates a fictional situation for the user who can manipulate any object with no restriction to weight, size, time, location or with any danger to his well-being. It was already applied in several training showcases, e.g. [2]. Still, up-to-date literature does not sufficiently describe the parts of a task that companies may train with VR. Therefore, the goal of this paper is to identify the benefits VR provides as a training technology and to reduce the effort of the trainer to prepare a training.

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Furthermore, this article shall propose an adequate information flow to increase the training outcome of complex manufacturing tasks.

2 Current State of Research

2.1 Training Content of Complex Manufacturing Tasks

To define suitable training courses, the training content and the target competence levels have to be defined. The training content is mainly determined by the intended outcome [3] – in this case a complex manufacturing task. These tasks may be described by the dimensions complexity, connectivity, non-transparency, dynamics and multiple targets [4]. To define which parts of a task may profit from VR based training, this paper uses a generic operating cycle developed by Tietze et al. It consists of the five generic steps information gathering and processing, material and tool allocation, component and site preparation, execution, feedback and post-processing [5]. These steps may be split into sub-processes focusing on different capability factors.

As the pure content of a task is not sufficient to clarify the outcome, the target competences have to be specified in a proper way [3]. In the context of maintenance tasks, especially cognitive and motor skills are relevant. Referring to the oxford dictionary, a cognitive skill is the ability to acquire and understand knowledge [6] and a motor skill is the ability to produce the required muscular movements [7]. Anderson et al. [8] present a revised taxonomy of Bloom for cognitive skills – from remembering to creating. Klemme et al. [9] present the taxonomy of Dave for psychomotor skills – from imitating to naturalization. The different levels of the taxonomy can be measured by specific indicators concerning potential, activity and output [10].

2.2 Training Technology

Many complex manufacturing tasks are usually required to meet certain standards of time and quality. As described in the introduction, today's training methods prepare the operator with written instructions and technical drafts. The preparation of these instructions is often time consuming and it usually takes a long time for the operator to find and understand the necessary information. Furthermore, written instructions provide no possibility to train motions for training purposes – not to mention necessary repetitions as crucial elements of successful trainings [11].

VR is a combination of a computer platform, scene data, an input and an output device and a VR software [12]. The input device enables the communication between the user and the software. It may work by a tracking of the user's motions. This combination gives the user the impression to be physically present in the virtual environment [12]. It can be realized among others in form of a VR Cave or with VR glasses. As it is a promising technology to solve the problems mentioned above, several authors describe VR based training scenarios – e.g. [13, 14]. Vaughan et al. [2] even present existing VR training systems used in five different sectors – medicine, industry and commerce, collaboration, serious games and rehabilitation. Their paper stresses the positive effects and the practicability of each concept. Still, none of the papers considers the implicit knowledge of experienced operators in the training. Rather, the authors focus on explicit knowledge – e.g. written instructions. Furthermore, the concepts do not consider the potential to partially compensate physical training with a tracking of motions in VR – only cognitive skills are under examination.

2.3 Training Procedure

Simplified, training processes can be divided into preparation, execution and evaluation (post-processing) [15]. In this context, the preparation mainly consists of the definition of the target competences, the definition of the resulting training technology and the authoring of a proper training scenario. For the execution and the evaluation, Haase et al. [13] propose four different strategies for VR-training: The discovery mode (no guidance, no evaluation), the presentation mode (full guidance, full evaluation), the guided mode (defined guidance and evaluation) and the free mode (no guidance, final evaluation). Even though Haase et al. explicitly exclude the training of motor skills, no restrictions disable the use of their training modes for this concept.

3 Combining Work Tasks and Training Aspects

This chapter connects a complex work tasks with the relevant aspects of a VR-based training. In this paper, a maintenance scenario of an engine is selected. Particularly, the operator shall clean the charge air cooler with a diameter of approx. 2 meters weighing about 450 kg. To handle the components the operator has to apply additional structures and a crane in non-ergonomically positions.

1. Information Gathering and Processing: The operator reads paper instructions for preparation. Thereby, he pictures the correct motions. Once on site, the operator compares the instructions, his perception and reality. He may repeat this, whenever a new part comes into sight during the disassembly process. This step contains only cognitive skills as knowledge and imagination. No motions are yet required. As the instructions provide most of the information necessary, the operator has to reach the level of applying for cognitive skills in terms of Blooms taxonomy.
2. Material and Tool Allocation: Prior to the planned maintenance stop, the operator chooses the required material and his tools and places them in a suitable manner. Therefore, this step requires cognitive skills in form of knowledge of the correct tools up to the level of applying. This is not necessarily described by the instructions. The motor skills of gathering the material can be neglected as this paper assumes that operators already have the motor skills for any sub-task of this step.
3. Component and Site Preparation: Again, prior to the planned maintenance stop, the operator gathers the necessary components and places them in a suitable manner. This step includes the correct use of the crane in a cramped area. Therefore, this step mainly consists of cognitive skills of knowing where to find the components up to the level of applying and motor skills for the correct use of the crane up to the level of manipulation.

4. Execution: The operator fulfills the tasks in accordance to his perception of the instructions. On demand, the operator goes back to the paper instructions and gathers further information. Usually, the operator is under time pressure during this step. At large, this step requires cognitive skills for applying the gathered information and motor skills for the correct execution up to the level of manipulation.
5. Feedback and Post-Processing: When production is re-initiated, the operator gathers the tools and components, cleans the workspace and documents his actions. Hence, only cognitive skills up to the level of applying are required.

At large, the training content requires the training technology to train cognitive skills up to the level of applying and motor skills up to the level of manipulation. While the cognitive skills of course can be taught in principle in advance via paper instructions, videos, 3D-PDFs and VR, the motor skills need physical practice. For evaluating to what degree VR can compensate the physical training, this paper provides the setup of a general training concept.

Generally, this concept shall provide benefits in terms of a higher profitability for the training as well as a higher quality and a lower execution time for the actual task. Thereby, the concept has to fulfill certain requirements. Contrary to the preparation of a training scenario, different operators with diverse skills perform the training. While the degree of difficulty is already defined by the task, the training software has to include different levels of assistance to meet the diverse requirements of the operators. Furthermore, as the time for the execution of the training is limited, the operator needs his feedback as soon as possible. When conducted with human aid, additional waiting times would have to be accepted. Therefore, at best the software shall conduct a fully automated evaluation based on the individual competence level immediately.

4 Implementing Training Procedures in Virtual Reality

4.1 Fundamental Concept

As three persons participate in the training process – the trainer as the editor of the training scenario, the student as the executor and the trainer as the final evaluator – the software shall provide the necessary views for each role. These views also refer to the simplified training process – one to support the preparation, one the execution and one the evaluation (Fig. 1).

The first part is the preparation of the training. Therefore, the trainer uses the editor view and the function *Editing* to issue the *Template*. It includes the written instructions in form of steps in the VR-environment as the explicit knowledge. Then, a skilled person executes the steps in the VR-environment using the function *Recording*. This may be the trainer or an experienced operator. The function records and saves the actions in the *Solution* – in an unpretentious manner, this represents the implicit knowledge.

Second part is the execution of the training by the student. On the one-hand-side, he has to follow the instructions of the maintenance plan, which are generally not highly detailed and on the other hand has to perform a specific motion sequence. While the student follows the same instructions as the experienced operator before, the software records and saves the students actions. Thus, he creates the *Result*.

Finally, the function *Evaluating* derives any discrepancy between the experienced operator and the student. The trainer may define minimum requirements that the student has to accomplish in order to pass. The software then creates the *Evaluation* containing the evaluated results of the student and the grade. Figure 1 summarizes this information flow and the according system architecture.

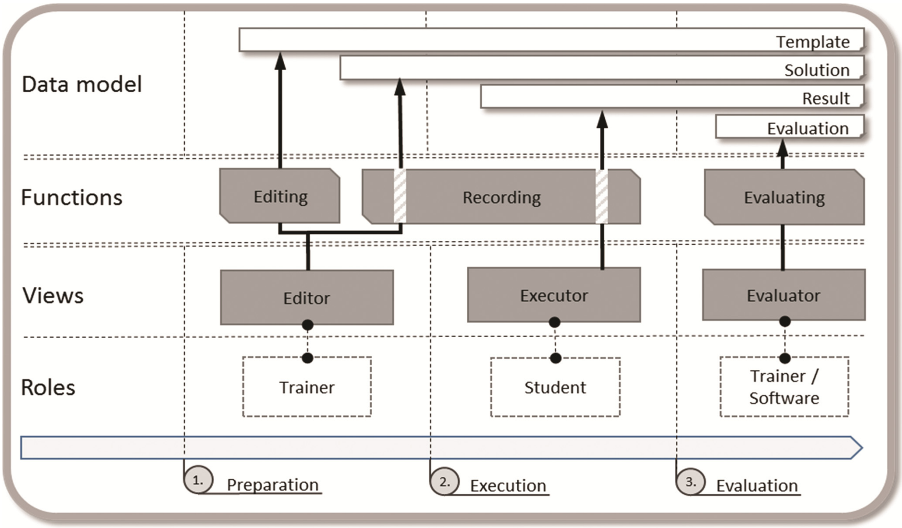

Fig. 1. Information flow and system architecture

As the implementation of a training – especially with VR – involves additional costs for hard- and software as well as the additional time for the training, the following chapters describe the setup and the expected benefits of each phase individually.

4.2 Preparation of the Training Content

Purpose of this phase is to enable the trainer to include both explicit and implicit knowledge and at the same time keep the necessary effort to a minimum. As stated in the previous chapter, the trainer includes the written instruction in a suitable format for the software. Then, he executes these instructions in VR. The software shall include the motions of the operator and thus allow the combination of explicit knowledge of the instructions and the implicit knowledge of the trainer in an unpretentious manner. There are two options to record the motions: (a) to develop standardized templates, adapt them to any new situation and compare their counterparts for evaluation (b) to divide any task into the smallest steps possible and compare them for evaluation. Option (a) results in a high amount of work, as the templates have to cover any of the existing situations. In addition, a VR software specialist must carry out this work instructed by the trainer.

Option (b) results in less work, as the specialist must not create a new template for any given situation. It is therefore the favored option.

Current instructions require the trainer to transfer the 3D-file to a technical 2D-draft. A positive consequence of the concept is that this part vanishes as the transmission from a 3D-file to VR is completely automated. On the negative side is the trainer who spends additional time as he carries out the instructions for the *Solution*.

4.3 Execution of the Training

Purpose of the execution is to teach the student all necessary skills defined by the trainer. He therefore executes the written instructions the same way the trainer did in the phase of preparation. As more or less experienced operators may participate in the training during this phase, the execution needs to provide different levels of assistance. The trainer may realize this either via (a) an adaption of the task or (b) an adaption of the aids. Option (a) results in a new training scenario as described in the previous chapter. When choosing option (b), the trainer may disable hints or instructions for the steps. The more experienced an operator becomes, the fewer hints are included by the trainer and thus, the more difficult a training becomes until the operator has gained the desired competences.

Trainings are more likely remembered when the student is involved rather than when he only observes a visual presentation, e.g. written instructions or 3D-PDFs [16]. Thus, using this concept has the potential to improve trainings and therefore reduces mistakes and working time of the work task. In addition, VR has the potential to partially compensate physical training by tracking the user's motions and therefore support the training of the required motor skills. This potential is not yet quantified.

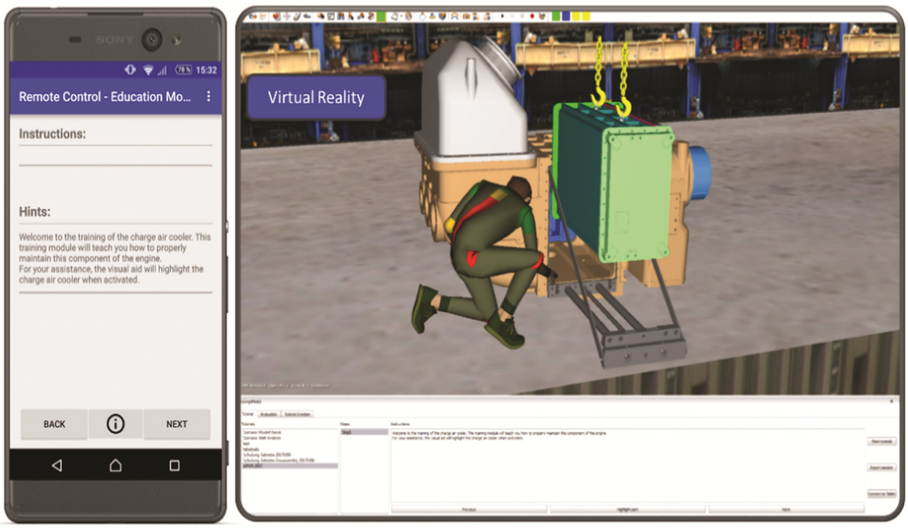

Fig. 2. Remote control and Virtual Reality

For a first proof of concept, the developed prototype uses the application programming interface of the software VDP by the ESI group. The developed module receives and saves the virtual coordinates of any object from the VDP to create the *Solution* and the *Result*. Next, the module compares the student's coordinates with the ones of the *Solution* and derives consequences. For a better comfort, the user may control the situation via smartphone or tablet within the immersive area of the Cave (Fig. 2).

4.4 Evaluation of the Training Results

The last phase is the measurement of the acquired competences. Therefore, the software describes and detects errors, rates solutions and determines the new competence level of the student.

In order to describe and detect errors, general criteria for the evaluation are defined. These are the time and the number of mistakes [17]. For an adequate feedback, it is necessary to further define the mistakes. For that, Berndt et al. propose the presence, the position and orientation of each part and the completeness of each working step [18]. These measurable criteria can then be connected to the acquired competences [10]. The software has knowledge of the coordinates of any object in each step. Thus, it can calculate the differences of the *Result* and the *Solution* for each criterion and therefore detect errors.

The function *Evaluating* rates the differences of each step. This is based on the calculated differences and on the defined tolerances that the trainer may define for each criterion, each step and for each operator individually– e.g. an object shall be placed within a diameter of 5 cm. In practice, the developed prototype generates the *Evaluation* automatically. As no human actions are required, no additional waiting time or effort has to be considered. The student can repeat the training with a full understanding of his previous mistakes and therefore improve his capabilities.

Finally, the software derives the acquired competence level based on the defined tolerances and on the errors of the student – e.g. the student is capable to perform a task in a given time. This is based on rules defined by the trainer for passing a new competence level – e.g. only a certain kind of error is detected in the training procedure.

5 Conclusion and Future Research

This paper outlines a concept for a VR-based training of a complex maintenance task. Therefore, it analyzes the generic operating cycle and determines the trainable parts for VR. These are especially cognitive and motor skills up to the level of applying respectively manipulation. Subsequently, the paper derives a concept with the three training phases preparation, execution and evaluation. It describes the resulting information flow and the expected benefits of each phase. At last, it proves the feasibility of the concept by presenting a basic prototype.

As this is only an early approach towards a comprehensive training concept, future research will cover a more detailed view on the generic operating cycle, the critical parts of the work task and the compensation of physical training with VR. In addition, it will extend the current results towards VR glasses and Augmented Reality.

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Productivity Strategies Using Digital Information Systems in Production Environments

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Abstract. High productivity is essential for companies in order to survive in international competition, especially for those located in high-wage countries. Recent developments of digitalization open up new opportunities to manage and increase productivity. The development of company-specific strategies for the management of productivity, which are increasingly embossed by digitalization, is therefore an elementary task. This paper presents a framework for systematic design of productivity strategies for industrial production and explains conceptual potentials for the design of strategies. A detailed description of terms provides the necessary understanding. The framework encompasses three axes, the goal of productivity, the application of digital information management in industrial production and the different direct production areas as well as indirect supporting areas. The application of this framework is described for different corporate levels considering task- and goal-setting for various time horizons as well as an integrative view on technological, organizational and personnel aspects.

Keywords: Productivity management · Industry 4.0 · Design framework · Digitalization · Strategic process development

1 Introduction

Successful companies guide their actions along a basic long-term guideline, the so-called vision. The approach for realizing this vision and thus the organization's orientation towards action in competition is known as a strategy (Neumann 2008).

In industrial manufacturing, processing is performed to transform input factors into output. These inputs contain raw materials and auxiliaries, intermediate products and other operating materials, which pass through value-adding production processes, resulting in finished products (Günther and Tempelmeier 2012). The relationship between output and the use of production factors is called productivity (Wöhe 2002).

The term Industry 4.0 describes the usage of information and communication technologies for industrial production processes to improve value creation (Roth 2016; ifaa 2016). Digitalized processes in the manufacturing industry open new possibilities for productivity improvement. At the same time, digitalization can be used to adjust a company's strategy as well as product and service offerings (Roth 2016).

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It is important for companies to have high productivity in order to survive in international competition. Productivity gains are essential to overcome higher costs compared to competitors. All processes in a company directly or indirectly influence its productivity. This applies to direct as well as to indirect areas.

For this reason, it is necessary to monitor productivity and influence it in an effective way. This should be done by planning and implementing a holistic strategic approach including strategic goals that can be measured by performance figures. They need to be continuously steered and controlled. These tasks are described by the term productivity management.

Productivity management is carried out for the continuous improvement of a company's activities with regard to increasing effectiveness and efficiency (Gackstatter 2011) and thus goes beyond the mere consideration of the ratio of output to input. The undertaken activities for influencing productivity should have at least a mid-term scope and therefore have to be linked to the company's strategic goals.

The term "productivity strategy" stands for the possibility to choose various options for influencing productivity within the boundaries of a previously defined organizational strategy with its business model and core activities (ifaa 2016). Within the context of strategic productivity management, a company's activities are geared towards long-term influencing and targeted use of productivity (enhancement) strategies. This includes the assurance of positive results by strategic productivity planning (e.g. defined values for selected productivity key performance indicators), the implementation of this planning, a continuous evaluation of the productivity development and its controlling (Dorner and Stowasser 2012; ifaa 2015).

Basically, productivity strategies can be classified by the aimed change of the ratio of output to input. Approaches to influence productivity focus – in general – either on the reduction of input (material, time etc.) or on the improvement of output (number of goods, customer satisfaction etc.) (Weber et al. 2017; Ruch 1982).

2 Use of Digitalization for Improving Productivity

A productivity strategy is determined by the production strategy chosen to implement the business strategy. The production strategy essentially describes the use of production concepts and technologies, including the production system and the process structure. To design a production system and its processes with an adequate flow of information, the design and implementation of state-of-the-art computer-assisted information systems is highly requested (Gackstatter 2011).

Improvements of productivity can be reached by using information and communication technologies if they are integrated in the design of industrial production and its processes. The recent developments of digitalization within this decade open up new opportunities for the management and improvement of production (e.g. human-robot-collaboration, data glasses, automated guided vehicles or exoskeletons, among others. See (ifaa 2016) for examples and their application). Mainly the adaptation of productivity strategies using computer-based information management in alignment with the specific surrounding conditions and requirements of the company in scope are promising. The degree of utilization of IT-integration and digitalization already implemented in the company needs obviously to be considered. In order to be able to use additional digital tools and IT technologies, it may be necessary to adapt the IT infrastructure (Schlick et al. 2017).

Possible outcomes of implementing productivity strategies based on IT are – for example – improved resource allocation by optimizing production, preventive maintenance based on sensor-captured real-time machine data or the use of extensive simulations based on a continuous digital engineering using Augmented or Virtual Reality (Roth 2016).

However, the diversity of techniques, standards and their impact on all business processes makes it difficult to choose and implement them (Samulat 2017). It is therefore necessary to develop strategies for the management of productivity in IT-integrated and digitized work systems and to prepare them for practical application. All potentials of digitalization should be taken into account for the design of work places and processes. The technology can be used to support human performance, or to decrease the consumption of material or energy. There is also a great possibility for decreasing actual process times (Weber et al. 2017; Meiller and Niewiera 2016).

Since digitalization allows an improved information provision, it can be used to reduce the complexity of information handling (collection, transferring, processing, providing, usage), while at the same time improving productivity. For this purpose, the necessary steps from data collection to data usage must be coordinated, so that the data can be processed fully-digitized without media breaks and can be used in an integrative manner to influence productivity management strategically.

3 Framework for Clustering Productivity Strategies

Operational decisions to improve productivity focus on influencing input and/or output factors. One should have the best possible understanding of the interdependencies between those factors (ifaa 2016). Based on the information provided previously, the productivity goal – influencing input or output – and possible applications of digital information management in industrial production can be combined to a matrix. Additionally, a third axis can be added to assign approaches out of the matrix to the tasks performed in different direct production areas – including all material handling and intralogistic activities – as well as in the indirect areas supporting production, such as scheduling, controlling, management and leadership, training, legal advisory service etc. The resulting cube (compare Fig. 1) serves as a framework for the classification and further development of productivity strategies.

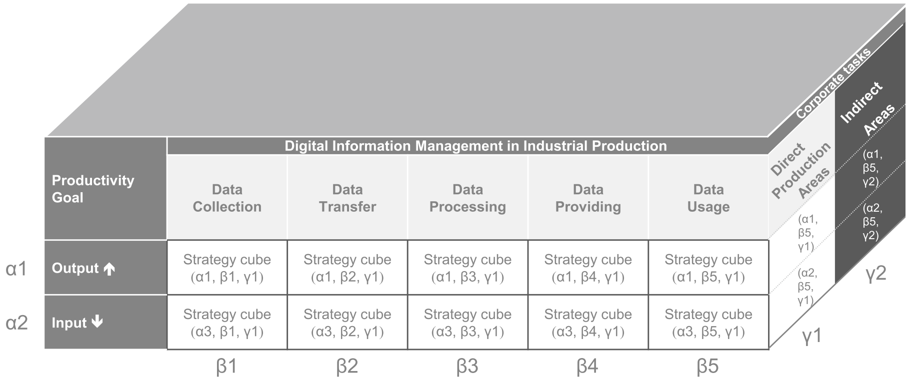

Fig. 1. Framework for systematic design of productivity strategies in digitized working environments.

For each of the twenty cubes of the so-called "organizational and design framework", different productivity strategies can be classified. These strategies can be independently of each other or have strong interactions with one another. Based on this framework, various productivity strategies for industrial production can be structured and evaluated, taking into account the impact of IT and digitalization. To do so, it is important to assess a productivity strategy for its contribution to each cube. Subsequently, fundamental potentials for the design and development of productivity strategies can be derived.

To identify a single cube, we use (α, β, γ) to describe them. α represents the main effect influencing productivity, β stands for the application of digital information management and γ for the corporate application area. α1 and α2 assign the productivity goals of output enhancement and input diminishment. Digital information management is described by using β1 to β5, referring to data collection, data transfer, data processing, data providing and data usage. Finally, γ1 is used for all direct production areas and γ2 for the supporting indirect areas.

For example, (α2, β4, γ1) describes the cube for productivity strategies aiming at a decrease of input (α2) using digitalization for data providing (β4) within the production (γ1). A practical application could be the usage of handheld tablets to support the worker in manufacturing operations – e.g. by showing each single assembling step – which will lead to a decrease in time input necessary for performing the task. Other examples are given in (Weber et al. 2017).

4 Application of the Framework

The framework serves as a basis to sort and categorize productivity strategies into so-called strategy cubes. On this basis, a systematic design of strategies is supported. According to the cubic structure, this includes first an integrated analysis of the application of digitalization (from data collection to data usage), second the distinction between direct and indirect production tasks and finally a view on different aims to be reached by the strategies (enlargement of output or decrease in input).

4.1 How to Classify Productivity Strategies

The following three-step procedure is generally recommended (other approaches are possible as well) for the classification of existing productivity strategies into the framework:

- Step 1: Identification of columns most suitable categorizing the technical solution based on information and communication technology (determining β).
- Step 2: Determination of the area where the technology is applied (determining γ).
- Step 3: Examination of the impacts that can be achieved or that are expected from using the technology (determining α).

Especially in step 1, the distinction has to be made between the aspects offered by the strategy itself, and the components needed for a successful implementation of the strategy that are provided by supporting use of other technologies (e.g. before using a tablet for data providing as a possible main scope of a productivity strategy, these data obviously have to be processed before).

4.2 How to Search for Productivity Strategies

Searching a strategy within the framework can be done vice versa using the above mentioned proceeding. For example one can first focus on the application area (γ) in which productivity should be improved. In the second step, it can be regarded what can be done to decrease input, e.g. reducing the need for raw materials (α). Finally an application area for digitalization can be chosen to do so (β).

Other search strategies are possible as well, depending on the scope of search. In general, the company's specific needs should trigger the search for a suitable strategy within the framework. For example, the starting point could be a specific technology already in use (e.g. data glasses) and the searcher may look for increased effectivity to influence productivity. In this case β would be the starting point for this search within the framework.

4.3 Combining Productivity Strategies

The applicability of the framework and thus the possibilities for the implementation of selected productivity strategies adapted to specific corporate needs are versatile. This includes the selection of adequate productivity strategies, i.e. a selection of several strategies for a targeted influence on productivity, taking into account the opportunities of digitalization. For example, usage of sensor applications and individualized information provision by means of tablets can be used in parallel and ideally complement each other. The parallel use of several strategies is called strategy mix. A mix will probably be necessary in most cases to cover all needs of the organization to successfully influence productivity on the one hand and to take into account all data-related aspects needed for the implementation of IT-based strategies on the other hand.

The long-term goal of influencing and developing productivity requires a dynamic adaptation of the strategy mix. This will enable the organization to have always those productivity strategies on hand that are currently required. The current status of usage of digitalization does not need to be the optimal one in another point in time.

Determining the right strategy mix is quite challenging. The non-linear and reciprocal relationships between input and output factors are often difficult to determine. In addition, the company should focus on those factors which it can directly affect (ifaa 2016; Wenger et al. 2011). Designing individualized productivity strategies and adapting them over time – within the constraints given or hardly to be changed – is an elementary task.

5 Incorporation of Productivity Goals and Data Management

Strategic approaches to achieve (long-term) productivity goals need to be successively broken down and concretized – e.g. in line with the St. Gallen management model (Rüegg-Stürm 2003) – in order to influence the daily work processes in a targeted manner. There are three major fields that need to be taken into regard (Fig. 2):

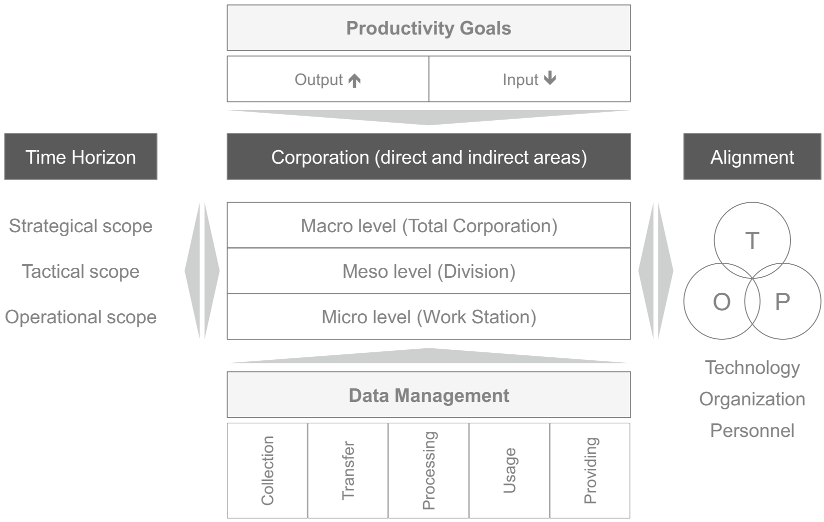

Fig. 2. Integrated view on productivity strategy implementation.

These three major fields to be considered while implementing productivity strategies can be specified as follows:

- Corporation: Productivity strategies using information and communication technologies – regardless of whether direct or indirect areas apply them – need first to be specified for different corporate levels. This means that the corporation as a whole (the macro level) needs to determine actions – as well as interdependencies among them, and these actions must be broken down for each single division (meso level) and further down to each single work stations (micro level).

- Time Horizon: For each application level of a productivity strategy, actions and goals – including key performance figures with their respective target values – must be set for several time horizons, namely for the long-term strategic scope, the mid-term tactical scope and the short-term operational scope. Therefore, every application level from macro to micro should have specific tasks and goals to be reached within different time horizons.
- Alignment: Finally, every usage of information and communication technology for long-term influencing of productivity must be successfully implemented. This requires that the three aspects technology (in a sense of selection, implementation etc.), organization (in a sense of process design and process interactions) and personnel (in a sense of ergonomics and human-oriented work design) need to be considered in an integrative manner.

For every productivity strategy categorized into the framework, all these aspects need to be considered to ensure a successful implementation.

6 Conclusion

Important terms like productivity management and strategies as well as an understanding of digitalization are explained in this article with regard to their integration into the strategic, long-term development of business models and processes. Fundamental opportunities of digitalization – also referred to as Industry 4.0, Smart Factory or Advanced Manufacturing among others – are presented. Based on this, a framework for systematic structuring and designing of productivity strategies is developed, in which various productivity strategies can be classified taking into account the use of information and communication technologies. This framework is based on three axes: the first axis addresses the desired outcome like improving output or decreasing input. The second axis describes the scope of the information and communication technique used. The third axis distinguishes direct or indirect areas for application.

Aspects for successful strategy implementation are mentioned, mainly that productivity strategies must be in-line with the actions performed by the whole company as well as by single work stations, that goals and tasks need to be specified for the long-run as well as for the short-run and that technological, organizational and personnel aspects need to be considered for designing work.

Researchers can classify IT-related strategies for productivity improvement by using the framework and taking into regard the above mentioned details while designing productivity strategies. Practitioners can first get ideas how to structure their existing approaches and how to search new ones systematically. In the long run, the framework will serve as a basis to list a multitude of productivity improvement strategies and identify good-practice examples. Therefore, the presented cube for structuring approaches of digitally supported productivity management and its integration into the strategic context of an organization needs to be further examined with regard to its operational applicability and practicability. The authors currently carry out several surveys to do so.

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Analysis of the Potential Benefits of Digital Assembly Instructions for Single and Small Batch Production

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Abstract. This paper presents the results of a study that was conducted in the Demonstration Factory Aachen in order to analyze the potential benefits of digital assembly instructions compared to paper-based ones. The aim of this study is to validate three hypotheses regarding the benefits in terms of productivity, quality and learning rate. The results will be used to assess the benefits of a potential rollout of digital assembly instructions in a German mid-size company that assembles multi-variant products in the machining equipment sector.

Keywords: Assembly · Digitization · Learning effects

1 Introduction

Individualization of products and reduction of lead-times within a production are two of a set of challenges for modern manufacturing companies. Still, high quality remains a crucial factor. Mass production of homogeneous products is increasingly replaced by more customer oriented manufacturing. [1] On the one hand, industrial production still tries to keep the costs low but on the other hand producers seek to serve the needs of the customers by supplying a high variety of products [2]. A big challenge for producers is to chase both goals without losing track of one of them [3]. In order to cope with these challenges, former manufacturing processes have to be revised as a whole [4]. The principles of Industry 4.0 are commonly seen as one of the most promising answers to the demands of a new efficient production [5].

Research in this area is not comprehensive yet, but the following two studies have been carried out. Höffler and Leutner give a summary of the research that was done in the field of digital assembly instructions [6]. Having analyzed 24 studies with in total 76 comparisons of the instructional effectiveness of animations and static pictures, they conclude that there is a "substantial overall advantage of animations over static pictures". How animations have been designed seems to play a major role for the effectiveness of an instructional animation. [7] After this summary, Curran et al. conducted a study

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similar to the one in this paper. However, they did not exclude learning effects in favor of digital instructions from analog ones as their study participants assembled the products with both an analog and subsequently with a digital instruction. [8]

Especially the findings from Höffler and Leutner emphasize the relevance of the regarded research question. In order to analyze the benefits of Industry 4.0 at a relatively basic level, a study was conducted researching the effects of using digital assembly instructions in comparison to conventional, paper-based ones in terms of productivity, quality and learning rate. In this study that will be presented in this paper, 24 test persons were asked to assemble penholders using either a digital or an analog assembly instruction and simulating a small batch production. The results have to be seen with caution, considering the number of test persons. Though this study serves as a first pointer for further research, the results suggest high benefits of implementing digital assembly instructions especially for single and small batch production. In the following chapter, the materials and methods used in the study are described.

2 Materials and Methods

The study was conducted at assembly stations in the Demonstration Factory Aachen (DFA), in which a transformable production is depicted in a real production environment and in which production systematic and logistical questions are researched on the basis of empirical data. The test persons were students of RWTH Aachen University who also work as student assistants in the Laboratory for Machine Tools and Production Engineering (WZL). None of the test persons knew the test before. In the following, the detailed execution of the tests is described and the underlying hypotheses presented.

2.1 Description of Test Execution

In total 24 students took part in the experiment on ten different dates in the DFA, assembling ten penholders per date using either a digital or an analog assembly instruction. On average, four test persons participated at each date. In order to get background information of the participants on age, field of studies and prior knowledge a questionnaire was handed out. Concerning prior knowledge the participants were asked for a self-assessment compared to their colleagues in terms of experience in assembling, experience in handling CAD programs, abilities in engineering drawing and overall technical abilities each on scale from one (very low) to five (very high). After completing the questionnaire, the test persons had to assemble a penholder by using either a digital assembly instruction or an analog one. A penholder consists of eight steel sheets that are to be assembled with different types of screws in several sizes combined with washers as shown in Fig. 1. The test persons needed to use Phillips and Allen screwdrivers in different sizes. They were told that they would assemble different versions of the penholder in each of the ten rounds. The exact number of variants was not known to the test persons. In fact, there have only been four different versions that differed in the orientation of the components and the selection of screws.

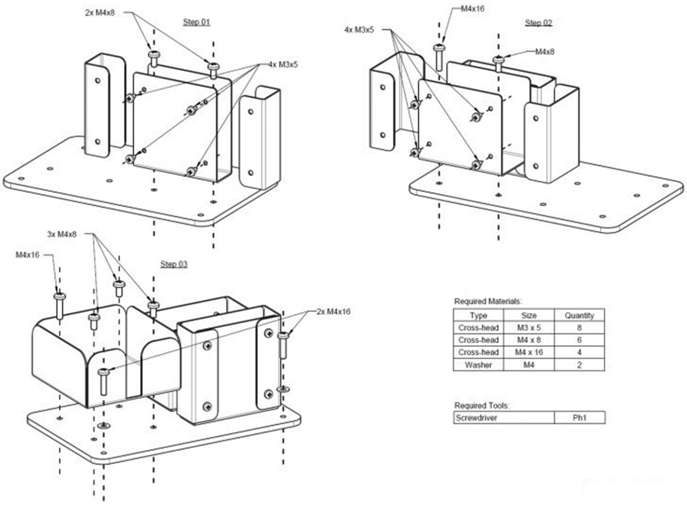

Fig. 1. Example of a variant of the penholder

The paper-based instructions looked like the one shown in Fig. 1. The instructions for the different variants were collected in folders at the assembly stations. When starting the time, each test person got the number of the version to assemble at a desk between the assembly stations. Having got the number, the test person walked to his/her assembly station, looked up the matching instruction and began to assemble the penholder using the components lying on the stations in several signed boxes. After completion, the test person brought the fully assembled penholder back to the starting point, checking the time again. Subsequently, the penholder was inspected on defects.

The test persons with the digital assembly instructions were handed a laminated sheet of paper with a Radio Frequency Identification (RFID) tag on its back, which is used to communicate with a sensor above the assembly station. Placing this sheet of paper on the sensor, the digital instruction was automatically loaded on a touch screen according to the matching version. The digital instructions consisted of step-by-step animations with a list of c-parts and highlighted the right parts to assemble in a special color on a tablet screen. By touching the screen, the test persons could switch between the assembly steps and were able to turn the images in three dimensions.

The group of participants consisted of 24 people being on average 22.2 years old. 21 test persons were male and three female. Half of the test persons were provided with digital assembly instructions and the other half got paper-based ones.

The participants were composed of students from the fields of mechanical engineering (25%), industrial engineering (50%) and scientific programming (25%). They were asked to give a self-assessment about several aspects on a scale from 1 (very low) to 5 (very high). With regard to the assessment of the technical skills, the values of the mechanical engineering students were with 2.83 just slightly higher than those of the industrial engineering students with 2.67. The students of scientific programming assessed their skills with a value of 1.64 substantially lower. The allocation of the analog and digital instructions to the group of participants was done randomly. However, the self-assessment of the technical skills in the group with the digital instructions was on average 35% higher than in the group using the analog one, which all scientific programmer were part of.

2.2 Hypotheses of the Benefits

Before the study was carried out, three qualitative hypotheses were proposed for the expected results with regard to the improvement of the benefits in terms of (1) productivity, (2) quality and (3) learning rate (see Fig. 2). The first hypothesis states that the productivity of assembling a variant with a digital assembly instruction is higher than with an analog one with regard to lead-time. The second hypothesis is that the number of errors per assembled penholder is lower when the penholder is assembled using a digital assembly instruction. As a third hypothesis it was formulated that assemblers are quicker to learn how to assemble the penholders when using a digital assembly instruction, being quantified by using the learning rate. The learning rate describes the inverse relationship between costs per unit and number of units being produced. In the study, a proportional relationship between lead-time and costs per unit is assumed. Even though the quality of the products produce it is not represented in this figure, it still has to be kept in mind when assessing the learning rate.

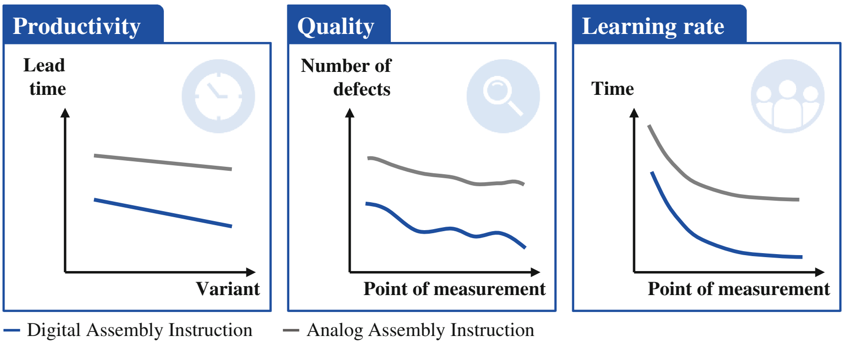

Fig. 2. Hypotheses

3 Results and Discussion

In the following, the results will be presented. Subsequently, the findings based on the results will be discussed.

3.1 Results

Before analyzing the data in depth, the sample is checked on outlier. Analyzing the defects it becomes obvious that there is one outlier in the group of participants using the digital assembly instruction. While the assemblers in the group of study participants using the analog instruction were a homogeneous group with a standard deviation of

1.19 with regard to quality, the group of participants using the digital instruction had one member who made disproportionately many mistakes resulting in a standard deviation of 2.6 for this group. Excluding this participant for the analysis of the data, the standard deviation drops from 2.6 to 1.24, which is close to the 1.19 of the other group. Hence, it makes sense from a statistical point of view to analyze the data excluding the outlier. The following results have arisen concerning the three hypotheses of productivity, quality and learning rate after excluding the outlier in the analysis.

The study confirms the expected outcome of a higher productivity when using a digital assembly instruction compared to the analog one (see Fig. 3). Assembling the first penholder, the study participants with the analog instruction needed on average 31.2% more time (in total 12 min and 51 s) than the participants did with the digital one (9 min and 48 s). Even though the difference became smaller with the number of penholders assembled, the results for the digital assembly instruction were for the last five points of measurement on average still 14.9% better. Overall, the productivity of the analog assembly instruction was 17.0% worse, meaning that assemblers needed on average 01:01 min more time per piece.

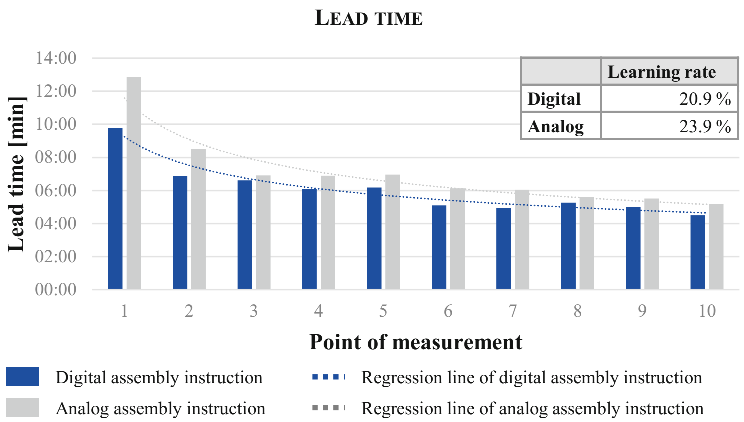

Fig. 3. Development of lead time

Before going into the analysis of the results, it is important to understand the performance indicator used to describe the quality. Instead of using the simple number of defects per unit, the defects are weighted based on their severity. For example, using a wrong screw (e.g. different length) is less important for a penholder than a wrong position of the objects on the main plate (e.g. the container). Hence, the defects are weighted with factors from one to three.

Analyzing the plain data, the outcome was that the weighted number of defects was 96 defects for the analog assembly instruction while using a digital one resulted in 76 defects. Overall, the numbers mean on average 0.8 defects per assembled penholder for the analog assembly instruction and 0.69 for the digital one, which leads to the conclusion that the hypotheses can be confirmed as well (Fig. 4). The outlier of weighted defects in the second point of measurement of the digital instruction can be explained by a high number of mistakes made by one test person. Comparing these figures, the study shows that the former group made on average 15.7% more defects per penholder than the group with a digital assembly instruction. Additionally, it can be seen in the study that in case of using a digital instruction the last 80% of the assembled penholders had only 6.6% of the total number of defects, whereas the analog instruction had in the same timeframe 26% of the total defects of the analog one. Directly comparing the absolute numbers, the group of assemblers with the analog instruction made five times more defects in this timeframe. For the first 20% of the assembled products the ratio between the two kinds of assembly instruction is 1:1. These findings can be explained by the hypothesis, that a digital assembly instruction helps assemblers to understand the way of assembling the product better and more sustainably than the analog one.

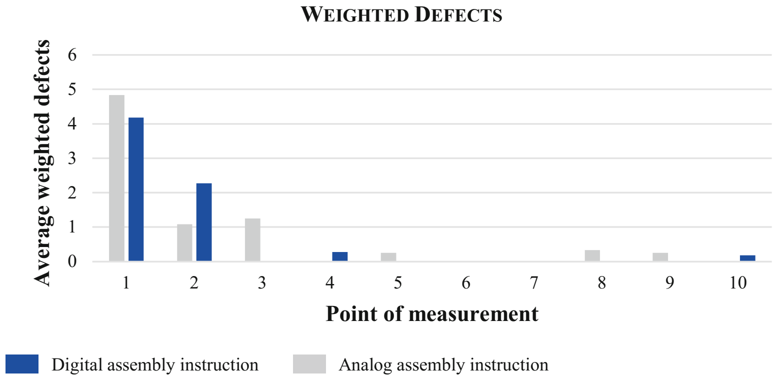

Fig. 4. Weighted defects

While the first two hypotheses can be confirmed, the last hypothesis concerning the learning effects has to be rejected. As can be seen in Fig. 3, the learning rate of assemblers using the digital assembly instruction was 20.9% whereas the assemblers with an analog instruction had a learning rate of 23.9%. This means that for every doubling of the number of penholders having been produced the costs per unit fell on average on 79.1% of the initial value of the assembly costs when using a digital instruction. Hence, the analog assembly instruction seems to be about three percentage points better with regard to the learning effects. However, taking quality in consideration when assessing this figure, the advantage of analog instructions declines.

3.2 Discussion

The results confirm two of the three hypotheses, if the outlier in the analysis of the quality is excluded. Still, it has to be pointed out that the number of participants in the study was small. Conducting the study with a higher number, the influence of the outlier on the results would have been less significant. With the number of participants being small, the results have to be seen critically. Especially the fact that the number of weighted defects of the last 80% of assembled products account only for 17.4% of the total number of defects and with 89.1% of all assembled products being flawless, indicates that the wealth of variants of the penholder was too low for the participants. On the other hand, those numbers can show that a digital assembly instruction helps to improve quality significantly compared to an analog one, when assembling similar products in high quantity.

Concerning the productivity, the results indicate that a digital assembly instruction has a significant potential of reducing the lead-time per unit. In particular, the study shows that the potential is even more promising, the more variants are assembled with a small number of totally assembled products as the difference in the lead-time is at the beginning substantially higher. This finding is especially interesting for companies with small lot sizes, i.e. companies in the single and small batch size industry, and companies having a high employee turnover. Considering current developments of shorter product life cycles, this advantage of the digital assembly instruction is even more promising even for other industries.

As stated in Sect. 2.1, all scientific programmers assembled the penholder using an analog instruction. With their self-assessment being as low as 1.64 compared to the 2.67 and 2.83 respectively, one might expect worse results for this group of participants. However, this is only the case in terms of quality but not in terms of lead-time. Having assembled almost twice as much defects (64.6% of the total amount of defects in the group of participants using the analog instruction), they were as fast as the other part of the group with just one second less of the overall time needed. If the digital assembly instruction truly helps to understand the way of assembling products better and more sustainably as stated in Sect. 3.1, needs to be further researched.

Having a look at the test execution, it has to be stated that there was a difference of the position of the assembly instruction. Whereas the analog one lied on the assembly table next to the components that were to be assembled, the screen for the digital one hung in front of the assemblers. Moving down the screen to the position of the analog instruction could lead to even better results of the digitally instructed products.

4 Conclusion

In times of an increasing amount of variants and shorter product life cycles, a study was conducted in order to analyze the potential of digital assembly instructions compared to analog ones in the closed environment of the DFA. Besides researching the consequences on lead-time and learning effects, the study observed the quality of the assembled products, in order to prevent a potential loss of quality in favor of lead-time.

As expected and formulated in the hypotheses, the study proved that digital assembly instructions lead to a rise in the productivity of the assemblers compared to their colleagues with analog instructions. Excluding one outlier from the test data of the digital assembly instruction, the study proved furthermore that a digital assembly instruction helps assemblers to assemble products not only faster but also with less defects in both short- and long-term perspective. In terms of learning effects, the analog assembly instruction showed better results, which is caused by high initial lead-times compared to the ones that used digital one. Hence, it is to further research under which conditions digital assembly instructions should be used, taking into consideration, that deriving digital instructions can be expensive in the single and small batch industry, it is to analyze how a critical number of products per variant can be determined to assess the economical suitability. By an increasing complexity of products, this question becomes even more relevant considering the advantages in terms of efficiency and quality.

With the number of participants being small, further research needs to be done to validate the results. In cooperation with the German mid-size company Ortlinghaus-Werke GmbH this will be done in their assembly lines in the plant Wermelskirchen.

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Integrated Production and Maintenance Scheduling Through Machine Monitoring and Augmented Reality: An Industry 4.0 Approach

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Abstract. Maintenance tasks are a frequent part of shop floor machines' schedule, varying in complexity, and as a result in required time and effort, from simple cutting tool replacement to time consuming procedures. Nowadays, these procedures are usually called by the machine operator or shop floor technicians, based on their expertise or machine failures, commonly without flagging the shop floor scheduling. Newer approaches promote mobile devices and wearables as a mean of communication among the shop floor operators and other departments, to quickly notify for similar incidents. Shop floor scheduling is frequently highly influenced by maintenance tasks, thus the need to include them into the machine schedule has arisen. Moreover, production is highly disturbed by unexpected failures. As a result, the last few years through the industry 4.0 paradigm, production line machinery is more and more equipped with monitoring software, so as to flag the technicians before a maintenance task is required. Towards that end, an integrated system is developed, under the Industry 4.0 concept, consisted of a machine tool monitoring tool and an augmented reality mobile application, which are interfaced with a shop-floor scheduling tool. The mobile application allows the operator to monitor the status of the machine based on the data from the monitoring tool and decide on immediately calling AR remote maintenance or scheduling maintenance tasks for later. The application retrieves the machine schedule, providing the available windows for maintenance planning and also notifies the schedule for the added task. The application is tested on a CNC milling machine.

Keywords: Maintenance · Scheduling · Augmented reality · Machine monitoring · Industry 4.0

1 Introduction

As modern manufacturing marches towards Industry 4.0, unified solutions that integrate Information and Communication technology (ICT) and sensors while remaining agile and adaptive to environment conditions are being developed, updating physical systems to cyber physical systems [1]. Currently, production scheduling software packages are

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used by the majority of manufacturing companies. Though capable of supporting the production in an adequate level, they fail to integrate production line disturbances, thus creating inaccuracies in high- altering systems [2]. One of the main causes of changes in the schedule is maintenance tasks, which, though they are a common part of the machine's lifecycle, are not reported back for rescheduling. Event-driven rescheduling could dictate a more flexible and close to the real system method of tackling this issue [3, 4].

Maintenance is an important part of products' lifecycle, accounting for a high percentage of its total cost [5] and having a high impact on the utilization period of the machine. In the last few years, manufacturing companies have started adopting monitoring solutions in order to increase system reliability through reducing the unplanned breakdowns. Machine condition monitoring systems are being implemented in modern machinery informing human operators for the majority of the upcoming maintenance tasks, based on Wireless Sensor Network (WSN) input [6], defining the remaining operating time between failure of the machine tools [7]. Moreover, the last few years, new technologies are starting to be implemented in maintenance processes in order to increase its efficiency and facilitate the maintenance support service provision. Augmented Reality is one of the upcoming technologies in manufacturing [8] with numerous applications aiming to provide remote maintenance support [9, 10], in an effort to facilitate technical knowledge distribution in a digitalized and easy-to-perceive way. Additionally, it poses a digitalized way of bridging the gap between the CAD files the maintenance instructions manuals. To facilitate system communication, cloud platforms have emerged as a viable solution in manufacturing systems, as they enable the seamless data and knowledge exchange from different systems embedded in the shopfloor and its users [11]. Moreover, high security of these systems makes them a viable solution to combine with different wireless sensor networks, providing unified solutions of monitoring and acting on the production line by bringing together different systems and stakeholders [7].

The literature review makes apparent that although there is a lot of progress in implementing isolated solutions for machine monitoring, scheduling and maintenance support, there are limited unified approaches integrating communication between operational planning and maintenance planning [12]. Aiming to create an integrated framework that, following the concept of Industry 4.0, will bring together these systems, an application that will support production and maintenance scheduling through machine monitoring and Augmented Reality maintenance instructions is developed. The developed application integrates all the necessary connections that will allow the machine operator to monitor the status of the machine, schedule maintenance tasks and communicate with a maintenance expert so as to receive AR maintenance instructions remotely. The developed application is applied in a CNC milling machine use case.

2 Integrated Production and Maintenance Scheduling via Machine Monitoring and AR Technology

This work proposes an integrated solution for combined production and maintenance scheduling, by receiving input from a machine monitoring system. The framework combines three major functionalities: (i) machine health status visualization, including the remaining operating time between failures (ROTBF), (ii) maintenance scheduling based on current production schedule and (iii) remote maintenance support supported by Augmented Reality. All the functionalities are bundled in a mobile device application that is used by the machine operator. The workflow that shows all the actions and the sub- systems of the framework is presented below in Fig. 1.

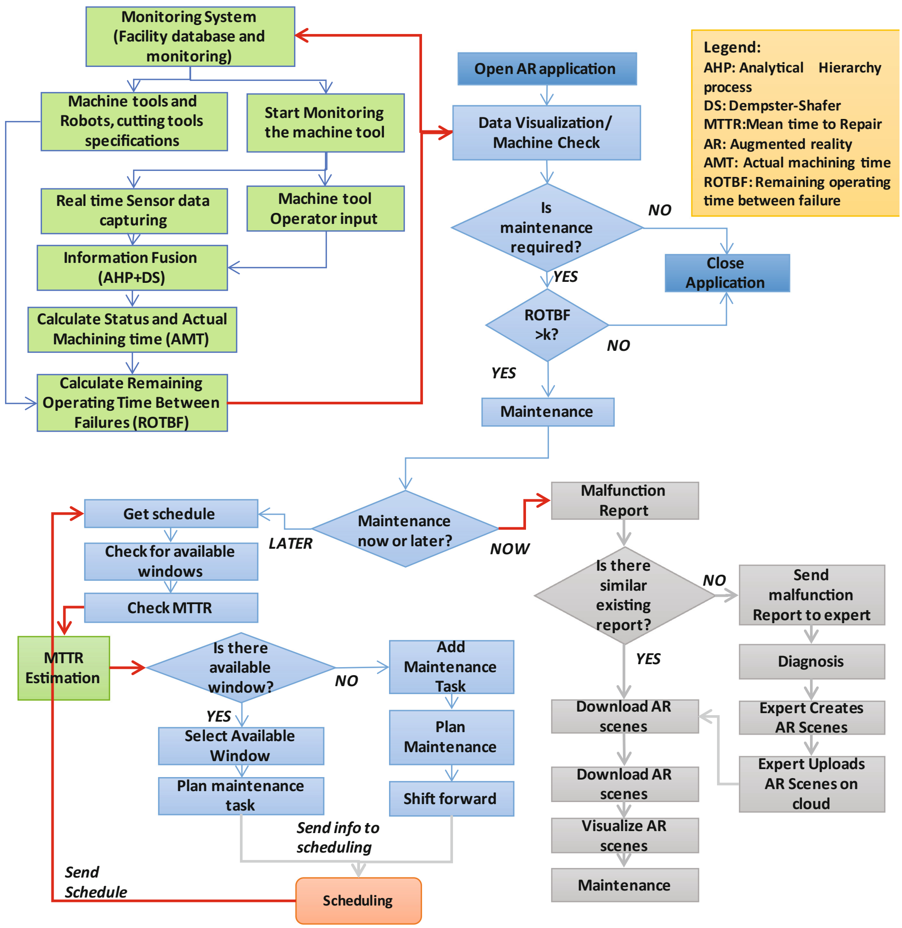

Fig. 1. Workflow of the proposed framework

The first step of using the developed application is the status monitoring of the machine. The machine is equipped with a data acquisition (DAQ) device that monitors the status of the manufacturing resources and especially machine tools [13]. The monitoring device, through current and voltage sensors, gathers real time sensor data and transmits them through a wireless sensor network to a central database where the status of the machine (down, busy or idle) is detected and the actual machining time (AMT), the machine tool utilization and availability are calculated. Since the mean time between failures (MTBF) per machine is known as a technical characteristic, using the following Equation, the remaining operating time between failures (ROTBF) is calculated:

$$\text{ROTBF} = \text{MTBF} - \text{AMT} \tag{1}$$

To connect the visualized results with each machine, an AR marker is placed on each one. The operator, using the developed application, scans the AR marker and calls the status information of the machine and the ROTBF in the GUI of the application. Then, based on the ROTBF of the machine, the operator may plan ahead the maintenance task. Whenever the ROTBF is below a preselected threshold k (e.g. 10%), the operator is notified that a maintenance task will be needed shortly. At this point, the operator calls, through the application, the machine schedule and the mean time to repair for the required process. The mean time to repair is either extracted by past maintenance tasks, if the same task has re-occurred or, by implementing sophisticated algorithms that may provide a trustworthy estimation, such as Case-based Reasoning (CBR) [14]. Based on the estimated duration of the maintenance task and the machine schedule, the operator may either, if possible, plan the task for a timeslot when the machine is idle or plan it whenever the operator thinks is necessary despite of the current schedule; this feature is highly important, especially in cases of unexpected breakdowns. In both cases, the information related to the maintenance planning is returned back to the scheduling system. In the present approach, the remaining tasks of the machine are shifted right on the schedule, always checking if a task has to be shifted to another working shift or even another day.

Moreover, the developed application supports the operator in dealing with maintenance procedures that the operator may have limited experience on. The operator, through the same application, receives the maintenance instructions by a maintenance expert that can be remote located, in a digitalized form, exploiting Augmented Reality [15]. The technician may connect to a cloud database that includes all the past AR maintenance instructions, organized per machine and named in an easy-to-perceive way, and download the required procedure. In case the malfunction is not listed in the database or the operator is not aware of the cause, a malfunction report is constituted by the operator and sent to the maintenance expert. The application allows the operator to write explanatory text, take photos and sound recordings that will facilitate the expert to diagnose the malfunction cause. This expert may either be from the machine manufacturer, an external specialized technician or even from the central maintenance department of the company. The expert diagnoses the malfunction cause and creates the AR maintenance instructions, which are sent back to the on-spot technician through the cloud database. To support this process, a series of pre-created part animations, GUIs and scripts have been developed. Moreover, an algorithm that breaks down the assembly

CAD to assembly/disassembly steps has been implemented; this way the instructions for the assembly processes of the maintenance task can be easily created, saving a lot of time since they account for a large part of the maintenance tasks [15]. The operator receives the AR instructions in the mobile device, performs the maintenance and validates that the machine is operational again.

3 System Implementation

In order to implement the machine monitoring, a data acquisition device was developed. It utilizes split-core current transformers as current sensors, a closed loop hall current sensor, voltage sensors, as well as a camera. A WSN is established so as to send the data from the DAQ for processing and to make them accessible by the integrated application. The WSN is facilitated with the use of DIGI XBee ZigBee RF module [16]. ZigBee is a specification of the IEEE 802.15.4 standard. The selection of ZigBee over other wireless standards is due to its support to various network topologies and encryption algorithms, and its robust operation with functionalities, such as collision avoidance, retries, and acknowledgments performed in the hardware. In order to derive the status of the machine, as well as the AMT, an information fusion technique consists of the Analytical Hierarchy Process (AHP) and the Dempster–Shafer (DS) theory of evidence [13] was applied. To develop the integrated application and also to create the AR maintenance instructions, two commercial software tools were used: Unity [18] and Vuforia [17]. The first one supports the creation of high quality and usability GUIs that guide the operator through the available functionalities and supports seamless connection with the cloud databases, while also allowing the application to be directly built as a mobile device app for Android OS. The latter, used as an add-on on the first, is used to add Augmented Reality features into the maintenance instructions and the monitoring application. Moreover, in an effort to support and partially automate the AR maintenance instructions generation process, an algorithm that breaks down the assembly CAD into steps of assembly and disassembly is implemented [15].

Furthermore, the algorithm detects the axis and direction of assembly/disassembly for each part thus allowing quick implementation of part animations in the AR scenes. An important part of the proposed framework is the integration and communication with various other platforms. The developed application connects to applications and cloud platforms via internet so as to send and receive data, creating a set of interconnected tools that function together; the data exchange between those tools can be seen in Fig. 2. The application receives the AMT as an input from the monitoring system through an xml file. When a maintenance task needs to be planned, the MTTR is either extracted by past maintenance tasks, if the same task has re-occurred or is estimated using similarity mechanisms and algorithms. Then, the machine schedule is called, updated with the task and returned back to the scheduling; both data exchanges are performed via xml. When sending a maintenance report, the operator sends text, photo and sound files and receives a sequence of AR scenes that can be directly loaded by the application.

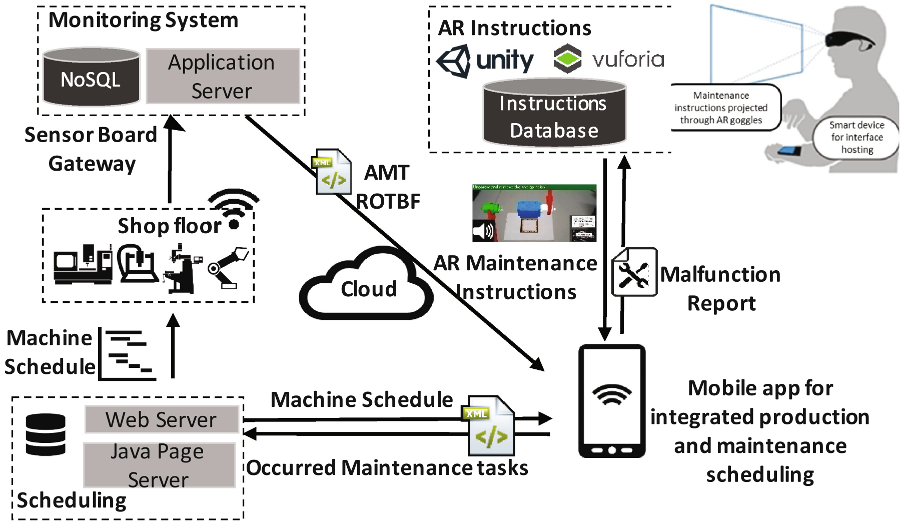

Fig. 2. Interfaces between the developed application and other tools and databases

4 Case Study and Results

The proposed applications are validated in a case study including a three axis CNC machine tool XYZ SMX SLV. In the current procedure, the operator of the machine tool plans a maintenance task based on a breakdown that may occur, without considering any data from the machine tool. The maintenance department is informed on the maintenance issue and deploys the maintenance expert to go on spot to diagnose the issue and physically perform the maintenance task in the production plant. In an effort to eliminate this need and reduce maintenance time and cost, the proposed system is applied. The developed monitoring system considering the data acquisition device and the WSN was set up. The monitoring system gathered all the necessary data to identify the machine tools status, the actual machining time, as well as the ROTBF.

Using the developed application, the technician could foresee the required maintenance task and plan it ahead in an available timeslot in the machine schedule. In this use case, an unexpected maintenance task is occurred, where the cutting tool and the tool holder needed replacement due to tool breakage. The operator directly connected to the AR maintenance instructions database, downloaded the corresponding maintenance instructions on how to change the cutting tool and the tool holder performing the maintenance task. Moreover, using the same application, the operator could plan the task for a later timeslot, and update the machine schedule. The sequence of actions followed by the technician are visualized in Fig. 3. By implementing this application on the shop-floor, the operator is capable of monitoring the status of the machine, pre-identifying malfunction and scheduling their repair, while updating the machine schedule in a way that is more efficient and easier to use than the currently existing methods, bundled into one software. In case of an unexpected maintenance task the operator through the proposed system calls the AR maintenance instructions and performs the maintenance tasks easily, quickly and with low cost. Based on the first implementation of the proposed tools, it is estimated that the awareness of machine tools' condition will be increased over 30% and the response time to changes will be decreased over 25%. Moving also towards Industry 4.0, the proposed approach enables the integration of different systems supporting integrated planning and control, increasing systems interoperability and efficiency.

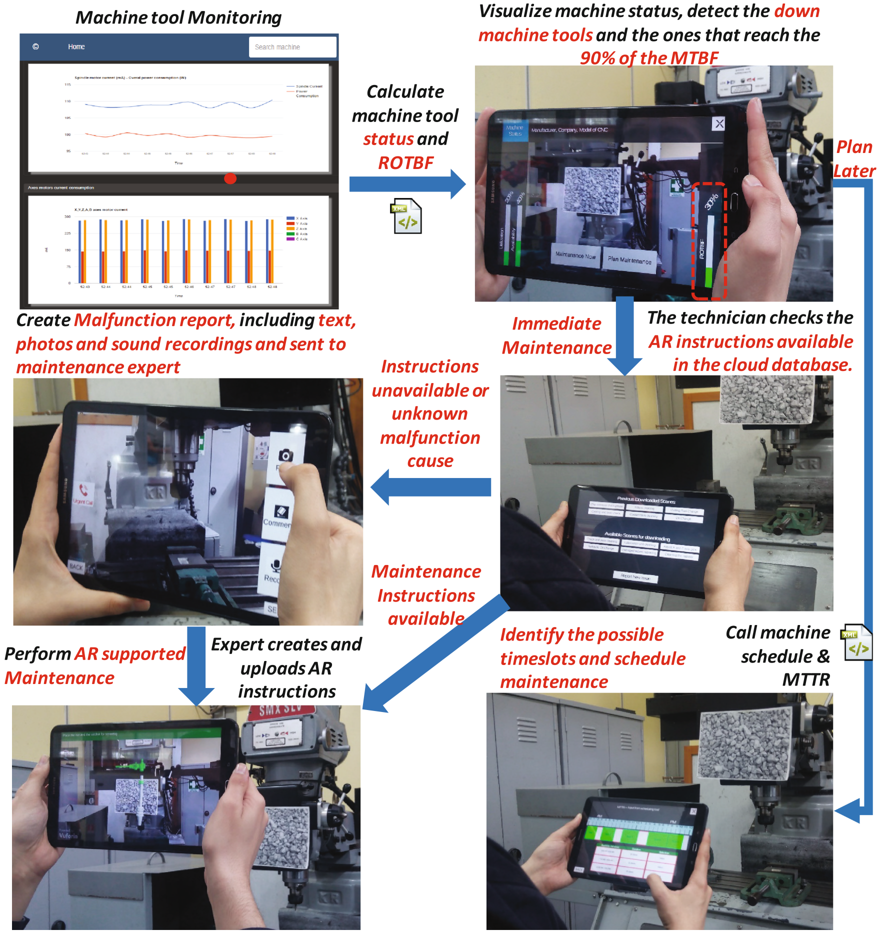

Fig. 3. Application of the developed framework

5 Conclusion and Future Work

The proposed work presents an integrated way of production and maintenance scheduling supported by augmented reality technology and real-time machine monitoring, aiming to move towards industry 4.0. The developed system exploits sensor data from production machines to perform condition-based maintenance and integrated scheduling and AR supported maintenance, implemented as a mobile device application. The system includes all the required connections that allow the application to receive data from the sensors so as to monitor the remaining operating time between failure, plan a maintenance task based on the available timeslots, update the machine schedule based on the maintenance task's duration and the connect to a cloud database of AR maintenance instructions. Moreover, in order to improve the AR maintenance instructions generation and secure the high quality of the generated result, the maintenance expert is supported by a set of functionalities that facilitate and accelerate the instructions generation process, based on an algorithm that breaks down the assembly tasks and pre-created GUIs and animations. The proposed system increases system's interoperability, efficiency, and communication, providing useful data from the monitoring system which can be further analyzed and transform isolated planning and control systems into adaptive. As a step towards Industry 4.0, the proposed system integrates data from different sources (scheduling system, monitoring system) and supports the human operator through a mobile device to plan and perform maintenance tasks easily and efficiently, increasing system's productivity. Future work will be focused on enhancing the existing approach and predicting the ROTBF based on the sensory data. Moreover, it is important to connect the developed application to other mobile devices, such as smartwatches, in the production line keeping in mind the projected marching towards Industry 4.0. Finally, it is important to study the implementation of the system to other, more complex use cases.

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Recipe-Based Engineering and Operator Support for Flexible Configuration of High-Mix Assembly

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Abstract. Nowadays, manufacturers must be increasingly flexible to quickly produce a high mix of on-demand, customer-specific, low volume product types. This requires flexible assembly lines with operators that are well-supported in their constantly changing assembly task, while producing high-quality, first-time-right, zero-defect products. Information coming from various supporting systems, such as ERP, MES and operator support systems, needs to be combined by the operator that configures the assembly line with materials, instructions and machine initialization settings. In this paper, we present a knowledge model that captures the main concepts and their relations in flexible manufacturing to deal with these challenges. This model is constructed by integrating existing manufacturing ontologies and can be used as the basis for information collection, exchange and analysis in information systems used in flexible manufacturing. The model supports (1) easy definition of recipe-based manufacturing instructions for engineers and operators, and (2) flexible, modular and adaptive support for human/cobot instructions. We also describe a demonstration set-up with an existing operator support system (OPS) in which the recipe concept is used in the engineering process to easily reuse existing modular components for assembling different product types.

Keywords: Recipe-based manufacturing · Operator support · Modular and adaptive instructions

1 Introduction

In the manufacturing industry, there is currently a trend towards personalized manufacturing to meet specific customer needs. Instead of mass-production of a single product type, manufacturers must be able to quickly produce on-demand, customer-specific, slightly different types of the same product. To avoid maintaining a large stock of each of these product types, these manufacturers must be able to handle a high mix of low volume product types. This requires flexible assembly lines with operators that are well-supported in their constantly changing assembly task. Flexibility in executing these assembly activities should increasingly lead to high-quality, first-time-right, zero-defect products.

In the context of this trend towards flexible manufacturing, currently available assembly manufacturing systems cannot cope well with the resulting requirements. These systems are usually manually configured for a new product order, which is

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increasingly inefficient in a flexible manufacturing environment that combines manual assembly cells, collaborative robots (cobots) and automated test stations. Information coming from various supporting systems, such as ERP, MES and operator support systems, needs to be combined by the operator that configures the assembly line with materials, instructions and machine initialization settings.

The IT support in current MES solutions is very solution-specific and does not make use of standardized, modular components to build recipes for production processes. Furthermore, state-of-the art operator support systems do not consider adaptability based on the actual skill level and instantaneous operator capacity. Feedback from real-time measurements of performance, workload and motivational aspects and assembly instructions can provide customized instructions to the human operator and thereby improve motivation, workload and productivity/product quality.

In this paper, we present a data-driven approach to deal with these challenges that results from the cooperation within the Dutch FlexMan project between three industry partners in the manufacturing area, Bronkhorst, Omron and TE Electronics, and TNO as knowledge institute. The FlexMan project is one of the fieldlabs in the Smart Industry Initiative, that aims to accelerate development, test and implementation of smart industry technologies in collaborating networks of companies[1]. We define a knowledge model that captures the main concepts and their relations in flexible manufacturing. This model can be used as the basis for information collection, exchange and analysis in information systems used in flexible manufacturing. The model supports (1) easy definition of recipe-based manufacturing instructions for engineers and operators, and (2) flexible, modular and adaptive support for human/cobot instructions.

In the next section, we discuss the concept of flexible, recipe-based assembly and describe in more detail the environment in which the engineer and the operator need to deal with a high mix of low-volume product types. Then, we introduce our knowledge model and describe the various views on products, processes, resources and recipes. Successively, we describe a set-up in which the recipe concept of this knowledge model is used in the engineering process to easily reuse existing modular components for assembling different product types. In addition, we describe how the operator is supported with generic instructions defined in the knowledge model. Finally, we present our conclusions and future work in this field.

2 Flexible, Recipe-Based Assembly

Manufacturers offer flexibility in products by giving customers the option to select for instance different colors, sizes, materials and other variables of the product in low volumes. This creates a few process engineering and operator support challenges.

Before introducing these flexibility options to the customer, the process engineer needs to design manufacturing processes for multiple types of the same product with only small differences. These manufacturing processes consist of a combination of assembly, configuration and testing steps including operator instructions that are mostly

[1] Smart Industry initiative, https://www.smartindustry.nl/en/.

generic and thus reusable for each product type. They only differ in the specific materials and resources to be used which can vary in number, size, colour etcetera as well as in the order in which the process steps need to be executed.

Consequently, the process engineer needs a design environment that gives support to the task of easily developing a manufacturing process for a new product type. The (re) use of recipes with basic configurations of process steps and their operator instructions is a good approach to this engineer task. From these recipes, flexible instruction sets can be automatically generated to guide the division of the tasks of the operator possibly in combination with a collaborative robot (cobot) during the manufacturing process.

In a flexible manufacturing environment, the assembly line operator is confronted with a high mix of assembly tasks resulting from customer-specific low-volume product orders. In principle, any next assembly task differs from the previous one as a different product or product type needs to be assembled.

In such a rapidly changing environment, the operator support should be maximally suited towards the operator by giving him/her simple and clear instructions on what to do. An example of such a support system can be found in Fig. 1 in which instructions and assembly locations are projected onto the working space of the operator. Apart from the exact technology of the front-end operator support system (projection, presentation, hololens), the main challenge is to switch rapidly between the instructions of different product types. A recipe-based IT system that supports the operator is well-suited for this challenge.

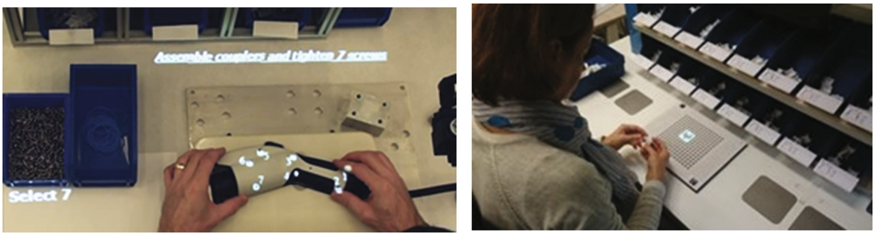

Fig. 1. Flexible operator support system with instruction projection.

Consequently, a recipe-based knowledge model is needed that is used to make the various IT systems involved in manufacturing interoperable, such as the ERP system with product orders, the engineer system that produces the recipes, the MES system that guides the operational manufacturing and the operator support system that instructs the operator. In the next section, we describe this knowledge model in more detail.

3 Related Work

Ontologies are explicit, formal specifications of terms in the domain and of the relations among them [1]; the fact that formal logic underlies the model makes the ontology machine-readable and – interpretable. Our knowledge model is an ontology of concepts and relations relevant to the processes of flexible manufacturing and recipe-based assembly.

Existing assembly design and manufacturing models have been studied to define our knowledge model. These ontology models for assembly processes focus among others on unified approaches towards reconfigurable assembly system design [2], geometry information or variability in an extensive assembly design ontology (AsD) [3] and assembly process planning, defining process operations and required resources [4]. MASON [5], is a well-known model that presents generic core ontologies for knowledge sharing and interoperability in the manufacturing domain, specifying concepts for products, operations and manufacturing resources. An MDA approach to define concepts in the product lifecycle is presented in [6]. The ontology we present here builds on these existing domain models by reusing concepts relevant to the context and needs of our model.

A recipe-based semantic approach to assembly has been presented in [7] as a methodology for product-resource requirement integration, without taking the concept of a recipe explicitly into account. International standardization for process control ANS/ISA-88-2010 [8] defines a procedural control models for batch process control. The ontology discussed in this paper, adapts some of the ideas behind this standard and defines the concept of recipe as well as recipe procedures explicitly in order to support recipe-based manufacturing in an assembly cell.

4 Knowledge Model for Flexible Manufacturing

We discern four distinct models to formally define the domain: (1) a product model that defines building blocks for products and how they are related, (2) a process model that describes both logical and temporal structures for activities, (3) a resource model that expresses a functional and logical structure for manufacturing facilities and resources and finally (4) a recipe model that defines recipes as a set of instructions for manufacturing products. The model has been designed with input from all stakeholders in the FlexMan project to assure its compliance with current practices in manufacturing.

Product Model

The product model (Fig. 2) consists of products (*Product*) as things that have been manufactured to be sold to a customer (third party). Products are manufactured in a facility (*ManufacturingFacility*) and are either components (*Component*) provided by third parties or complex subassemblies (*Assembly*) of their own that come from a source outside the assembling system in question. Every product is an assembly object (*AssemblyObject*) that has a certain state (*State*). That state (ready, nearly-ready, in-progress, etc.) changes due to activities in the manufacturing process (cf. process model). Manufacturing resources such as parts (*Part*) and raw material (*RawMaterial*) are input to the assembly process.

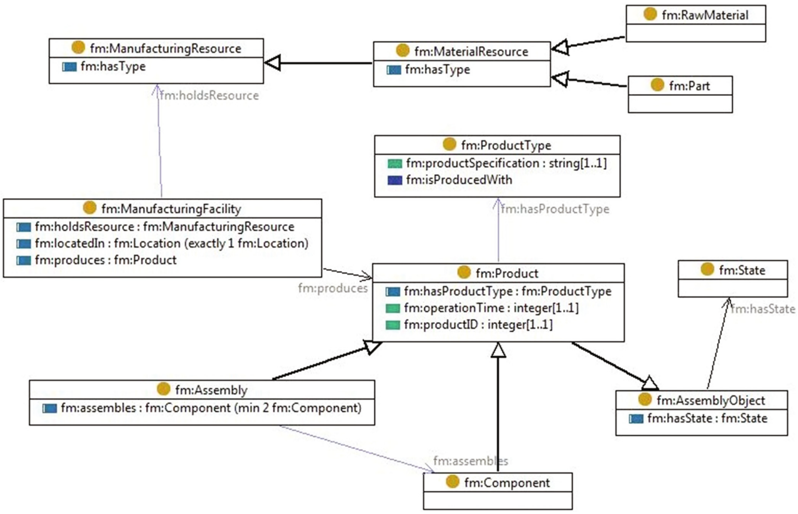

Fig. 2. Product modelling in the knowledge model.

Process Model

The process model (Fig. 3) describes both logical and temporal structures for activities (*ActivityType*) on four different levels:

- Processes (*ProcessType*), are collections of lower level activities with the purpose of facilitating assembling of an assembly or subassembly. They are described by means of recipes (e.g. assemble PC) and are composed of tasks.
- Tasks (*TaskType*) are processes which facilitate a clearly definable portion of work towards the completion of a product (e.g. assemble parts A and B). A task is composed of a set of operations.
- Operations (*OperationType*) are activities which facilitate a state change of entities that are part of a product within the scope of a specific Task. An Operation is composed of a set of Actions. Operations are normally carried out by Equipment Units.
- Actions (*ActionType*) are the most fundamental activities (hold part A with tool 1), defined by use of equipment (*EquipmentResourceType*) and requiring a certain capability (Capability) from a physical agent (human, robot/cobot).

Every activity has a description (*ActivityDescription*) and several time parameters (*TimePoint*), such as start/stopping time.

Recipe Model

In the context of assembly, we consider a recipe to be a set of instructions on manufacturing a product. Rather than viewing it as an object with properties we consider it to be a process, which has a series of steps or activities required for its execution and the materials and utensils needed. In our model (Fig. 3), a recipe (*Recipe*) holds the necessary set of information that uniquely defines the production requirements for a

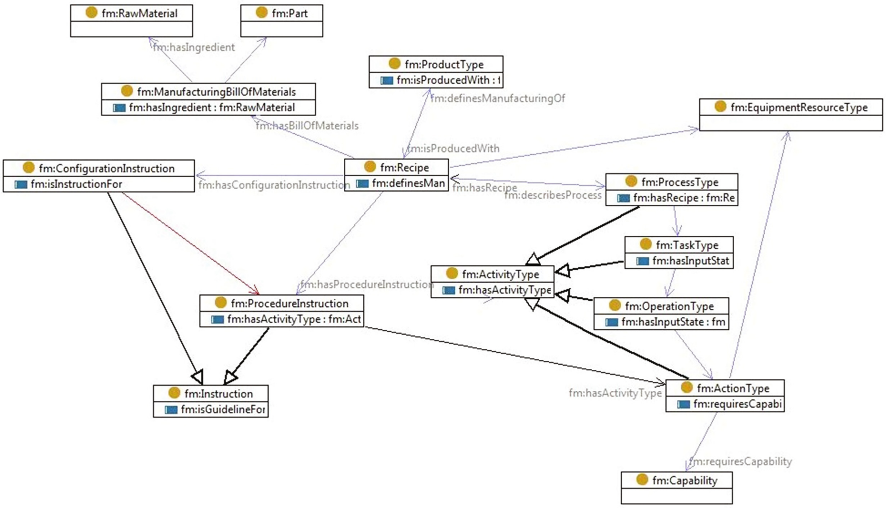

Fig. 3. Recipe and process modelling in the knowledge model.

specific product, in accordance with [8]. It consists of a set of instructions (*Instruction*) that detail a manufacturing process by describing:

- What equipment is required (*EquipmentResourceType*).
- How equipment must be configured (*ConfigurationInstruction*).
- What ingredients are required (*ManufacturingBillofMaterials*).
- The procedure to execute the recipe in several steps (*ProcedureInstruction*).

Resource Model
Our resource model expresses both a functional and logical structure for manufacturing facilities and resources (Fig. 4). A manufacturing resource (*ManufacturingResourceType*) is (1) a piece of equipment (*EquipmentResource*) such as a tool or a machine, (2) an agent (*PhysicalAgent*), being either a human (*Human*) or a robot (*Robot*) that has the capability (C*apability*) to perform an activity or (3) a certain material (*MaterialResource*). Manufacturing resources are present in a production facility (*ManufacturingFacility*), in a toplogy that may contain cells (*Cell*) with optionally one or more work stations (*WorkStation*).

The current knowledge model provides a vocabulary and model for reasoning about recipe-based operator support in flexible manufacturing. By adhering to Gruber's principle of minimal ontological commitment and extendibility [9], we allow freedom to specialize and instantiate the model in a variety of manufacturing environments and provide support for a variety of assembly activities. The minimal manufacturing facility topology or equipment resource type specification e.g. both provide a basis for future extensions.

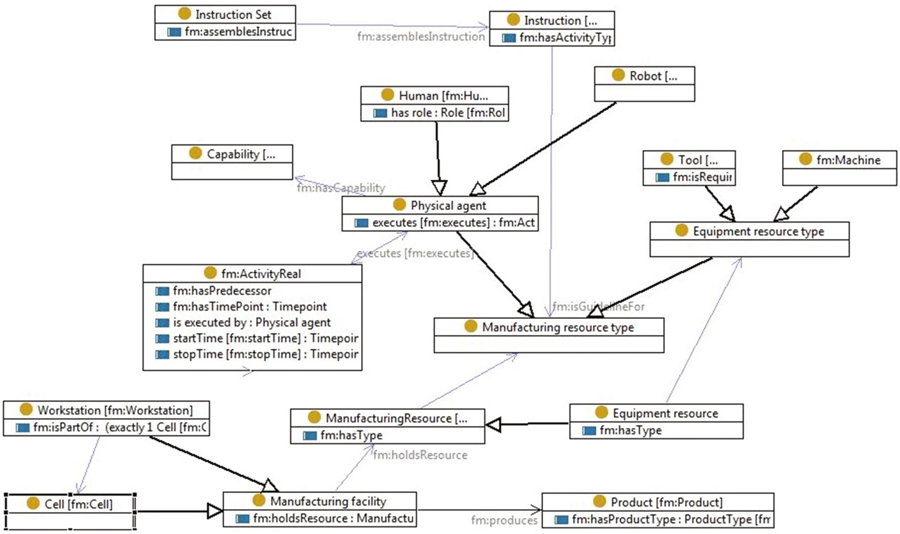

Fig. 4. Resource modelling in the knowledge model.

5 Demonstration Set-up

To validate the usefulness of our knowledge model, we have created a demonstration environment (Fig. 5). The environment contains a process engineering system with a knowledge modelling tool, Topbraid Composer, that is used by the process engineer to instantiate basic, reusable process steps and their operator instructions based on our knowledge model. The process engineer can then use these reusable process steps and their operator instructions to define a master recipe for the assembly of a certain product type. These reusable process steps in the master recipe are independent of the actual OPS system that is used to support the operator in the assembly task.

The master recipe is being exported as an XML-file from the knowledge modelling tool and imported into the OPS MES system. This system has a specific editing tool that is used to extend the master recipe with OPS-specific configuration actions, such as the exact position on the assembly canvas. This results in an OPS-specific control recipe to be used by the operator. In our demonstration set-up, we use the OPS Light Guide system as the operator support system that instructs the operator.

For demonstration purposes, we have used our knowledge modelling tool to define modular reusable process steps for three different types of the same flowsensor product manufactured by one of our project partners in the FlexMan project. A master recipe was generated for each of the three flowsensor types using these reusable process steps. The master recipes were only slightly different for each type in terms of size and color of material to be used. The master recipes could then be easily used to define three control recipes for the three types of flowsensors. When generating the master recipes, we encountered the following limitations and challenges:

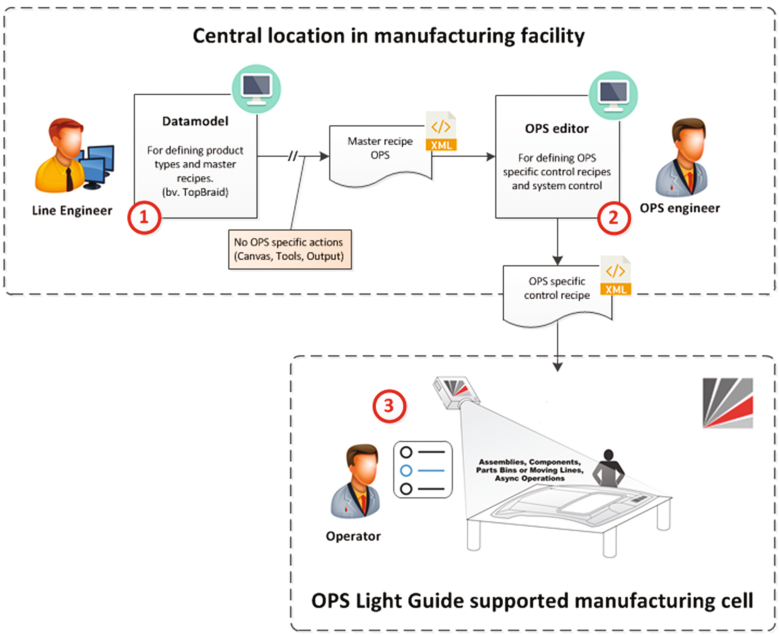

Fig. 5. Demonstration set-up of flexible manufacturing based on the knowledge model.

- Generating a master recipe was done by instantiation of the knowledge model for a flowsensor type. Although the master recipe can be reused, adapting it to get a new master recipe for another flowsensor needs to be done carefully. Some of the instances can be copy-pasted and adapted, while others need to be reused as they are. For instance, *ProcessType* and *TaskType* instances need to be copy-pasted and slightly changed, while *OperationType*, *ActionType* and *OperatorInstructions* can be reused as they are or extended with new ones. This needs to be well-thought of by the process engineer.
- Although the master recipe is meant to be independent of OPS-specific configurations, most of the instructions in these configurations are the same. Therefore, the wish emerged to add these reusable configuration instructions to the knowledge model. The challenge is then to not mix up the master recipe and the control recipe in the knowledge model and its instantiations.

Finally, we emulated an ERP system with product orders for the three types of flowsensors. These sequence of product orders was such that the operator was presented with a mix of the three types and thus with a flexible and changing assembly task. When using the knowledge model in the process engineering environment and the operator support system, we learned some lessons:

- Usage of modular reusable process steps simplifies the task of the process engineering for quickly designing a manufacturing process for a new product type.

- Designing an OPS-independent master recipe for a product type is an advantage for the process engineer as he/she does not have to deal with all the configuration details of a specific OPS-system.
- The assembly line can easily switch between different product types as the control recipes are available for the operator with a specific set of assembly instructions to be executed.

6 Conclusions and Future Work

This paper discusses the development of a knowledge model for (1) recipe-based product design and configuration of assembly cells and (2) automated generation of operator instructions. The first version of the knowledge model specifies a model that focuses on composite assembly activities and provides recipe-based support for instruction sets that can be generated specifically for the product type that is to be assembled. This ontology is then used in a scenario to provide the master recipe with accompanying instruction set to an operator support system. Currently, the application scenario focuses on flexibility in providing operator support in a high-mix product variety. In more advanced scenarios, we can further improve flexibility by considering specific human/cobot capabilities, manufacturing facility dynamics and operator context, operator behavior and/or experience. As a future enhancement to the knowledge model, we are also considering product feature variability scenarios, that introduce more complex configurations of the same product type in manufacturing.

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Evaluation of Functioning of an Innovating Enterprise Considering the Social Dimension

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Abstract. The paper presents a holistic evaluation model of an innovating enterprise that considers the social dimension. The design and functioning of the model is consistent with the paradigm that assumes a balance between economy, natural environment and the society. The evaluation is conducted with the use of a three-step approach (size – module – evaluation factor), and it also takes into account relations between particular structural elements.

Keywords: Innovating enterprise · Holistic evaluation · Social dimension

1 Introduction

The evaluation of the functioning of an innovating enterprise is a complex and difficult research issue due to the necessity to take into account in the evaluation: its multiple dimensions, more and more common and powerful turbulences and changes that take place in the environment, the anticipated risk that also has a multiple dimension character.

Thanks to the varied dimensions of the evaluation, the measures applied have both quantitative and qualitative character, and such a complex measure is difficult to apply when conducting a synthetic valuation. Therefore, evaluation of the functioning of an innovating enterprise considering the social dimension, that prefers qualitative evaluations, tends to be difficult. However, it is necessary when adopting the paradigm of a sustainable development.

2 Key Terms Related to Evaluation of an Innovating Enterprise

While examining the evaluation of the functioning of an economic entity considering the social aspect, it is necessary to define the basic terms connected with the problem, such as: innovative enterprise, efficiency (outputs vs inputs), effectiveness (outputs vs targets), performance (state of achievements), utility (results vs needs), productivity (products vs utilized resources). The literature described them in various, often different manner [1]. However, some conclusions and recommendations aimed at reducing ambiguity were presented [2].

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Innovating enterprise is defined as an enterprise that in the tested period (predominantly three years) – implemented at least one product or technological innovation: a new or improved product, or a new or improved mechanism that are a novelty at least from the perspective of the enterprise [3]. An innovating enterprise could be seen as an intelligent organization that constantly generates and implements innovations, appreciated by customers for high level of modernity and competitiveness [4].

In order to get a better understanding of the term, the features of an innovating enterprise are often formulated, that is [5]: wide range of R&D works, continuous implementation of scientific and technical solutions, significant share of technological, product and organizational novelties, constantly launches innovations on the market, able to predict future, characterized by flexibility of activities, creative teams, characterized by the ability to tap into the innovative potential, in constant contact with clients, able to generate innovations constantly.

The term performance is wider than efficiency which does not include setting goals and allocation of resources. Therefore, the term effectiveness has the closest meaning to the word performance. Then, activity is marked by the maximum effectiveness, feasible in the given conditions in methodological meaning, if the operator did his best in the given conditions to ensure that the operation has the maximum real effectiveness in all aspects. Such an achieved effectiveness may be lower than the planned one due to unforeseeable difficulties [6].

The performance term has multidimensional character, it assumes that each member (element) of the organization has his aspirations. In order to measure the degree of such aspirations specific measures of effectiveness, efficacy or productivity may be adopted. The approach provides for the basic aspect connected with the understanding of the type of "performance" that specific parts of the organization may have contradictory objectives. And this type of understanding turns out to be vital if we want to take into account the social as well as the environmental dimension in the evaluation.

When adopting the holistic approach to the evaluation, as it is in the presented paper, it is necessary to take into account the three approaches in the literature:

- purpose-bound – assuming that organizations aim at achieving specific, ultimate objectives (consistent with 'effectiveness'),
- resource - assuming that organizations have to operate in order to protect and use the limited and particularly valuable resources (similar to 'performance'),
- process – defining performance in the context of the behavior of the organization members (elements) [7, 8].

3 Holistic Approach to the Enterprise Evaluation

The idea of the holistic approach is a notion implying that all social phenomena constitute holistic systems subject to specific regularities that cannot be inferred basing on the knowledge of regularities governing their elements [9]. The principle of the holistic approach is analysis of all existing conditions and all occurring phenomena from the point of view of a holistic system, not taking into consideration the individualism methodology. Departure from the individualism methodology in the evaluation processes has been widely discussed in literature [10]. The holistic approach to the evaluation should encompass all its dimensions, that are economic, technical and technological, legal, social and environmental. When adopting such an approach it is necessary to characterize each of the listed dimensions [11, 12].

The holistic approach to the evaluation of the functioning of an enterprise, regardless of its character, should be in line with the universal idea of the holistic approach (Fig. 1).

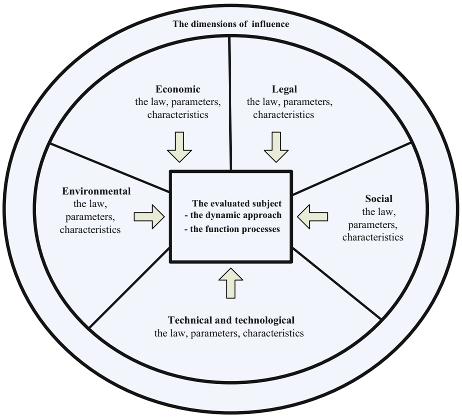

Fig. 1. The universal idea of the holistic approach

The dimensions cover the key assessment areas that should be taken into consideration by innovative entity operating in developed country and following the idea of sustainable growth. Each of them should be assessed from internal and external perspective. The external perspective considers the influence of outside conditions on management decisions (especially: legal, social, economic, and technical) and influence of the activity on surrounding (especially natural environment). The internal perspective describes how the available resources are managed and utilized.

4 The Importance of the Social Dimension in the Holistic Evaluation of the Enterprise

When presenting the problem regarding the evaluation of functioning of an innovating enterprise, one should advance a thesis that, apart from the economic and financial, technological, environmental protection and formal and legal dimension, above all the social dimension is an important element that affects the evaluation of the enterprise effectiveness and efficacy in the operations. It results from the occurring regularity that the environmental and social dimension plays growing part in the evaluation of the productivity of production processes. It is connected with the fact that the listed dimensions in many cases in the 21st century will determine, or determine now the effectiveness of the applied production processes. It is clearly reflected e.g. in the production of electricity, but it may also occur in the manufacturing of modern products or services in various branches of the developed market economy. Therefore, an innovating enterprise should be perceived as an economic entity that functions in a dynamic environment, characterized by the implementation of time-varying innovative actions: processes and tasks.

Analyzing the literature it may be concluded that most organizational and social innovations occur inside the society, and in many cases the enterprise workers are their authors [13]. It is consistent with the whole chain of links, relations, attitudes, notions and values that evolve slowly and transform in time, and they tend to assume complex character. It is therefore beyond doubts that accepting to implement a new solution (innovation) at the enterprise level, is a result of dynamic and turbulent changes both of the environment and inside and it should inevitably affect its evaluation.

An enterprise development should be attested not only by economic and financial or technological indicators, but also by changes occurring in the sphere of attitudes, values or employees and consumer behaviors. Very often it is the decisive, creative and open approach of the employees that becomes the determinant of progress that confirms the enterprise innovativeness and it allows to achieve a strong market position. Taking into account the contemporary reality of the competitive economy, it needs to be noted that development should be coupled with social capital. The implemented innovations should force the employees to change their attitudes, values and knowledge etc. As a result, it creates an innovative culture in the enterprise allowing to survive in the long term. Continuous development of the innovative culture requires constant reinforcing of the belief that the implemented solutions are effective, as well as social acceptance and an assent to such an enterprise development. It leads to more and more effective innovations, which translates into an increase in economic benefits of economic units which, in the long or short run, increase the standard of living in the society [14]. Summing up, it should be explicitly stated that the innovation theory has a complex character especially in the social dimension, which increases the importance of the raised problem. When presenting the holistic approach, it must be noted that the most effective innovations in the social dimension occurred in the 60's of the 20th century and in the early years of the 21st century.

The innovativeness level of the enterprises is affected by human resources of the enterprise, as well as the wider society (clients, contractors, competitors etc.). the general social factors that affect the evaluation process and its results include historical conditions, culture, lifestyle, and the integration of the society. More specific factors, that should absolutely be covered by evaluation, include the availability of professionals (qualified staff), education and knowledge level of the employees, as well as their creativity and imagination, client's trust in the enterprise ability to implement innovative actions and other sociological and psychological features. Each innovation implemented by a specific economic unit brings about certain changes, it destroys the existing organizational order and it introduces a new one. Some employees react to it with fear and resistance, others are positive about it. When evaluating the enterprise operations it is vital to learn in advance about the employees' attitude towards various actions and to react properly to the existing situation. It may take one of the four forms [15]: acceptance, indifference, passive or active resistance. The approach to various types of the enterprise operations in the internal dimension comes down to the subjective employee evaluation resulting from the employment situation, their knowledge and experience. The most common barriers in acceptance for operations are psycho-social ones and they need to be broken skillfully with the employees' previous acceptance.

When trying to sum up the discussed problems one may notice that specific factors of the evaluation of enterprise operations in the social dimension tend to be connected with the internal environment, whereas general factors – with the external environment.

5 The Holistic Model of the Enterprise Evaluation

The holistic model of the evaluation of the enterprise operation constitutes the basis of presenting the place of the social dimension in the evaluation (Fig. 2).

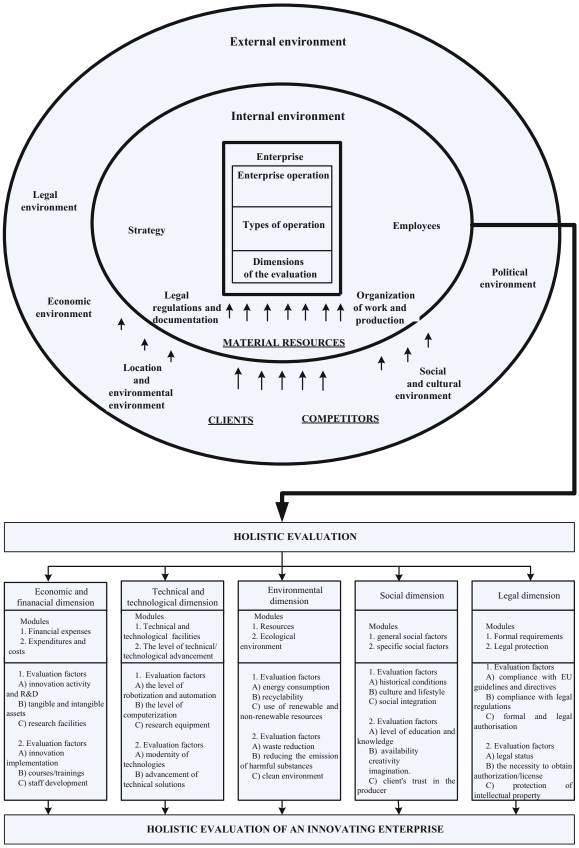

Fig. 2. The ideational model of the holistic evaluation of an innovating enterprise considering the social dimension

The presented approach to the evaluation could be find in the literature related to sustainable enterprises. However, it is not dominant approach for innovation assessment. In the literature can be find models that used different than suggested in the paper dimensions [16, 17].

The model presents the relationship among its elements and points out the needs of vide evaluation. Analysing the business solutions the proper concentration on political and social environment is the main area of improvement, because of their qualitative nature and problems with reliable valuation. In order to avoid passing over the selected areas the examples of measures were presented. However, each entity should develop their own measures relecting the type of activity and manager’s needs.

6 The Conditions in Implementation of the Holistic Model of the Operations of an Innovating Enterprise

As it was stated before in the paper, the social dimension may be properly included in the evaluation only when adopting the holistic approach.

The conditions in implementation of the holistic model of the operations of an innovating enterprise may vary. They result from areas that the holistic evaluation encompasses and from universal rules that the innovating enterprise is subject to. The classification of the possible conditions has been presented in Table 1.

Table 1. Classification of conditions from the perspective of how their effect on the holistic evaluation.

	Classification criterion of the condition	**Distinguished dimensions/types**	**Features of conditions**	
Type of condition	A. DIMENSION	1. economic and financial 2. technical and technological 3. environmental 4. social 5. legal	1. requisiteness / optionality	**The influence of conditions on the evaluation level: efficiency, productivity, effectiveness, efficacy**
	B. GOAL	1. general 2. particular 3. operational 4. tactical 5. strategic	2. the possibility to grade the level	
	C. RULE	1. global 2. regional (continental) 3. domestic 4. territorial (local government)	3. the possibility to identify in time	

Basing on the presented classification of conditions it may be observed that it is not their type but above all the features they display that have significant influence on the holistic evaluation. As a result, they determine the level and character of the evaluation conducted according to the previously adopted method or procedure. Each of the management methods used in the process, such as management by objectives, controlling, Lean Management etc., are well known in the literature. The choice usually depends on the adopted and preferred at a given moment management paradigms adequate for the economic paradigms.

7 Summary

When presenting the evaluation of the functioning of an innovating enterprise in conditions providing for the social dimension, it must be emphasized that it is only possible for the holistic approach. Then the social dimension may be correctly isolated, and it enables to make and attempt at quantifying it through the application of adequate measures. The presented measures should reflect the character of the social dimension and they should ensure consistency with other dimensions that ought to constitute the elements of the holistic method. Therefore, we may conclude that ensuring the specific character and consistency are the two main problems that must be solved by the evaluators.

The presented proposal has some limitations. It is the theoretical framework that utilization should be evaluated by entities in the future. The analysis in presented dimensions follows the theory of sustainable development and includes all weaknesses of its. Exploitation of the model needs from organization a lot of additional effort in controlling and application in decision taking process. Because of additional inputs the model can be adapted especially by the organization that want to develop in long-term perspective and operate in sensitive sector from the customer perspective.

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Intelligent Diagnostics and Maintenance Solutions

On the Advancement of Maintenance Management Towards Smart Maintenance in Manufacturing

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Abstract. The purpose of this work is to envision the future of maintenance without forgetting the past and present of maintenance practices. Indeed, there is a big potential for maintenance, fostered by the promises of the Fourth Industrial Revolution. At the same time, there is still a widespread evidence of the state of practices leading to assert that maintenance is not yet advanced as it would be expected. Thus, comparing the vision supported by advanced maintenance systems, through the concepts of E-maintenance, Internet of Things and Cyber Physical Systems, with the evidences on the state of practices collected based on a sample of more than 300 industrial plants, we come up with a reflection on the advancement of maintenance management towards Smart Maintenance.

Keywords: Smart Maintenance · Maturity assessment · Survey · Manufacturing · Industry 4.0

1 Introduction

In recent years, the maintenance management discipline is focusing on the role of maintenance to contribute to value for business [1]. The emerging perspective was that maintenance should not be viewed only at a narrow operational level representing an unavoidable cost; but it must be viewed in the long-term strategic context, integrating technical and commercial issues in an effective manner [2]. The strategic role of maintenance was remarked primarily by viewing it from the overall business perspective, pointing out that its effectiveness is a result of a multi-disciplinary approach [2–7]. Today, maintenance is seen as source of added-value, with key role for driving performance improvement [1]. This is an evolution of the past developments of maintenance. If we consider a short overview of history, attention to maintenance management has been growing along the years. At the beginning of 20^{th} century, before the First Industrial Revolution occurred, homemade production was just requiring Corrective Maintenance (CM). Only with mass production, the need for preventive maintenance programs was growing, mainly with the purpose to keep quality of processes and machines required by the production volume to be released to the market. This led to the growth of Time-Based Maintenance (TBM) practices. With the growing complexity of industrial plants and the awareness that TBM was not really a cost-effective solution when applied to complex physical assets, industrial development led to the introduction of diagnostics

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techniques: these were the first signs of a change, towards the introduction of the so-called Condition Based Maintenance (CBM) programs [8]. The approach used to attack problems in CBM was primarily built on technical insights, due to the measurement of the physical parameters used as symptoms of asset degradation; this brought a wide set of technical specializations, such as in vibration analysis, oil analysis, thermography, etc. In the meanwhile, two relevant maintenance success stories occurred, originally in specific industry sectors, leading to the two well-known methodologies of RCM (Reliability Centred Maintenance) [9] and TPM (Total Productive Maintenance) [10]. The former had its origin in sectors such as aerospace and aeronautics, where reliability and risk analysis were relevant for safety reasons. The latter is historically associated to the Toyota Production System, related to the needs arising in Just in Time, Total Quality Management and continuous improvement practices. It is worth observing that such developments had a common feature: they were bringing knowledge on engineering methodologies (i.e. FMECA, FTA, Pareto analysis, 5 whys, etc.), providing means to identify and prioritize maintenance problems, and to subsequently discover improvement solutions. Especially after TPM, a wide literature emerged regarding the so-called lean production, focused on organizational aspects. Since that time, maintenance is seen as a relevant function called, thanks to its technical authority, to participate to problem solving, contributing to operational excellence.

All the developments mentioned above had in common, as underlying concept, a blend of technical, engineering and organizational factors. Information and Communication Technologies (ICTs) came out only partially during this historical development. Around the 90ies, this happened with the development of Computerised Maintenance Management Systems (CMMS), used to cover the needs for controlling maintenance management and managing the information related to the maintenance activities. Around the 90ies, the first ideas of exploiting Internet for providing tele-maintenance services emerged, typically pushed by Original Equipment Manufacturers (OEMs). Nowadays, we are observing a new technology wave, where OEMs play, of course, a role. Indeed, it is remarkable how the vision of Industry 4.0 pushes the role of ICTs as primary technology enabler for enhanced maintenance practices. Given the vision of Industry 4.0, the present paper aims at reflecting on the expected trends, starting from state of practice in industry. It may be appropriate to address a balanced development due, on one hand, to the "technology-push" for the future and, on the other hand, to the "process-pull" resulting from past and present status.

To this end, Sect. 2 provides a vision of the "technology-push", with the actual and future developments, primarily in relationship to Cyber Physical Systems (CPS) applied to maintenance. Section 3 looks at the missing or poor practices observed in the maintenance processes in manufacturing industry. This evidence is based on a benchmarking activity carried out, across Italy, in the context of the Observatory on Technologies and Services for Maintenance (TeSeM) of the School of Management of Politecnico di Milano. Section 4 reflects on an overall approach to master the deployment of the technology promise in an existent company. Conclusions envision the remarks for future research works on this matter, and the subsequently planned activities in the context of the current TeSeM's yearly research.

2 Vision on the Different Technologies

Industry 4.0 is leading to think of maintenance as a relevant function for strategic improvement of Industry 4.0-like solutions. The Fourth Industrial Revolution enhances what past visions, as E-maintenance and Intelligent Maintenance Systems (IMS), have achieved, employing the related key enabling technologies (Internet of Things, Cyber Physical Systems, etc.) for building advanced maintenance systems [11–13]. Above all, a blend of ICT- and plant automation-enabled solutions is expected to grow, thus empowering the traditional features of maintenance management, based on the blend of technical, engineering and organizational factors. Considering an overall strategic perspective of Industry 4.0, that would better consider a "process pull", the short/middle term vision considers a technology push. The technology push moves around some main drivers, related with different technologies that can be considered for maintenance activities and in particular:

- Technologies for maintenance analysis that can improve the diagnostic and prognostic capabilities of the actual CBM system.
- Technologies for communication and cloud computing that can guarantee: on one side the deployment of sensor network that can push the creation of communication backbone within the plants or among plants for the deployment of maintenance services (also considering OEM perspective); on the other side, the diffusion of maintenance analysis solutions, guaranteeing remote activity for maintenance engineering.
- Technologies for operator enhancement, such as new information systems, new portable devices and other new means to consider the operator in the loop. To this category belongs also the solution for augmented and virtual reality that are emerging, even if not yet applied extensively to the maintenance processes.
- Technologies for data analytics are pushing a new way to analyse maintenance data, paving the way also for new engineering profile, namely closer to mathematical engineers than to mechanical or electrical engineers for maintenance analysis.

3 State of Practice

The analysis of the current state of practice is presented referring to the data collected by the research of the TeSeM Observatory, that issued the first research in 2013, aiming to implement a maturity level analysis on the current maintenance management practices of production companies in Italy. Three hundred industrial companies in different industrial sectors (mechanical, food, chemical-pharmaceutical and others) and of different sizes (34% SMEs and 66% Big) compose the reference sample. The research is based on a maintenance maturity assessment method developed by the TeSeM and implemented through a questionnaire [14]. The method allows assessing the maintenance maturity both as a synthetic index - in the remainder general maturity index (GMI), for measuring the general Maturity Level (ML) - and a set of component indexes accordingly with the need to measure the managerial, organizational and technological capabilities of the maintenance department. A scale of five maturity levels is used. ML1 is the initial level (meaning that the process is weakly controlled, or not controlled at all).

ML5 is the optimizing one (meaning that process is managed by ensuring the continuous improvement; causes of defects and problems in the processes are identified and actions taken in order to prevent problems from occurring in the future) [14]. A general overview regarding the GMI in the Italian industry nowadays is given in Fig. 1. Almost 50% of the analyzed companies are still presenting a GMI at ML1 and ML2, giving a first general indication about a great area for improvement in the current practices.

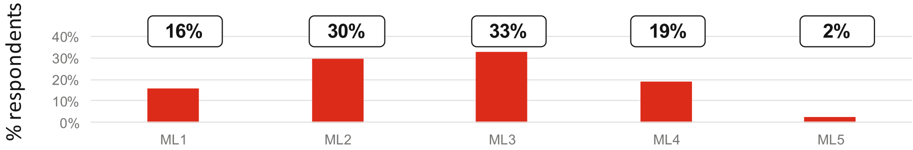

Fig. 1. Distribution of General Maturity Index of the sample

When considering in detail the current state of practice on CBM implementations, the statistics are the following. Only few companies (around 30% in each considered industrial sector) have monitoring/inspection tools connected with maintenance decision support tools (i.e. diagnostics and prognostics).

Moreover, only few companies implemented a "network integration" of the tools used for CBM in order to provide a remote connection/access to the maintenance information system. Only the Chemical-Pharmaceutical sector demonstrates a reasonable (even if not so high) tendency to network integration (28%) (Fig. 3).

Finally, looking at how companies analyse data obtained from inspections/monitoring and how they make decisions about CBM, in the majority of cases, data analytics is not adequately used in order to support management decisions. In figure, about 70% of companies in each sector do not implement in-depth analysis using specialist software; present no systematic filing of data and decisions are based mainly on information available at the last inspection/most recent monitoring. Only a limited number of cases is featuring advanced uses of data analytics for management decisions. Those are the cases where specialist software are used and data are recorded in the CMMS and/or other specialist tools for maintenance engineering.

4 On the Advancement Towards Smart Maintenance

Given the current state of practice, we may deduce that problems still exist that could prevent or slow down the capability to digitize maintenance. It is evident that a profound distance exists between the vision suggested by Industry 4.0 and the CBM status in different industries. Today, the data-to-information and -to-knowledge-conversion are still fragmented and incomplete, emerging from the statistics above shown (see Figs. 2, 3 and 4). Wastes are subsequently generated during maintenance operations, while reduced improvements (compared to the desired targets) in terms of, e.g., Overall Equipment Effectiveness can be expected. Overall, a reduced cost-effectiveness of the CBM programs is the outcome. Besides, it is worth remarking that cost-effectiveness depends on the type of resource required by CBM activities. As professionals with high-level qualification, experience and use of sophisticated equipment and decision models are often required in case of critical assets not manageable using resources and competences inside a company, an increase of cost is directly associated to the CBM program execution. Relating to the technology promise, the question that arises is: "can CPS applied to maintenance enable to reduce the drawbacks of the actual CBM status?" CPSs are promising at least two major properties: a seamless integration and an enhanced intelligence in maintenance activities, that are the two main levers to improve the actual status. CPS-based integration is a mechanism to limit the fragmentation, connecting the "islands" of maintenance specialists through CPS-ization (and, eventually, subsequent "social networks" of machines, featuring capabilities for analysing different degradation processes and failure modes). Depending on the CPS-ization, different levels of integrations can be defined into the management system, enabling to achieve the degree of completeness that is required for a CBM process by the asset criticalities. Indeed, not always a full integration is required for what concern the CBM program execution, i.e. integration from state detection to health and prognostics assessment and even maintenance within production scheduling. Seamless integration would help defining the integration that best fits the requirements due to the asset criticalities. Intelligence will eventually enable better accuracy in the functions executed along the CBM process. In fact, as each function of the CBM process is executed based on proper models bringing intelligence – either statistical, physical, soft computing or operations research models, it would result in higher expectation for achieving the Overall Equipment Effectiveness's target. In this regard, CPS-ization may be also a relevant means to bring on-line all engineering knowledge – as intelligence – even considering methodologies – as FMECA, HAZOP, etc. – traditionally adopted in an off-line fashion for designing industrial plants, processes and management policies.

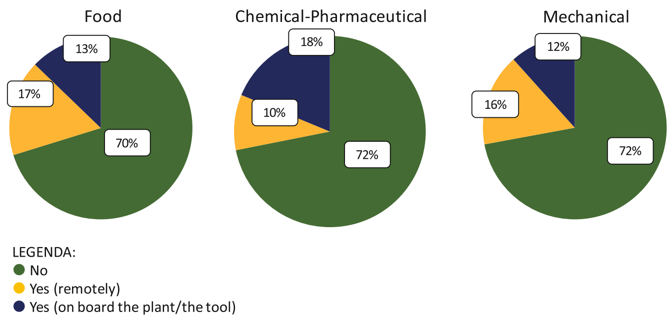

Fig. 2. Statistics on the connection of monitoring/inspecting tools with fault diagnosis and/or prognostic tools within the plants in the sample, divided by sector

If the technology promise is convincing for CBM operations, the question that now arises is: "can an existent Maintenance Organization rely on new technologies as CPSs to reduce the drawbacks of the actual CBM status?" Maintenance organization is a relevant issue for digitization: it is an evidence achieved during the first workshop of a series of the new research, in the context of TeSeM Observatory, on digital readiness of

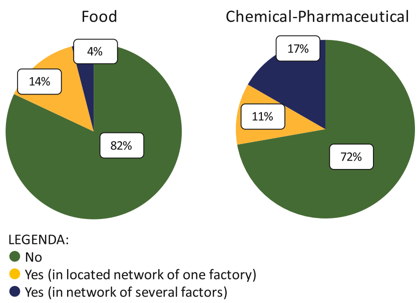

Fig. 3. Statistics on "network integration" to provide a remote connection/access to the maintenance information system within the plants in the sample, divided by sector

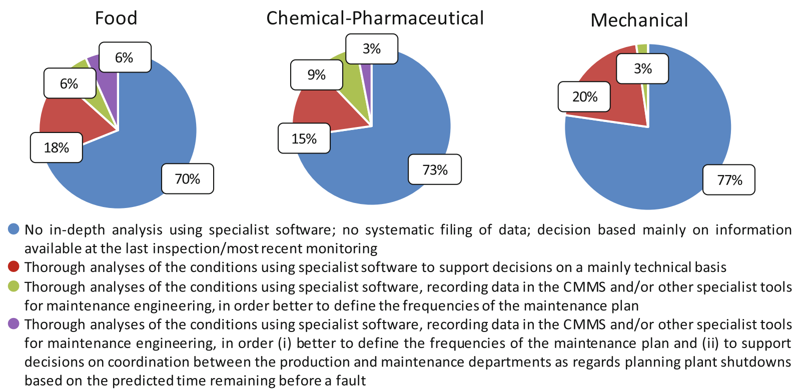

Fig. 4. Statistics on how companies analyse data obtained from inspections/monitoring and how they make decisions about condition-based maintenance

maintenance. In this regard, four organizational criteria came out during the workshop: (i) maintenance engineering not only comprises engineering knowledge, but it is an organizational unit that can promote and support the implementation of innovation projects in asset management; (ii) utilizing new technologies should be supported by the developments of people that are using them in their tasks, as their tasks are changing; (iii) change management requires a participative approach from different levels in the organization, only so real commitment to the change is possible; (iv) global organization could be a relevant way to strengthen the probability of success of a digitization process, as it may enable the identification of different areas of implementation in various plants worldwide, and global sharing of best practices growing in such areas.

Overall, CPS in maintenance requires more than technology to enable the construction of an advanced maintenance management system. Digitization requires to master technology and organization, in order to move forward to build a Smart Maintenance system. Therefore, an organizational perspective should be taken, covering different aspects, as e.g. maintenance activities and tasks in the organization, decisions and roles to be supported, skills etc. A particular need that seems to be relevant in this end is the focus on the processes executed by maintenance. Figure 5 represents maintenance processes, derived – by translation and minor adaptations – from the UNI norm [15].

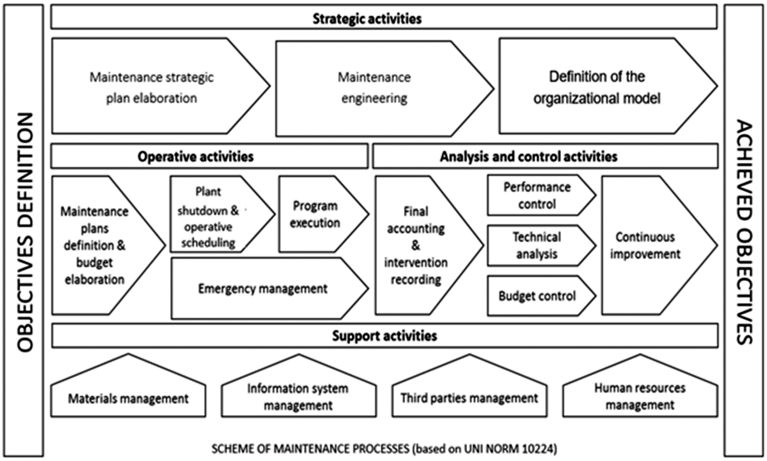

Fig. 5. Maintenance processes [UNI 10224:2007]

A process map can support targeting areas for digitization in maintenance, as a lever to contribute to business value. In this sense, it allows not only to consider the "technology push" – due the potentials of different technologies envisioned by Industry 4.0 – but to drive decisions based on a strategic prioritization of maintenance processes, according to the fact that processes and their gaps pulls the need for technology improvement, i.e. "process-pull". In this reflection, we assume that a company may look at such processes both considering their status (and thus gaps with respect to the Industry 4.0 vision) and their prominence for the business value. Maturity assessment of maintenance processes as well as the subsequent understanding of their digital readiness appear relevant research topics to connect the technology promise with the maintenance actual needs.

5 Conclusions

This paper initiated a reflection that is at the background of the activities carried on during the past and present yearly researches by the TeSeM Observatory of the School of Management of Politecnico di Milano. Based on the actual results reported in the paper, we can remark that benchmarking of maintenance management practices appears to be a relevant tool to assess the actual maintenance status. It enables to support the identification of gaps with respect to the Industry 4.0 vision. This can be relevant to assess the real capability to plan for digitization initiatives, verifying the digital readiness of maintenance. Overall, this approach enables to think of a balanced development due, on one hand, to the "technology-push" for the future and, on the other hand, to the "process-pull" resulting from past and present status. In fact, it is difficult for a company to focus a decision when a number of requests comes from technology providers, that apparently sell the best of Industry 4.0-solutions. A strategic assessment of needs and gaps in a company enable a clearer view of the need of maintenance in the contingency of its industry. The yearly research of TeSeM will develop a number of empirical studies, with the purpose to develop a roadmap of digitization for maintenance, providing a balanced perspective between "technology-push" and "process pull".

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New Threats for Old Manufacturing Problems: Secure IoT-Enabled Monitoring of Legacy Production Machinery

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Abstract. The digitization of manufacturing through the introduction of Industrie 4.0 technologies creates additional business opportunities and technical challenges. The integration of such technologies on legacy production machinery can upgrade them to become part of the digital and smart manufacturing environment. A typical example is that of industrial monitoring and maintenance, which can benefit from internet of things (IoT) solutions. This paper presents the development of an-IoT-enabled monitoring solution for machine tools as part of a remote maintenance approach. While the technical challenges pertaining to the development and integration of such solutions in a manufacturing environment have been the subject of relevant research in the literature, the corresponding new security challenges arising from the introduction of such technologies have not received equal attention. Failure to adequately handle such issues is a key barrier to the adoption of such solutions by industry. This paper aims to assess and classify the security aspects of integrating IoT technology with monitoring systems in manufacturing environments and propose a systematic view of relevant vulnerabilities and threats by taking an IoT architecture point of view. Our analysis has led to proposing a novel modular approach for secure IoT-enabled monitoring for legacy production machinery. The introduced approach is implemented on a case study of machine tool monitoring, highlighting key findings and issues for further research.

Keywords: Production machinery monitoring · Internet of things · Security

1 Introduction

Machine tools are among the key production equipment in manufacturing environments. Monitoring machinery health status enables preventive, predictive and proactive actions to be taken, leading to reducing downtime and breakdowns. When integrated with the overall production management considerations, including costs and planning considerations, this in turn can lead to improved production performance through higher overall equipment efficiency (OEE), while offering additional support towards meeting

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production and costs/profits targets are met. In this context, the introduction of internet of things (IoT) technologies constitute a prime enabler for the integration of legacy production machinery to the digital factory era, enabling ubiquitous availability of machinery status and performance information through different networking technologies.

IoT technology, among other, enables a growing number of sensors, devices, assets and other human and non-human actors to communicate over wired and wireless networks, creating opportunities for new applications and services to be offered over the cloud. A typical manufacturing environment with legacy machine tools often lacks built-in sensors, external communication capabilities and applications or services for real-time monitoring. Computer numeric control (CNC) machines are also often present, which do have communication capabilities (Ethernet) and an Application Programming Interface (API) for exchanging data through third-party applications [1]. The lack of provisions to easily monitor machine capabilities within the entire factory gives rise to a higher cost of integration through additional hardware and software in order to capture data autonomously and achieve some level of information integration in production environments. The use of IoT technologies can empower legacy machine tools to become smart and connected. In this setting, machines, sensors, devices, computing entities, human operators and the cloud become contributing constituents to a digital and smart manufacturing environment.

However, the introduction of such technologies also brings in additional challenges and in particular raises security concerns. Such concerns are yet to be sufficiently addressed in industry practice, especially concerning efforts to upgrade legacy equipment to the Industrie 4.0 era. Contributing in the direction of addressing such challenges, this paper analyses security risks associated with introducing IoT devices in production environments. We propose a monitoring architecture through a novel modular IoT unit for legacy machine tools, equipped with the introduction of a novel multi-stage and adaptive authentication protocol at the hardware level. The security advantages arising from its use, compared to standard practices, are outlined. The paper is organized as follows. Section 2 gives an overview of relevant literature. Section 3 presents the approach used for the design and development of the modular IoT unit, paying attention to security issues. Section 4 describes a number of case studies with a DMG Mori Seiki machine tool, and the pilot architecture to address security weaknesses. Section 5 states our conclusions and provides pointers to future work.

2 IoT Security Challenges in Manufacturing Environments

Networks of smart objects are employed in safety and security applications and are projected to scale up to involve millions of embedded devices in both commercial and industrial sectors [2, 3]. Solutions based on IoT technology can significantly upgrade the data-generation and integration capabilities of production systems, further pushing for the integration of cloud computing and big data into manufacturing environments. While process and safety-critical data can thus become integrated, the underlying potential security and privacy vulnerabilities of such a process, if not appropriately handled, make the connected factory more susceptible to attacks [4–6]. This is particularly important as many studies have revealed security weaknesses in embedded devices [7–9]. Such threats have profound commercial, legal, safety and social implications. A smart manufacturing system may comprise several cyber physical production systems (CPPs), which involve monitoring hardware and software components as integrated circuits [10]. Based on the software interactions with humans and CPPs and the involved different communication protocols, such hardware is exposed to physical attacks, including invasive hardware attacks, side-channel attacks and reverse engineering attacks [11]. Software can be compromised by malicious code, such as Trojans, viruses and runtime attacks [12], while different denial-of-service (DoS) communication protocols can be subjected to various attacks, such as denial-of-service attacks [13, 14].

Currently, security limitations of IoT devices generate new challenges for the design and implementation of embedded solutions. Typical security issues for embedded systems involve compromising the boot process as in the Google Nest Thermostat [15], hardware exploitation which involves implementing parts of software/firmware [16], chip exploitation with invasive intrusion to take secret information stored in the chip [17], cryptographic vulnerability in applications [18], backdoors in remote access channels able to find out credentials for administrator access [19] and traditional software vulnerabilities. These devices are intended to be part of an industrial IoT architecture which may become under-attack too. For example, in [20], a successful attack against an industrial control system through a computer virus that infected the transportation network leading to a complete stop of passenger and freight train function is presented. Other industrial attacks are also described in the literature [21, 22] and one of the most famous is the Stuxnet attack [23] which caused the failure of centrifuges within Iranian nuclear facilities. It is therefore necessary to develop strategies, architectures and solutions which address such challenges. Relevant work includes common standard protocols used in SCADA systems, emphasizing security threats and vulnerabilities [24], with standard communication protocols considered at three different layers: the Physical/Link layer, the Network/Transport Layer and the Application Layer [25]. This paper analyses relevant requirements and present s the design and development of a new security architecture for IoT-enabled data exchanges in an industrial setting. This is introduced in the next section.

3 A Modular Approach for IoT Security in Manufacturing

The multiple vulnerabilities associated with the introduction of IoT technology in manufacturing and especially on legacy production machinery, require a re-thinking of the design approach to security. Instead of adding complexity at single security control mechanisms, such as in encryption or authentication for accessing a networked device, one approach would be to de-compose the whole device into multiple components, each contributing additional security barriers. Furthermore, the very nature of such security barriers may be adaptive, adding further complexity needs to any mechanism design to attack an IoT-enabled solution. Our innovative modular approach to IoT security in manufacturing environments employs such concepts to increase the overall complexity needed for an attack to succeed, while remaining simple to implement. To illustrate this, we present a new modular design for an IoT data acquisition (DAQ) unit, aimed at machine tools monitoring.

Figure 1 illustrates the modular IoT DAQ proposed for communicating at the Machine-to-Machine (M2M) level, as well as with others IoT layers. The design decomposes the overall device to independent modules for sensing and communicating, indicated as 1st module and 3rd module. An intermediate unit, marked as 2nd module, is the key to mediate between collecting and processing data from several sensors and sending them outside the factory. The device size is small so to allow comfortably fitting into a machine tool. Such IoT modules can use different communication protocols to share information inside and outside the factory. The sensed data can be sent to the cloud, managed by different services, and shared with the end-user devices or sent to a service providing vendor, tasked with monitoring in real time the status of the machines. One of the advantages of this architecture is the flexibility in terms of easy replacement or re-use of individual components. The modularization yields low power needs in terms of device capability, making it also possible to isolate sensing by accommodating a single sensor instead of several sensors per module. Furthermore, the modular IoT DAQ can work as a modem able to convert one communication protocol into another. These features allow building a robust IoT device, which can work areas with high electronic noise, such as around the machine spindle and drives. At the same time, they maintain the flexibility of multi-connectivity, being able to support different wireless protocols, each with own security provisions. The proposed modular IoT DAQ employs a hardware and software authorization protocol of cascaded complexity, allowing access to the module data for authorized users [25].

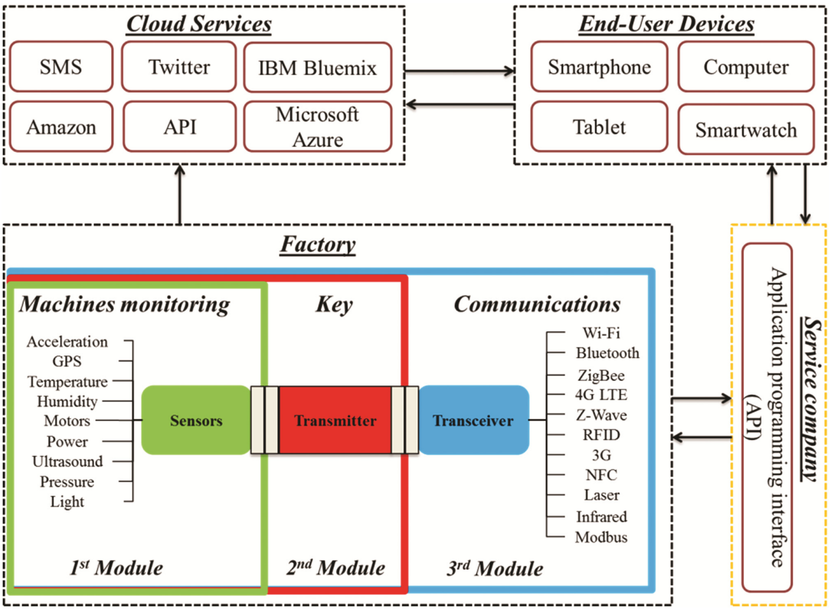

Fig. 1. The modular IoT DAQ

The proposed authentication protocol is illustrated in Fig. 2. The slave unit represents sensing and communication entities (1st and 3rd modules) while the master is the key (2nd module). The protocol comprises four phases for enabling the sensor operation and accessing its data. The initial phase involves the physical authentication between the sensors, transceiver technologies, and the key. Each sensor and communication module is equipped with an ID number, to be recognized only by the key module. The next phase is an agreement about the baud rate to share signals, information and password. The master offers a new baud rate and the slave will accept after evaluating requirements, such as frequency and time. The third phase consists of sending the hardware password by the master to the slave. This hardware password is a specific frequency agreed beforehand between the two parts. The last phase consists of recognizing the alphanumeric password sent by the slave and executes the code to collect sensor data. All phases are supported with AES cryptography. Adopting a modular IoT approach, instead of employing monolithic IoT devices, offers the possibility to personalize the choice of the device setup, to replace single modules without compromising the entire device and to cascade the complexity of security provisions.

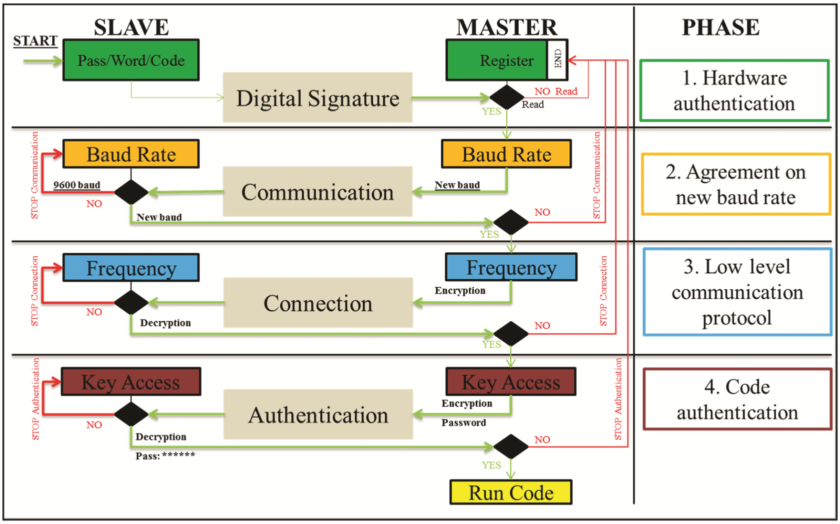

Fig. 2. Secure authentication protocol

4 Case Study and Pilot Implementation

We present an instantiation of the proposed architecture on a problem of considerable interest for industry, that of introducing legacy machine tools with IoT-emabled monitoring capabilities. Most legacy machine tools do not have built-in sensors and do not have any local or external network communication. Interconnecting such machinery introduces security threats related not only to the machine tools but to everything around them and everything that interfaces with them.

Figure 3, shows the implementation of the modular IoT DAQ with a legacy machine tool (DMG NTX 1000/W). A real industrial case was built around the machine to simulate and study possible weaknesses in implementing the IoT technology. The top left shows the spindle during normal operation, equipped with the sensor module (1st module), which is inactive until the connection with the key module (2nd module) is established. The key module executes code for sensing, processing and communicating, as well as the code to read the CPU usage for each authentication protocol phase. The communication module (3rd module) consists of different ways to share data into the local or external network. Typically, this configuration would be susceptible to the types of attacks discussed in Sect. 2. Figure 3 illustrates a case where RF component employs the Wi-Fi module (3rd module), which comes under attack, changing CPU from 50% to 65%. The modular IoT will change the communication protocol into ZigBee protocol and will send data to the service company and the cloud or end-user devices, while the Wi-Fi operation shuts. All information shared within this IoT architecture is encrypted and only the key module is equipped with an SD card to store the data for limited time before transferring outside. In case of transferring malicious code to the IoT module, attempting to compromise the data, the authentication protocol prevents unauthorised users from accessing device files and codes. This case illustrates initial implementation steps of the modular secure IoT architecture for manufacturing environments, with minimal hardware costs, but significant data handling and CPU capacity.

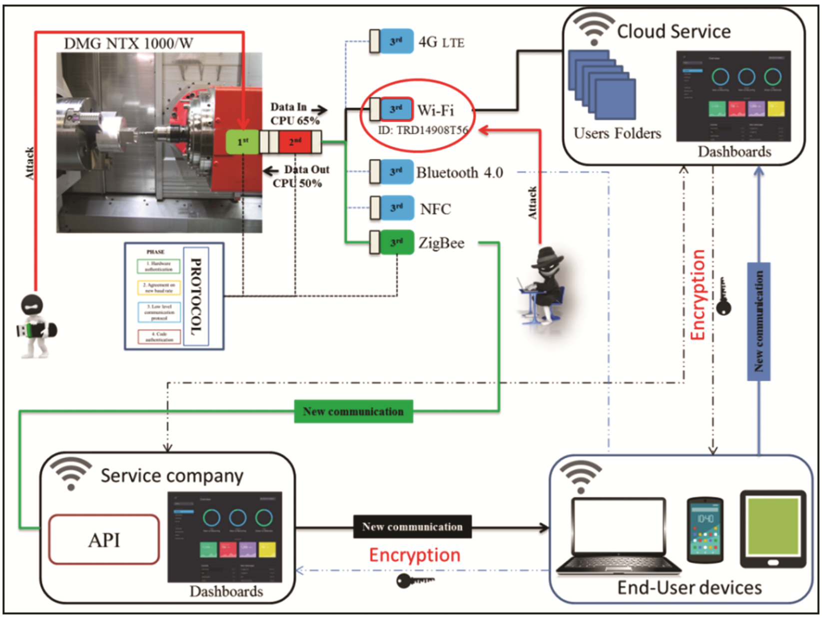

Fig. 3. The modular IoT implementation for legacy machine tools

5 Conclusion

This paper deals with integrating IoT technology with security provisions on legacy production machinery monitoring. The proposed approach adopts a modular architecture instantiated on an IoT DAQ, which employs a hybrid authentication protocol addressed both at the hardware as well as communication levels. The architecture was implemented on a DMG Mori Seiki machine tool as an example of the applicability to a wide ranging legacy systems, aimed at bringing them towards the Industrie 4.0 era. The next steps include extensive testing of the proposed solution, extension to handle additional security threats, as well as the migration of the components of the modular architecture into an industry-grade device, while also extending its' operation as a remote control system for different actuators. This architecture can be employed within a broader architecture for the predictive maintenance of legacy machine tools.

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Condition-Based Predictive Maintenance in the Frame of Industry 4.0

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Abstract. The emergence of Industry 4.0 leads to the optimization of all the industrial operations management. Maintenance is a key operation function, since it contributes significantly to the business performance. However, the definition and conceptualization of Condition-based Predictive Maintenance (CPM) in the frame of Industry 4.0 is not clear yet. In the current paper, we: (i) explicitly define CPM in the frame of Industry 4.0 (alternatively referred as Proactive Maintenance); (ii) develop a unified approach for its implementation; and, (iii) provide a conceptual architecture for associated information systems.

Keywords: Proactive Maintenance · E-maintenance · Event processing

1 Introduction

Industry 4.0 indicates the flexibility that exists in value-creating networks which enables machines and plants to adapt their behavior to changing orders and operating conditions through self-optimization and reconfiguration. To do this, they perceive information, derive findings and change their behavior accordingly. At the same time, they store knowledge gained from experience with the aim to implement distributed and interconnected production facilities in future smart factories [1]. Industry 4.0 combines computer science with electrical and mechanical engineering and is considered to be a revolution on a business level and an evolution on a technological level.

Maintenance is a key operation function, since it is related to all the manufacturing processes and focuses not only on avoiding the equipment breakdown but also on improving business performance in terms of productivity, quality and logistics management [2, 3]. Existing maintenance strategies can broadly be distinguished to three categories: (a) Breakdown Maintenance; (b) Time-based Preventive Maintenance; (c) Condition-based Predictive Maintenance (CPM) [2]. Since products have become more and more complex due to the evolution of technology, the costs of time-based preventive maintenance have increased and CPM has evolved as a novel lever for maintenance management [4]. However, there is not a clear classification in literature, while CPM in the context of Industry 4.0 has not been concretely defined. Currently, even large manufacturing companies have not developed a complete CPM strategy and appropriate sensor-driven, real-time systems in order to utilize its benefits [2]. Existing CPM

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solutions suffer from several limitations: (i) Most of them focus on product maintenance, i.e. on the service stage of the Product Lifecycle Management (PLM) (e.g. warranty failures) and not on industrial maintenance, i.e. on the manufacturing stage of the PLM; (ii) They are mainly based upon physical, domain-specific models that are not easily extensible for other equipment or for other industries; (iii) They rarely exploit big data processing infrastructures for real-time, sensor data, since they usually use batches of data, while the level of data analytics maturity is usually low; (iv) Each one of them focuses on a specific aspect of CPM (e.g. condition monitoring, diagnostics, etc.) instead of having a unified approach for covering all the phases and industrial operations-related aspects.

The objectives of the current paper are: (i) to explicitly define CPM in the frame of Industry 4.0; (ii) to develop a unified approach for its implementation; and, (iii) to provide a generic reference conceptual architecture for the development of associated information systems. The rest of the paper is organized as follows. Section 2 discusses the literature review. Section 3 includes the definition of CPM in the frame of Industry 4.0, i.e. Proactive Maintenance. Section 4 outlines a unified approach for Proactive Maintenance implementation, while Sect. 5 presents a generic reference conceptual architecture. Section 6 concludes the paper and discusses the future work.

2 Literature Review

2.1 Condition-Based Predictive Maintenance and E-maintenance

CPM is an evolving maintenance strategy that is increasingly gathering the interest of modern manufacturing companies by utilizing the capabilities of condition monitoring. Condition monitoring is usually realized with equipment-installed sensors, which have the capability of measuring with high frequency a multitude of parameters [5] leading to processing and storage of a huge amount of data. Big data pose challenges to the subsequent processing pipeline of data analysis, knowledge extraction and decision making [2]. The classical industrial view of CPM is mainly focused on the use of condition monitoring techniques such as vibration analysis, thermography, acoustic emission or tribology [5]. The recent developments of maintenance management lead to a physical understanding of a system's useful life and health state prediction through dynamic pattern recognition in various available data sources. Despite the plethora of CPM frameworks existing both in the academic and the industrial realms, there is still a large gap for effective implementation of CPM extensively in industry, mainly due to complexity of these solutions and their life cycle [4].

E-maintenance refers to the convergence of emerging information and communication technologies with systems which take into account the resources, services and management to enable decision making in a proactive way [3] and thus, to enhance and extend the CPM framework [4]. E-maintenance incorporates emerging technologies capable of optimizing maintenance-related workflows and integrating business performance with other components of e-enterprise [4]. The development of e-maintenance systems can be distinguished in two chronological periods which have different characteristics. The first wave of appearance, development and deployment of e-maintenance concepts and prototypes was during the period 2003–2008 (see e.g. [6–8]). The second wave of e-maintenance paradigms has appeared in 2014 due to the emerging opportunities of the Industrial Internet of Things (IIoT), big data infrastructures and communication devices, but also due to the increasing financial pressures leading to a significant demand of eliminating maintenance costs (see e.g. [9, 10]).

2.2 Industrial Internet of Things, Big Data and Proactive Event Processing

A CPM strategy implementation requires a complete methodology as well as appropriate information systems capable of processing information captured by sensors in order to provide added value insights [2]. It can take advantage of IIoT advances for handling failure uncertainty, since the stochastic nature of the equipment degradation process leads to high uncertainty in decision making [11]. Since the manufacturing domain is driven by events gathered through sensors, there is the need for event monitoring and big data processing information systems [12]. Modern manufacturing companies have started to collect and store operations-related data or even utilize technological infrastructures and information systems for monitoring various parameters that are known to affect equipment condition and detecting early warning signals that machines or systems are degrading or in danger of breakdown [2]. However, the strategic value of data analysis in the modern dynamic manufacturing enterprises should be increased by augmenting the level of data analytics maturity, through efficiently processing of real-time big data and supporting multi-directional knowledge flows, in order to enable the maintenance strategy transformation.

Proactivity in terms of information systems is driven by predictions, leading to increased situation awareness and decision making capabilities ahead of time. Proactive computing extends the reactive pattern known as ‘Sense-and-Respond’ [13] or ‘Detect-and-Act’ [14] to a novel pattern which consists of four phases [15]: Detect, Predict, Decide, Act. This proactive principle can be the base for a unified CPM framework and for its implementation with an appropriate information system by mapping the maintenance and other industrial operations (e.g. warehouse management, production planning, quality improvement) to these phases.

3 Definition of Proactive Maintenance

CPM in the frame of Industry 4.0 should be clearly defined taking into account the state-of-the-art theories, concepts and technologies in order to pave the way for the complete transformation of manufacturing enterprises from reactive to proactive. We argue that Proactive Maintenance indicates the CPM in the frame of Industry 4.0 in the sense that it brings together maintenance management and proactivity in terms of information systems. Proactive Maintenance has a managerial and a technological perspective. From a managerial point of view, its implementation requires the identification of the need for a different maintenance strategy through feasibility studies [16] as well as the radical change of maintenance-related business processes and operations in all the enterprise organizational levels (operational, management, strategic). From a technological point of view, it requires appropriate technologies and information systems for effectively supporting the Industry 4.0 principles. Therefore, Proactive Maintenance should include the following characteristics:

- **IoT-based Condition Monitoring.** Condition monitoring is applied with sensors at a component, machine or production process level. The decisions about their type and their distribution (placement) are affected by the manufacturing system examined. These hardware and/or software sensors generate huge amounts of real-time data (big data) in the context of IIoT which are further processed through appropriate infrastructures. The term "predictive maintenance" that is often used does not necessarily include real-time condition monitoring through sensors.
- **Event-driven Architecture.** Event processing is used to process massive primitive events and get valuable high level information from them by continuously monitoring the event flow. Therefore, through the event triggers, event-driven infrastructures are able to handle big data in a scalable and efficient way.
- **Prognosis Lifecycle.** Prognostic lifecycle covers all the maintenance phases, through which information is processed; from signal processing and diagnostics till prognostics and maintenance decision making along with continuous improvement during actions implementation. Predictions about the future equipment condition, on the basis of which mitigating actions can be applied ahead of time, constitute the backbone of CPM. They can be realized with associated predictive event processing agents. The term "Condition Based Maintenance" that is usually used does not necessarily include predictions, since it may refer to (near) real-time diagnostic outcomes, i.e. detection of the current condition.
- **Proactive Computing.** Proactive event processing makes it possible to anticipate potential issues during process execution and thereby enables proactive process management, i.e. to decide and act on the basis of real-time predictions. The proactive event-driven applications are subjected to the proactive principle. A proactive situation includes a future event, a predictive pattern, the probability distribution function of the event occurrence, a list of mitigating actions and costs (e.g. the cost of the future event, the costs of actions as function of implementation time) [15].
- **E-maintenance Support.** The e-maintenance concept is linked to the CPM framework, since it provides the communication and technological background for real-time data processing and information exposure to the users and thus, it can support all the phases of the proactive principle. E-maintenance applications and platforms can facilitate proactivity and further advance to a greater value with the development of Cyber-Physical Systems, while they are able to utilize an event-driven architecture for scalable sensor-generated big data processing.
- **Interaction with other Industrial Operations.** Since, every change in industrial operations affects the others, CPM should be considered along with its interactions with the other operations. A reduction in production, quality and inventory costs is considered as one of the most important indirect benefits of CPM [11]. For instance, due to the available real-time prognostic information, predictive maintenance actions along with quality improvement and production activities can be recommended and spare parts can be ordered just in time.

4 A Unified Approach for Proactive Maintenance

The proposed unified approach combines and extends existing CPM approaches [2]. It aims to frame and conceptualize Proactive Maintenance in order to enable manufacturing companies to fully exploit the availability of huge amounts of real-time and historical data with respect to the implementation of Proactive Maintenance by advancing their data analytics maturity. Unification can be achieved by bringing together approaches, tools and services each one of which implements a different phase of the Proactive Maintenance framework in order to effectively support different enterprise management layers, i.e. operational, management, strategic. Moreover, it enables data aggregation and interpretation as well as information sharing throughout the whole organization, both horizontally and vertically.

The systematic representation of any Proactive Maintenance solution allows its application in the production process of any manufacturing company regardless their processes, products and physical model used, while additional aspects (e.g. company policies) can be addressed with context-awareness. The proposed framework aims to cover the whole prognostic lifecycle along with their interactions with quality management, production planning and logistics decisions. The overall unified approach for Proactive Maintenance is depicted graphically in Fig. 1. Each conceptual block should incorporate an e-maintenance service or tool implementing appropriate methods and algorithms. The conceptual blocks are communicated among them through events. The event-driven approach enables the combination of model-based, knowledge-based and data-driven algorithms and methods existing in each conceptual block provided that each one is able to provide the required output that the next one requires. The scope of each conceptual block is explained below:

- **Signal Processing:** It consists of the "Data Acquisition" and "Data Manipulation" steps, being performed in a modular way utilizing new emerging technologies. It should be able to connect and acquire data from heterogeneous data sources and integrate them for further processing.
- **Diagnosis:** It consists of the "State Detection" and "Health Assessment" steps. It may include real-time model-based, knowledge-based and/or data-driven methods, embedded in appropriate and continuously processing software in order to recognize the presence of an unusual state with respect to a model of 'normal' behavior.
- **Prognosis:** It includes state prediction of a whole system or components with respect to a mechanical system, e.g. prediction about the time-to-failure and the probability distribution function of the failure occurrence, the Remaining Useful Life (RUL), the Remaining Life Distribution (RLD). The analysis can be carried out by model-based, knowledge-based and/or data-driven algorithms.
- **Maintenance Decision Making:** It includes decision making algorithms for taking decisions automatically or for providing recommendations ahead of time, on the basis of real-time prognostic information and maintenance-related expert knowledge. Thus, the optimal mitigating (perfect or imperfect) maintenance actions and the optimal times for their implementation are derived. The decisions can be continuously improved through a Sensor-Enabled Feedback (SEF) mechanism.

- **Maintenance Action Implementation:** It includes a real-time feedback mechanism for gathering, storing, aggregating, analyzing and visualizing data and information with respect to the actual actions implementation. The actions are implemented based on the generated decisions either automatically or by humans receiving the recommendations. The sensor-generated data are further processed in order to continuously update and improve the diagnostic, prognostic (through FMECA) and decision (through SEF) models and their continuous learning capability.
- **FMECA:** Apart from their visualization, in order to further be processed, the actions-related data and information feed into the Failures Modes Effects and Criticality Analysis (FMECA) mechanism, which incorporates algorithms for the identification of potentially relevant and critical failures modes. FMECA can be implemented either on a physical model base or on a data analytics base.
- **Industrial Operations Management:** It is based upon data and information about production planning, logistics management and quality management. They are stored in company's systems (e.g. ERP, MES) and are gathered in order to consider the industrial operations affected by maintenance processes (e.g. quality levels, production activities, spare parts inventory) and optimize the overall business performance. The data are processed according to the proactive principle and interact with the e-maintenance services. Examples of their utilization could be production-related predictions, joint maintenance and inventory optimization algorithms, quality-related constraints in the maintenance utility function optimization, etc.

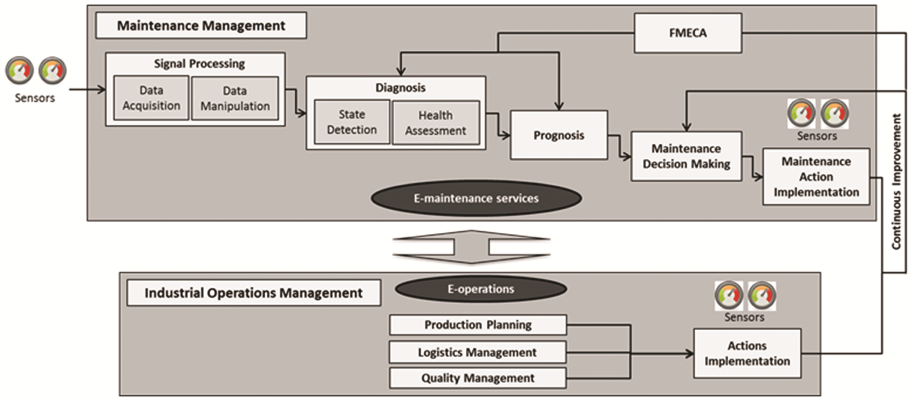

Fig. 1. The unified approach for proactive maintenance

5 Conceptual Architecture of a Proactive Maintenance System

The conceptual architecture of a Proactive Maintenance intelligent information system is shown in Fig. 2. It consists of 3 layers which are further described below:

- **User Interaction Layer.** The user interaction layer occupies the top level of the architecture and includes a configuration and visualization dashboard that supports the configuration of the architecture and the embodiment of the appropriate expert knowledge, as well as the visualization of the current and the predicted equipment behavior, the generated recommendations, etc. with the use of appropriate graphs.

- **Real-time Processing Layer.** The real-time processing layer deals with the continuous processing of sensor data according to the Proactive Maintenance framework by applying the proactive principle of information systems in both the e-maintenance and e-operations services, which can interact between them with the aim to schedule the maintenance activities together with the production, the quality and the logistics ones.
- **Data Layer.** The data layer of the architecture includes a Database Abstraction Layer and houses a relational database engine where all information needed by the other two layers is stored and retrieved.

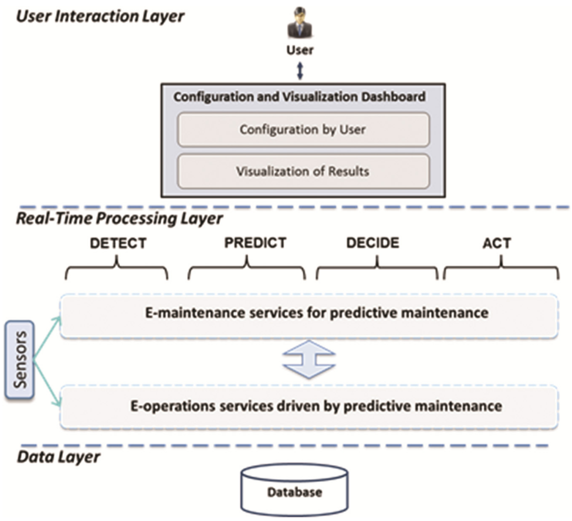

Fig. 2. The conceptual architecture of a proactive maintenance system

6 Conclusions and Future Work

In the current paper, we explicitly defined CPM in the frame of Industry 4.0, which can be referred as Proactive Maintenance, we developed a unified approach for its implementation and we provided a generic reference conceptual architecture for the development of Proactive Maintenance systems with the aim to maximize the expected utility of manufacturing firms and to exploit the full potential of predictive maintenance management, condition monitoring, sensor-generated big data processing, e-maintenance and proactive computing. Regarding our future work, we plan to develop a unified Proactive Maintenance information system by using, extending, developing and integrating new e-maintenance services and tools addressing the various phases of the aforementioned framework for exploiting the full potential of Proactive Maintenance. Then, we aim to validate our approach in industrial environment.

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A Review of Current Machine Learning Techniques Used in Manufacturing Diagnosis

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Abstract. Artificial intelligence applications are increasing due to advances in data collection systems, algorithms, and affordability of computing power. Within the manufacturing industry, machine learning algorithms are often used for improving manufacturing system fault diagnosis. This study focuses on a review of recent fault diagnosis applications in manufacturing that are based on several prominent machine learning algorithms. Papers published from 2007 to 2017 were reviewed and keywords were used to identify 20 articles spanning the most prominent machine learning algorithms. Most articles reviewed consisted of training data obtained from sensors attached to the equipment. The training of the machine learning algorithm consisted of designed experiments to simulate different faulty and normal processing conditions. The areas of application varied from wear of cutting tool in computer numeric control (CNC) machine, surface roughness fault, to wafer etching process in semiconductor manufacturing. In all cases, high fault classification rates were obtained. As the interest in smart manufacturing increases, this review serves to address one of the cornerstones of emerging production systems.

Keywords: Artificial intelligence · Machine learning · Manufacturing diagnosis · Fault Detection · Intelligent maintenance · Industrie 4.0

1 Introduction

Timely diagnosis of process faults provides a key advantage to help manufacturing companies stay competitive by reducing machine downtimes as more customers require manufacturers to provide the products quickly, at low cost and with high quality. Also, during machine downtimes, most of the time spent is on localization of the fault rather than carrying out the actual remediation, as fault diagnosis is the most challenging phase of machine repairs [1]. This has resulted in companies looking for new ways to improve their fault root cause analysis (RCA) process.

With current improvement in sensor technology, data storage, and internet speeds, factories are becoming smarter and more process data is generated. Research projects are focusing on how to utilize this 'big data' to improve manufacturing competitiveness.

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One such effort is a project at the National Institute of Standards and Technology (NIST) titled prognosis and health management for smart manufacturing (PHM4SMS) which is aimed at developing the necessary measurement science to enable and enhance condition-monitoring, diagnostics and prognostics [2]. Part of this effort is the utilization of machine learning techniques to improve fault detection (FD) in manufacturing.

The aim of this paper is to review the recent application of machine learning techniques to manufacturing process diagnosis. This review covers papers published from 2007 to 2017 that utilized machine learning techniques for manufacturing fault diagnosis. This review covers 20 articles. The keywords used in the search are “machine learning application in manufacturing process diagnosis”. The search was filtered to focus on artificial neural networks (ANN), Bayesian networks (BN), support vector machine (SVM) and hidden Markov model (HMM) techniques. The rest of the paper reviews findings in each of these prominent techniques and provides conclusion along with future directions of research.

2 Bayesian Networks

Bayesian networks are a commonly used machine learning technique for FD. BN is a directed acyclic graph whose nodes represent random variables and their conditional dependencies are depicted by directed arcs linking the nodes [3].

Modeling a problem using BN requires specification of the network structure as well as the probabilities for each node. For generating tree structures, different authors proposed using several tools that depict the cause and effect relationship between these nodes. In generating the tree structure, De et al. [4] and Pradhan et al. [5] proposed the use of failure mode and effect analysis (FMEA), Pradhan et al. [5] and Nguyen et al. [6] utilized fishbone diagrams (cause and effect diagram), Pradhan et al. [5] utilized fault-tree analysis and variation sensitivity matrix, and finite element analysis (FEA) was used by Liu & Jin [7]. The precise construction of the tree structure of a BN from data is an NP-hard optimization problem [8]. Yang & Lee [9] and Correa et al. [10] made use of K2 [11] and Chow-Liu [12], algorithms respectively to generate trees from data. Jeong et al. [13] extract the cause-effect relationship for the equipment that is diagnosed from the equipment’s maintenance manual. Process data obtained from sensors and stored in manufacturing execution systems (MES) or maintenance databases are then used to generate the conditional probabilities of the network.

The areas of application of BN vary across manufacturing industries. In the semiconductor industry, Yang & Lee [9] and Nguyen et al. [6] used a BN to evaluate process variable influence on wafer quality to diagnose root cause of defective wafers using historic process data. Other application areas include the automobile industry [7] where BN is used to diagnose fixture fault in a taillight assembly and in machining [10] where BN is used to diagnose surface roughness fault. Data sources include quality management systems (QMS), manufacturing execution systems (MES), recipe management systems (RMS), computerized maintenance management systems (CMMS), and coordinate measuring machines (CMM). Table 1 gives a summary of the data sources, algorithms or methods used to determine the tree structure and case study or area of application for each of the BN papers surveyed.

Table 1. Summary of BN applications

Ref.	Tree structure	Data source	Case study/Industry applied
4	FMEA	QMS systems: warranty data, corrective action reports (CAR)	N/A
5	Ontology and failure related knowledge	QMS systems: 5-why, 8-D & field failure report; MES data	Original equipment manufacturers and their tiered suppliers
6	Cause and effect (fishbone) diagram	Historic process data in MES, CMMS and RMS databases	Semiconductor manufacturing process
7	Variation sensitivity matrix and FEA	Metrology data from CMM	Taillight assembly process
9	K2 algorithm	Historic process data from sensors	Semiconductor manufacturing process
10	Chow-Liu algorithm	Sensor data from designed experiments	Surface roughness in machining
13	Equipment maintenance manual	Simulated data stored in a lookup table	Machines in an electronics manufacturing company

BN is a white box model as the graphical representation makes it intuitively easy for the user to understand the interaction between the model variables. It is useful for modeling uncertainty and can be readily used to model hierarchical levels of multiple causes and effects with data from numerous sources, which is typically found in manufacturing systems. The same BN model can be used for both prediction and diagnosis. The main challenge of training a BN is in the construction of the tree structure and several methods including expert opinion have been proposed to mitigate this challenge [14].

3 Artificial Neural Network

Artificial neural network is a non-parametric machine learning algorithm inspired by the functioning of the human central nervous system [15]. The adaptive nature provides a powerful modeling capability suited for non-linear relationships among features.

ANN has been used for many manufacturing FD applications. For complex problems with multiple layers and nodes, the network's training time might be significant. To decrease this training time, Barakat et al. [16] developed a self-adaptive fault diagnosis ANN which adjusts the number of nodes according to the network's input parameters and terminates the training process according to a set of criteria. The idea was illustrated in the detection and isolation of disturbances in a chemical reactor simulator. Demetgul et al. [17] also proposed an optimal configuration algorithm for neural networks used for FD. The algorithm combined genetic algorithm (GA) and ANN to eliminate the trial and error process for selection of the fastest and most accurate ANN configuration by using a fitness function to keep the number of hidden layer(s) and nodes at the minimum possible. The performance of Demetgul's [17] proposed system in FD was evaluated using experimental data collected from a bottle capping pneumatic work cell.

To add FD capabilities to control charts, Zhao & Camelio [18] integrated a neural network (NN) with a statistical process control (SPC) chart. The authors incorporated process knowledge and measurements of a single sheet metal part to detect and diagnose fixture location fault in an assembly system as a proof of concept. Zhao & Camelio [18] also applied the SPC and NN in an automotive assembly process by using measurement data from the door subassembly to detect potential sources of variation during the assembly of the door to the vehicle.

The direct use of data from analog sensors or multivariate data sensors for FD applications requires a signal processing technique or dimension reduction techniques in the case of multivariate data in conjunction with a machine learning technique. Hong et al. [19] proposed an algorithm that combines principle component analysis (PCA), modular neural network and Dempster-Shafer (D-S) theory to detect fault in an etcher system in semiconductor manufacturing. Process data was acquired by sensors and PCA reduced the dimensionality of the multivariate tool data set [19]. Zhang et al. [20] also proposed a critical component monitoring method that utilizes Fast Fourier Transform to extract features from sensor signals followed by training an ANN with the transformed data to predict machine degradation and identify component faults.

Yu et al. [21] used clustering as an unsupervised procedure to obtain informative features from vibration sensor signals attached to the motor housing of a machine to determine the bearing condition. An ANN was used for diagnosing machine faults based on these feature vectors [21]. Fernando & Surgenor [22] utilized an unsupervised ANN based on Adaptive Resonance Theory (ART) for FD and identification on an automated O-ring assembly machine testbed. Sensor data was collected while the machine was operating under different conditions (normal condition as well as faulty conditions) and features extracted from the raw sensor data. ART ANN could achieve excellent FD performance with minimal modeling requirements [22].

ANN's non-parametric nature and its capability to model nonlinear complex problems with high degree of accuracy has made ANN applicable to FD problems. The model is easy to initialize as there is no need to specify the tree structure like in the case of BN. However, disadvantages include the "black box" nature which makes it difficult to interpret the model. Also, ANN often cannot deal with uncertainty in inputs and is computational intensive making convergence typically slow during training. ANN is prone to overfitting and requires large diversified training data to prevent this problem.

4 Support Vector Machine

SVM uses different kernel functions like radial basis function (RBF) or polynomial kernel to find a hyperplane that best separates data into their classes, and has good classification performance when used with small training sets [23]. Successful areas of application of SVM range from face recognition, recognition of handwritten characters, speech recognition, image retrieval, prediction, etc. [24].

Application of SVM exist in fault localization, although it is not as common as BN and ANN [25]. The technique was used by Hsueg & Yang [26] to diagnose tool breakage fault in a face milling process under varying cutting conditions. Kumar et al. [27] created a MapReduce framework for automatic diagnosis for cloud based manufacturing using SVM as the classification algorithm and validated this with a case study of fault diagnosis using the steel plate manufacturing data available on UCI Machine Learning Repository [28]. Demetgul [23] used SVM to classify 9 fault states in a modular production system (MPS) using data obtained from eight sensors, and experimented with 4 different kernel functions namely RBF, sigmoid, polynomial and linear kernel functions, and got 100% classification rate on all except for sigmoid kernel which had 52.08% classification rate. Decision tree technique developed using QUEST (Quick, Unbiased and Efficient Statistical Tree), C&RT (Classification and Regression Tree), and C5.0 algorithms were also applied to the same dataset and 100% classification rate was obtained, and 95.83% for Chi-square automatic interaction detection (CHAID) [23]. Demetgul [23] concluded that SVM and decision tree algorithms are very effective monitoring and diagnostic tools for industrial production systems.

SVM is an excellent technique in modeling both linear and nonlinear relationships. Computation time is relatively fast when compared with other nonparametric techniques, such as ANN. Availability of large training datasets is a challenge in machine learning, however SVM tends to generalize well even with a limited amount of training data. Also, NIST is actively developing use cases that are representative of common manufacturing processes to support prognosis and health management research [29].

5 Hidden Markov Model

Hidden Markov Model is an extension of the Markov chain model used to estimate the probability distributions of state transitions and that of the measurement outputs in a dynamic process, given unobservable states of the process [30].

HMM has been used in fault diagnostics of both continuous and discrete manufacturing systems. In the continuous case, Yu [31] proposed a new multiway discrete hidden Markov model (MDHMM) for FD and classification in complex batch or semi batch production processes with inherent system uncertainty. Yu [31] applied the proposed MDHMM approach to the fed-batch penicillin fermentation process which classified different types of process faults with high fidelity. For the discrete case, HMM was applied by Boutros & Liang [32] to detect and diagnose tool wear/fracture and ball bearing faults. The model correctly detected the state of the tool (i.e., sharp, worn, or broken) and correctly classified the severity of the fault seeded in two different engine bearings [32]. In addition to the fault severity classification, a location index was developed to determine the fault location (inner race, ball, or outer race) [32].

As with analogue sensor signal used along with ANNs, Yuwono et al. [33] also used HMM along with advanced signal processing techniques to discover the source of defect in a ball bearing. The algorithm was based on Swarm Rapid Centroid Estimation (SRCE) and HMM and the defect frequency signatures extracted with Wavelet Kurtogram and Cepstral Liftering were used to achieve on average the sensitivity, specificity, and error rate of 98.02%, 96.03%, and 2.65%, respectively, on bearing fault vibration data provided by Case School of Engineering, Case Western Reserve University [33].

HMM is a probabilistic model that is excellent at modeling processes with unobservable states such as chemical processes or equipment's health status, thus a good fit for FD. However, the training process is usually computationally intensive.

6 Conclusion and Future Research Direction

A summary of the different techniques' advantages and disadvantages are presented in Table 2. Most data used was process data acquired using sensors and training was done through designed experiments either in a laboratory or in an industry setting. The authors that proposed using data from QMSs did not validate their proposal with data from real applications because of the difficulty in obtaining real data or the challenge in mining Quality Information System (QIS) data such as corrective action reports, or warranty

Table 2. Pros and Cons of each Technique

Technique	Advantage	Disadvantage
BN	Intuitively easy to understand Good for modeling uncertainty Can be used to model hierarchical levels of multiple causes and effects Can reason in both directions (prediction and diagnosis)	The tree structure makes it relatively less easy to initialize Constructing the tree structure may be challenging
ANN	Can model nonlinear complex problems with high degree of accuracy Relatively easier to initialize, no need to specify the network structure like in the case of BN	The model is not easy to interpret and cannot deal with uncertainty in inputs Computationally intensive making convergence typically slow during training Prone to overfitting
SVM	Excellent in modeling linear and nonlinear relationships Computation time is relatively fast when compared with ANN Tends to generalize well even with limited amount of training data	Selection of the kernel function parameters is challenging Not easy to incorporate domain knowledge Difficult to understand the learned function
HMM	Excellent at modeling processes with unobservable states	Training process is usually computationally intensive

information, which are mostly in paper form. Also, most of the case studies in the papers were limited to FD in a single machine; therefore diagnosis of a whole factory or manufacturing line consisting of multiple machines was not considered.

BN and HMM techniques are both excellent at modeling fault diagnosis with hierarchical levels consisting of multiple causes and effects. BN requires less computational power than HMM. ANN produced very accurate results and several approaches were proposed to reduce the large training time it required. ANN was also used in conjunction with a signal processing technique for applications with analogue sensor data. Unlike the other models, ANN is a black box and it is not easy to visualize what is occurring in the model. ANN is also prone to overfitting. Although not often used in fault diagnosis in comparison to other machine learning methods surveyed, SVM produced high fault classification rate at less computation time than ANN.

Future work will explore using real QIS data to further improve the diagnosis process as well as extending the single stage diagnosis to multi stages to include the entire manufacturing factory.

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A Framework for Integrated Proactive Maintenance Decision Making and Supplier Selection

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Abstract. The increasing use of sensors in manufacturing enterprises has led to the need for real-time data-driven information systems capable of processing huge amounts of data in order to provide meaningful insights about the actual and the predicted business performance. We propose a framework for real-time, event-driven proactive supplier selection driven by Condition Based Maintenance (CBM). The proposed framework was tested in a real in automotive lighting equipment scenario.

Keywords: Condition Based Maintenance · Supplier selection · Proactive computing · Event processing

1 Introduction

The emergence of the Internet of Things (IoT) enhances the extensive use of sensors generating huge amounts of data and consequently the need of real-time data-driven information systems in order not only to react on actual problems but also to provide meaningful insights about potential future undesired events or opportunities [1]. This proactive approach can significantly enforce decision making processes in the context of various manufacturing operations and functions of manufacturing enterprises, such as maintenance and purchasing. Since manufacturing companies need to work with different suppliers of maintenance spare parts, the purchasing department can play a key role in cost reduction and risk optimization as well as in empowering the suppliers for improved quality, response time and reliability of supplies deliveries [2]. In this sense, the strategic process of supplier management is replacing the function of purchasing [2] involving a smaller numbers of highly qualified buyers, decentralized control of non-value adding items and greater planning activity horizons. Consequently, supplier selection becomes one of the most important operations of supply chain management, since it should split the order quantities among suppliers for creating a constant environment of competitiveness [2]. Our approach utilizes the proactive event-driven computing principles, the Condition Based Maintenance (CBM) concept and the purchasing management theory in order to form a framework for real-time, event-driven proactive

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supplier selection. The rest of the paper is organized as follows. Section 2 discusses the literature review. Section 3 presents the proposed framework, while Sect. 4 describes the implemented system. Section 5 presents its application in real industrial environment, Sect. 6 shows the comparative and sensitivity analysis and Sect. 7 concludes the paper and discusses the future work.

2 Literature Review

2.1 Proactive Event-Driven Computing and Condition-Based Maintenance

The use of sensors in enterprises enhances the IoT paradigm and leads to the development of event-driven information systems capable of processing sensor-generated data in complex, dynamic environments. Therefore, there is the capability to decide and act ahead of time, in a proactive way [1]. Proactivity refers to the ability to avoid or mitigate the impact of future undesired events, or to exploit future opportunities, by applying real-time prediction and automated decision making technologies [1]. Several works in the past have spotted proactivity as the next evolutionary step in event processing systems [1, 3] and proactive computing in different application domains has started to emerge. The manufacturing domain has not exploited its capabilities in a real-time streaming environment in order to facilitate proactive decision making [1]. In the manufacturing domain, maintenance is related to all the industrial operations and focuses not only on avoiding the manufacturing failures but also on improving the whole business performance. CBM incorporates condition monitoring, enabled by manufacturing sensors, for identifying and predicting the health state of a manufacturing system in order to better support decision making process [4].

2.2 Purchasing Management

In manufacturing enterprises, procurement deals not only with the raw materials required for the production process, but also with spare parts needed for maintenance. Therefore, the supplier relationship strategy should be aligned with the equipment maintenance strategy. Since the supplier selection process occupies a large amount of resources, companies expect to conclude in high value contracts. However, prices of spare parts and raw materials are subjected to fluctuations with uncertain trends, making procurement, and especially supplier relationship management, a key element of business performance [2]. Suppliers' prices affect long-term business profitability, business reputation and output product's price, thus suppliers' prices prediction algorithms and autonomous interacting software agents have gathered an increased interest during the last years [5]. At the same time, procurement management should ensure reliability and quality of supplies in conjunction with the transaction costs and risks in a dynamic uncertain environment [2]. Procurement management driven by CBM can be benefit from lean manufacturing in order to eliminate operation's wastes during the production process [6]. Cooperating with one outsourced supplier may cause significant problems [6], so having more choices of suppliers that produce and deliver the same components can lead to less future risks and costs [2].

3 The Proposed Framework

The proposed framework, built on the CBM concept [4] and on a real-time architecture for proactive decision making [1], covers the whole prediction lifecycle from sensing till automated proactive decision making and monitoring. The framework consists of a user interaction, a real-time processing and a data layer, as shown in Fig. 1. The user interaction layer supports the configuration of the architecture and the visualization of appropriate information through a GUI. The real-time processing layer is based on the "Detect- Derive- Decide- Do" (4D) model of situational awareness in sensor-based real-time intelligent systems [7] and consists of two information processing pipelines working in parallel but at different timestamps (asynchronous processing). These two pipelines are represented by two components: a maintenance and a supplier selection component. The framework does the mapping of the 4D phases to CBM and supplier selection phases and extends previous research works by utilizing the proactivity principles, the event processing technologies and the recent advances in maintenance and logistics management. The maintenance component implements the CBM steps for diagnosis, prognosis, action recommendation and action implementation, while the supplier selection component consists of an indicator detection, a prices prediction, a supplier recommendation and purchasing. The services in each phase for each component are described below.

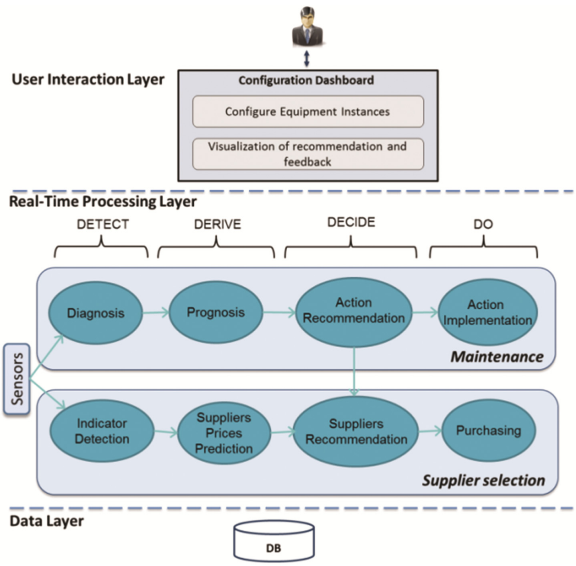

Fig. 1. The proposed framework for real-time, event-driven proactive supplier selection in manufacturing enterprises.

Detect: This phase deals with sensing, data collection and acquisition in order to discover unusual situations on the basis of complex enriched events identified by a Complex Event Processing (CEP) service. In the <u>maintenance</u> component, the CEP engine deals with the detection of an abnormal behaviour of the equipment on the basis of hardware sensor data (e.g. manufacturing sensors). The supplier selection component deals with the detection of indicators (causes) that suppliers' prices are to increase (e.g. the start of a negotiation process after an invitation to bid) on the basis of software sensor data (e.g. ERP system containing data collected through Electronic Data Interchange (EDI) from suppliers with a strategic partnership).

Derive: This phase deals with a predictive analytics service, which enables the generation of real-time, event-driven predictions of future undesired events, i.e. failures. Predictions are triggered on the basis of unusual situations identified by the Detect phase. In the maintenance component, it deals with the development of a prognostic model about a future failure in order to predict the Probability Distribution Function (PDF) of the failure occurrence. In the supplier selection component, this phase deals with the prediction of suppliers' prices on the basis of the associated detection event throughout a decision horizon (e.g. until next planned maintenance).

Decide: This phase includes a decision management service that provides proactive recommendations on the basis of the prediction events generated by the Derive phase. In the maintenance component, it deals with uncertain decision making ahead of time, e.g. about the optimal time for a maintenance action implementation along with the optimal time of ordering the required spare parts Just-In-Time. This recommendation feeds as input into the supplier selection component that provides recommendations about the optimal portfolio of suppliers given the purchasing budget at the recommended future ordering time so that the expected losses are minimized. The use of a portfolio optimization approach supports the allocation of scarce resources in the manufacturing enterprise to different supplier relationships and thus, the minimization of supply-related risks. Since information processing is asynchronous, the suppliers' recommendation part of supplier selection component receives and stores the most recent update of the suppliers' prices predictions in order to use it when the action recommendation part of maintenance component triggers the supplier recommendation part of supplier selection component.

Do: This phase deals with the continuous monitoring and the actual implementation of the recommended actions in order to adapt the whole 4D cycle of the operational system closing the feedback loop and leading to the continuous proactive business performance optimization. The feedback gathered from the Do phase is transferred to all the previous phases for both components according to which one corresponds. In the maintenance component, feedback is collected through hardware sensors and measuring devices and deals with the actual complex pattern that would led to failure, the actual time of the failure occurrence (if it finally occurs) as well as the actual maintenance and inventory costs during the action implementation. Then, the previous phases are updated offline accordingly. In the supplier selection component, feedback is collected through software sensors (e.g. ERP) and deals with the actual cause that led to prices fluctuations, the actual prices fluctuations in the course of time and the actual suppliers' prices at the time of spare parts ordering. Then, the previous phases are updated offline accordingly.

4 The Implemented System

Based on the framework, we developed an information system. The User Interaction Layer has been implemented as a web-based application using web2py, while the real-time processing layer as a Storm topology. For each consisting module, we integrated existing systems, we embedded modifications of existing algorithms and we developed new models as explained below.

Detect: In this phase, we used an existing tool called "StreamPipes", which defines and executes stream processing pipelines consisting of multiple heterogeneous runtime implementations [8]. It is used in both components with a different formulation. In the maintenance management component, it is used for the detection of abnormal equipment behavior on the basis of manufacturing sensor observations that may be causes of a future failure (e.g. temperature, vibration, etc.). In the supplier selection module, it is used for the detection of indicators for a possible future prices change on the basis of observations of changes in the ERP system due to EDI (e.g. start of negotiation process, change in profitability of suppliers, etc.).

Derive: In this phase, the maintenance component was implemented by integrating an existing system called "StreamStory" [9], which allows the simultaneous analysis of multiple data streams by their modelling as hierarchical Markovian model on the basis of complex event patterns. Then, it provides predictions about the PDF of future failures (prognostic information). As far as the supplier selection component is concerned, we embedded a modification of an existing algorithm for suppliers' prices prediction using Artificial Neural Networks (ANN) [5] so that it becomes dynamic [7] and event-driven in order to utilize the detected indicators of the previous phase. Its output is the prediction of suppliers' prices throughout a decision horizon, sent and stored in the suppliers recommendation part of supplier selection component.

Decide: In this phase, both the maintenance and the supplier selection components were implemented in a tool for proactive decision making which incorporates a joint predictive maintenance and spare parts inventory optimization method for providing a recommendation about the optimal time of applying a maintenance action and the optimal time of ordering the required spare parts [10]. This output triggers the suppliers' recommendation part of the supplier selection component and is used along with the stored suppliers' prices prediction event as input to a Markowitz Portfolio Theory (MPT)-based optimization algorithm [11] where the assets correspond to suppliers. Thus, MPT method is applied on the basis of the recommended optimal ordering time and the predictions for the suppliers' future prices in order to enable the purchasing department to decide in advance what proportion of the procurement budget should be spent to each supplier. The MPT algorithm is solved using convex optimization [12] because it is a complex problem with bounds, constraints and a Lagrange multiplier.

Do: In this phase, we used a tool for monitoring and updating the input parameters of the joint decision model (e.g. actual costs) by using a Sensor- Enabled Feedback mechanism (SEF) [13] for both the maintenance and supplier selection components.

5 Application in Industrial Environment

We validated our proposed framework by deploying the aforementioned system in a manufacturing company in the area of automotive lighting equipment production. However, due to the lack of prices-related data and historical portfolios, we also used simulation based on prior expert knowledge. The manufacturing process deals with the production of the headlamps' components. Until now, the company conducted time-based maintenance by cleaning the moulding machine from dust and replacing the moulds once per month. Its aim is to turn into CBM by adapting at the same time its spare parts ordering policy according to the 'just-in-time' concept and by deciding proactively about the portfolio of its suppliers. After implementing the aforementioned system, the manufacturing company started a negotiation process with its 4 suppliers. This information along with suppliers-related data (inventory level, scheduled production plan, capacity, etc.) is continuously updated in ERP through EDI. At some time, an abnormal equipment behavior was identified and the implemented system followed the process described in Table 1.

Table 1. Inputs and outputs of each 4D phase for the current scenario

4D model		Maintenance	Supplier selection
Detect	Input	Dust levels, environmental sensors (temperature, humidity)	Negotiation process start, 4 suppliers, bid prices, suppliers-related data, economic environment (e.g. taxes)
	Output	Complex pattern about an abnormal equipment behavior	Complex pattern about a possible future price change
Derive	Input	Complex pattern about an abnormal equipment behavior	Complex pattern about a possible future price change
	Output	Exponential PDF of cover lens scrap rate exceeding 25% with $\lambda = 1/\text{time-to-failure}$ (12 days)	Prices prediction until the next planned maintenance (Fig. 2)
Decide	Input	Exponential PDF of scrap rate exceeding 25% with $\lambda = 1/12$	Prices prediction till next planned maintenance, Recommended time for ordering
	Output	Recommendation to conduct maintenance in 3.5 days and to order the associated spare parts, i.e. moulds, in 1.3 days (Fig. 4)	'Markowitz bullet' and its 'efficient frontier' (through the simulation of mean returns and volatility for 100 portfolios) (Fig. 3), The optimal portfolio of suppliers (Table 2)
Do	Input	Recommended times for maintenance and ordering	The optimal portfolio of suppliers
	Output	Cost monitoring and update	Cost monitoring and update

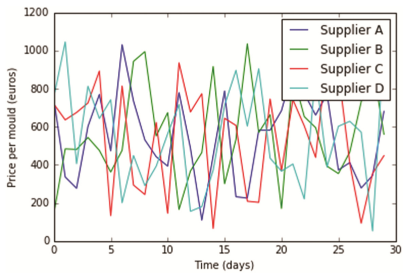

Fig. 2. The prices prediction in the course of time until the decision horizon.

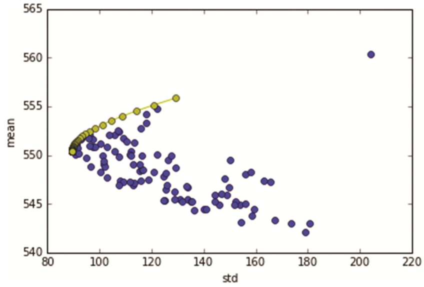

Fig. 3. The markowitz bullet and its efficient frontier for the portfolios.

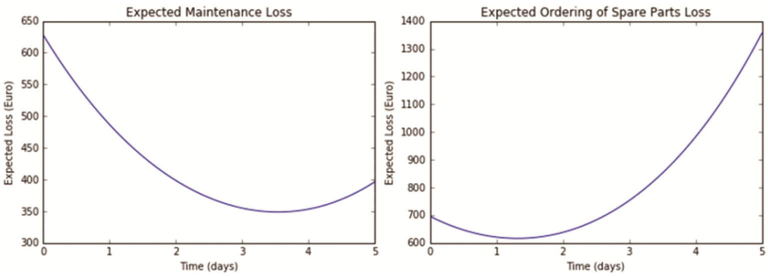

Fig. 4. The expected maintenance and ordering of spare parts loss functions.

Table 2. The optimal portfolio of suppliers.

Supplier A	Supplier B	Supplier C	Supplier D
0.14	0.38	0.26	0.22

6 Comparative and Sensitivity Analysis

We compared our approach with two scenarios under several executions: a reactive scenario, having no prediction (with corrective actions and emergency spare parts ordering when the failure occurs) and one where there is a prediction algorithm but not automated decision making. In the first case, corrective maintenance actions last more than predictive ones due to the lack of root causes knowledge, while emergency, unplanned ordering of spare parts requires a longer lead time and leads to a penalty cost due to unplanned distribution. In the second case, due to the failure prediction, either corrective actions are implemented when the failure actually occurs (with the previously referred costs and lead time), or immediate preventive actions are applied, according to a cost-benefit analysis. These results are shown in Table 3.

Table 3. Results of comparative and sensitivity analysis.

Approach	Maintenance cost	Inventory cost	Supplies cost	Total cost
No prediction	1,466 ± 58	1,013 ± 27	1,195 ± 34	3,674 ± 119
Only prediction	1,355 ± 112	905 ± 89	1,069 ± 121	3,329 ± 322
Proposed approach	823 ± 46	708 ± 38	802 ± 44	2,333 ± 128

7 Conclusions and Future Work

We presented a framework for real-time, event-driven proactive supplier selection driven by CBM. An information system was developed and validated in industrial environment in the area of automotive lighting equipment. The evaluation results showed that our approach reduces the costs related to maintenance, inventory and supply of spare parts by enabling the transformation of the company's maintenance and purchasing strategy from reactive to proactive. Regarding our future work, we aim to develop more advanced visualization techniques and to add a context-awareness mechanism integrated with the whole 4D cycle.

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Toward Semi-autonomous Information

Extraction for Unstructured Maintenance Data in Root Cause Analysis

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Abstract. To facilitate root cause analysis in the manufacturing industry, maintenance technicians often fill out "maintenance tickets" to track issues and corresponding corrective actions. A database of these maintenance-logs can provide problem descriptions, causes, and treatments for the facility at large. However, when similar issues occur, different technicians rarely describe the same problem in an identical manner. This leads to description inconsistencies within the database, which makes it difficult to categorize issues or learn from similar cause-effect relationships. If such relationships could be identified, there is the potential to discover more insight into system performance. One way to address this opportunity is via the application of natural language processing (NLP) techniques to tag similar ticket descriptions, allowing for more formalized statistical learning of patterns in the maintenance data as a special type of short-text data. This paper showcases a proof-of-concept pipeline for merging multiple machine learning (ML) and NLP techniques to cluster and tag maintenance data, as part of a broader research thrust to extract insight from largely unstructured natural-language maintenance logs. The accuracy of the proposed method is tested on real data from a small manufacturer.

Keywords: Natural language processing · Root cause analysis · Manufacturing maintenance

1 Introduction

Multiple industries often use root cause analysis (RCA) techniques to diagnose the underlying cause(s) of problems (Shrouti et al. 2013). Within the manufacturing industry, there are a variety of RCA techniques that are utilized: Six Sigma, including DMAIC (Define, Measure, Analyze, Improve, Control) and DFSS (Design-For-Six-Sigma) (BOUTI and KADI 1994), Failure Mode and Effect Analysis (FMEA) (Liu et al. 2013), and fishbone diagrams, also known as Ishikawa diagrams (Juran and Godfrey 1999) are just a few. While there are many techniques, instances of RCA are often problem-specific studies, where results are not readily available for wide retrieval in future studies. A framework was developed previously in Brundage et al. (2017) to help alleviate this issue, providing mechanisms for accessing previous problems to aid in diagnosing the

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root cause. However, the developed framework relies on readily structured descriptions of causes-effects-treatments; generally such patterns are derived from raw information tracked via a Computerized Maintenance Management System (CMMS). Such clearly structured information is rarely found in practice, as technicians often inconsistently record informal prose rather than clearly filling in discrete fields for causes, effects, and treatments. Such inconsistencies make it difficult to perform diagnosis procedures. This paper begins to address that issue by providing NLP and ML techniques to prepare, clean, and tag the data for use in the diagnosis framework. It is aimed at cases where a CMMS may not be properly implemented, or in a well managed CMMS to help capture in-explicit information from any free form descriptions or comments within the system.

2 Motivation

Using NLP techniques in a maintenance data-set, unlike the more popular applications of NLP that have huge amounts of casual and/or complete-sentence phrases (such as Yelp R reviews or a Twitter R feed), requires treatment of documents generally smaller in nature, which at times have entries with fragmented sentence structure or are written in domain-specific shorthand. In addition, to the authors' knowledge, no definitive corpus or thesaurus of maintenance log terms and terminology currently exists that spans all companies in an industry setting. Nor, in many cases, would one be appropriate, as each company—or even each work site—will often develop their own short hand vocabulary and "tribal knowledge" set that could be meaningless to anyone not immersed in that environment. This work seeks to provide a method for working within these environments in order to characterize and categorize often dissimilar entries.

The authors envision a mature information extraction tool as autonomously tagging and structuring extracted information from the short, often fragmented entries that are common characteristics of many industrial maintenance logs. Achieving such vision would require both additional data sets, as well as comparative analysis with a wider breadth of existing NLP and ML techniques. The following is presented as a preliminary proof of concept (PoC), articulating the basic road map shown in Fig. 1. The result of this PoC expresses the viability of implementing computer–augmented maintenance history analysis.

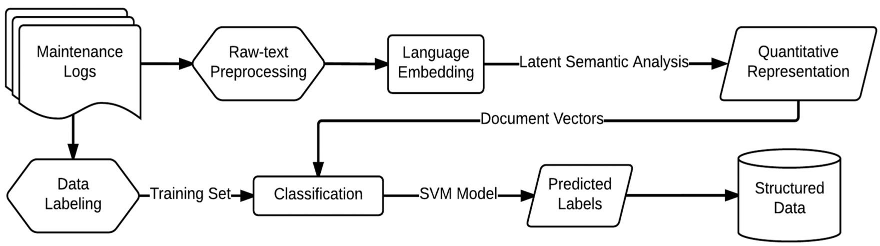

Fig. 1. An overview of the information extraction pipeline for maintenance log text

3 Methodology

3.1 Process Overview

Solutions to classification problems are generalized based on their method of training: supervised, semi-supervised, or unsupervised. This paper uses a supervised classification, meaning that pre-defined ground truth labels must be assigned to a training set by an "expert", and a trained model can then be used to predict labels for previously unseen entries. The data set used in this work consists of 779 hand-labeled entries from a manufacturing company's actual maintenance log over the period of several months.

3.2 Data Collection and Labeling

Using text-mining methods in general, and specifically NLP as implemented here, requires several components:

1. Data collection and labeling
2. Text preprocessing and language embedding (vectorization)
3. Classification model training and validation

This process is summarized briefly in Fig. 1. The data set of 779 entries was manually labeled from short form problem descriptions to train a classifier (Sect. 3.2). To represent the logs numerically, vectorization was done using a version of Topic modeling closely related to Latent Semantic Analysis (Sect. 3.3). Finally, a Support Vector Machine (SVM) was trained to label documents based on the provided training set (Sect. 3.4).

3.3 Text Preprocessing and Vectorization

To train a classifier on the labeled data, a numeric representation of the text based maintenance logs (the documents) is needed. This semantic language embedding is done in two steps: (1) preprocess the text to cleanse it of non-useful artifacts, and (2) vectorize the processed text into manageable form by using a topic model.

Raw-Text Preprocessing

Cleaning each query (i.e. each issue as described in a string of words) by removing extraneous punctuation and inconsequential words (a.k.a. stop words) (Leskovec et al. 2014) is common practice in NLP techniques. After cleaning, the string is parsed into words and phrases up to N words long and placed in sparse word frequency matrix via the Bag of Words (BoW) technique. During the construction of this matrix, common pluralizations of words are combined (i.e. treated as a single entry) and tokens that have a very low occurrence rate within the corpus (less than 3 instances) are removed. In this context, a token is a word, or group of ordered words (phrase) that appear in the corpus. This dimensionality reduction aids both in convergence and processing time for the language embedding and classification algorithms.

Language Embedding

To create a numeric feature space, useful for computerized classification, this work loosely follows the process used in Latent Semantic Analysis (Dumais 2004). The entire set of text (the corpus) is represented as a term-document Matrix, a frequency-based vectorization of word occurrence (BoW, as referred earlier).

To reduce the dimensionality of this corpus word-frequency feature space, a reduced-rank Principal Component Decomposition was performed, and the top n-largest principal components were retained so that the rank-n approximation had 90% variance retention. One interpretation of each of the n the principal component vectors is as a weighted combination of words/phrases forming a topic in the corpus. Thus the name, "Topic Model".

Finally, due to very low term-overlap between maintenance topics within this corpus, the document vectors were weighted by the most common token found elsewhere in the corpus. This was done with an ordinary-least-squares (OLS) mapping, essentially a prediction on how a phrase would be most commonly talked about in the rest of the corpus. The authors hypothesize that this might take advantage of the natural structure of maintenance-like data, and preliminary results suggest accurate performance under this weighting scheme.

3.4 Classifications: SVM Model

The last phase of the presented method is to train a supervised classifier on the expert diagnostic tags provided for each training entry. Here, a Support Vector Machine (SVM) classifier was selected for this task, which has been previously shown to have excellent ability in text classification (Joachims 1998).

Data is randomly split into train- and test-groups, allowing the SVM to learn on a subset of the data, and then be validated by predicting labels on another, smaller subset (see Sect. 4.1 for a discussion on the effect of training-set size). The classifier was trained against binary vectors representing the target "ground truth" label. Upon subsequent input, it outputs a relative likelihood for each of the possible category labels, and assigns the most probable label to that input.

As a modification to the default labeling, if none of the potential labels had a relative likelihood 0.5 (50% likely) or more, the input was deemed too far away from previous training vectors and therefore an "uncharacterized set entry". This "uncharacterized set" labeling is crucial for identifying labels that are not well characterized in the model so that they can be further analyzed by the expert and retrained into the model, when Human-in-the-Loop training is possible.

4 Results

The results presented in this section enumerate classification performance averaged over twenty trials where the designation of training, testing, and validation samples are randomized between tests. The influence of training set size on performance is detailed, though this is recognized as only a small subset of controllable parameters in this model. A broad-sensitivity study, though outside the scope of this work, is a crucial part of future work (Sect. 5).

4.1 Training Set Size

To determine the robustness of the described method to the availability of training data, the SVM was trained on varying proportions of the data selected at random (see Fig. 2). Each increase in the proportion of training data is analogous to a human manually tagging entries marked by the algorithm as unknown, and/or correcting any observed mislabeling, then iteratively retraining the model. In this way we can simulate Human-in-the-Loop training. Note that as this data-set is finite in size, when an increasing amount (e.g. 80%) is used for training, the total number of validation instances or examples reported in the results must drop (e.g. to 20%) corresponding to the total available entries.

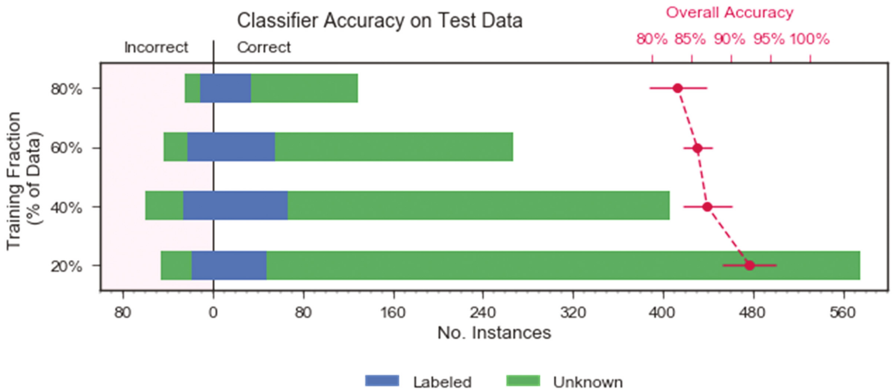

Fig. 2. The effects on classification accuracy of the fraction of data used for training the SVM. Mean number of correct and incorrect labellings over 20 trials are shown against the lower axis for each training-fraction setting. Additionally, the overall prediction accuracy is shown against the upper axis with 1σ uncertainty bars.

For this work, an "uncharacterized set entry" is a label that has too few (or zero) examples in the training set to be confidently characterized by the classification model. Intuitively, as the percentage of training examples increases, this number of "uncharacterized set entries" will likely decrease somewhat. However, for this data-set, and likely any coming from real world industry maintenance logs, there is a base level of these rarely occurring entries. Thus as important as it is to correctly classify or label those entries that can be characterized by the model, it is equally important to identify those that cannot. This not only lowers misclassification chances, it also allows such entries to be flagged for further investigations by an external human operator, who can then correctly label and add it to the model.

It is important to note that the classifier's ability to correctly identify well documented labels (i.e. ones not in the "uncharacterized set") is relatively invariant across training-set sizes. This implies that, once the model has learned which labels are reliable, its confidence level in predicting them—and by extension, its performance—is likely to remain consistent, even as new information is added to the model. In other words, these results imply that once any arbitrary label obtains enough entries to be able to be characterized by the model, the expected correct classification rate of that label is consistent, regardless of what the label actually is. Thus adding additional labeled examples is more about extending the model coverage than improving performance; although intuitively performance should also somewhat improve.

In addition, the model is able to correctly isolate the "uncharacterized set entries" not previously seen in the training data, but this ability decreases with a broader selection of labeled entries in the training set. This indicates that, as more of the feature space is populated, an entry must be further away from any known labels to be identified as unknown. Consequently, a dynamic, rather than static threshold of confidence when classifying "uncharacterized set entries" as outliers may be more appropriate for this type of discrimination. Lowering the confidence criteria for labeling "uncharacterized set entries" from 50% to 40% in one of the tests caused an average increase of 3% in correct classification, but also a drop of 6% in the correct identification of "uncharacterized set" labels. Significant improvement might come from re-defining the confidence threshold on-the-fly, or defining it in a feature-specific manner.

As shown in Fig. 2, the increased total accuracy at lower levels of training data is driven by the model's increased ability to identify unknown entries. This should not lead one to assume that less training data is a favorable; rather, this reaffirms the need to accurately identify the "uncharacterized set entries" at higher proportions of training data, where the total feature space becomes more populated. As the well-characterized areas—the "known" areas of the feature space–become more dense, the "uncharacterized set" areas become harder to distinguish. Additional investigations into methods for managing and mitigating this effect will be part of on going work, perhaps utilizing more crisp kernel models in the classification algorithm, or other similar techniques.

Additional investigations on n-gram parsing (Brown et al. 1992) and rare token exclusion have been performed, but a full review is left out due to space constraints. In brief, it was found that additional complexity added via n-gram parsing was unnecessary, likely due to the domain-targeted language of the data set. Conversely, regulating the minimal word token occurrence frequency did seem to have a significant effect on the model's performance. Removal of highly superfluous or infrequent terms aided classification through dimensionality reduction with indications that, for a given data set, there is an optimal occurrence frequency band to include in the model. Further investigations into the generalization to a broader range of data sets of these findings as well as additional areas of inquiry are left for future work.

5 Conclusions and Future Work

Virtual mountains of historic maintenance logs representing an untold wealth of diagnostic knowledge exist throughout industry. Without proper tools and techniques to analyze and contextualize that data, the usefulness of these maintenance logs is severely limited. Presented in this work is a proof-of-concept algorithmic framework for characterizing one aspect of that data. By categorically labeling the generally free form and fragmented text patterns associated with industrial maintenance logs, historical commonalities and recurring problem areas can readily be identified and targeted for process improvement.

The methodology detailed in this work is shown on a preliminary case study to consistently categorize and label a free form maintenance log entry from a set of known labels with over 70% accuracy. Additionally, the algorithm can correctly identify log entries as unique (or potentially needing better labeling) with over 85% accuracy.

Work in this area is a fertile ground for many avenues of continuing and future research. Especially apparent is the need for a broad overview of available methods for training and classifying natural-language texts in the form of maintenance logs. Automated selection of an optimal model for prediction of labels in a given industry or use case is crucial to ensure the best performance. Comparing other quantitative representations for language, like Word2Vec semantic embedding, will provide an excellent means of discovering maintenance-specific patterns in the text logs. In addition, the efficient utilization of domain-expert knowledge will be crucial in implementing systems like this one, leading to a more dynamic ability to parse data with Human-in-the-Loop system schemes.

The authors believe a set of guidelines for selecting appropriate algorithms based on amount and quality of data, as well as the desired outputs, could accelerate maintenance information utilization. Taking advantage of information hidden in maintenance logs could help bolster productivity, improve maintenance practices, and ultimately save time and money wasted on patching trivial symptomatic problems instead of focusing on the root cause.

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A Component Selection Method for Prioritized Predictive Maintenance

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Abstract. Predictive maintenance is a maintenance strategy of diagnosing and prognosing a machine based on its condition. Compared with other maintenance strategies, the predictive maintenance strategy has the advantage of lowering the maintenance cost and time. Thus, many studies have been conducted to develop a predictive maintenance model based on a growth of prediction methodology. However, these studies tend to focus on building the predictive model and measuring its performance, rather than selecting the appropriate components for predictive maintenance. Nevertheless, selecting the predictive maintenance policy and target component are as important as model selection and performance measurement. In this paper, a selection method is proposed to improve component selection by referencing current literature and industry expert knowledge. The results of this research can serve as a foundation for further studies in this area.

Keywords: Predictive maintenance · Condition-based maintenance · Component prioritization · Machine condition · Intelligent manufacturing

1 Introduction

Regardless of how well a manufacturing machine is designed, the machine degrades over time because operation causes stress to each machine component and random event causes machine degradation (Jardine et al. 2006). As a result, maintenance is an inevitable endeavor of most manufacturing industries. It can be classified into three types of strategies: corrective, preventive, and predictive (Bertolini and Bevilacqua 2006).

Corrective maintenance is a run-to failure or reactive maintenance strategy (Ahmad and Kamaruddin 2012). This strategy thus leads to considerable machine downtime and high maintenance costs (Ahmad and Kamaruddin 2012). However, corrective maintenance is used as an adjunct operation because it is impossible to respond to all failures before a machine fails.

The second strategy is preventive maintenance, which is also known as preventative maintenance. In this strategy, maintenance is performed to each component on a specific

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unit interval (e.g., x cycles, y hours) and it is widely used in the manufacturing industry (Coats et al. 2011).

Predictive maintenance is the third maintenance strategy. It is similar to the condition-based maintenance approach. It employs condition and performance data, which are captured from the machine to indicate when maintenance should be performed (Byington et al. 2002). Compared with the first two maintenance strategies, the predictive maintenance strategy has the advantage of reducing both the maintenance cost and time. Thus, many studies have been conducted on building a reliable predictive maintenance model to minimize maintenance costs and time.

The remainder of this paper is organized as follows. In Sect. 2, a literature review on existing predictive maintenance approaches is provided. A process of identifying appropriate components for predictive maintenance is proposed in Sect. 3. In Sect. 4, the characteristics relating to a component's criticality are analyzed for component prioritization. A component selection method for prioritized in predictive maintenance is then proposed in Sect. 5. Our conclusions and future work on component prioritization in predictive maintenance are presented in Sect. 6.

2 Research Background

In this section, existing literature is briefly reviewed to introduce predictive maintenance before addressing component prioritization. Predictive maintenance was introduced in 1975 to maximize the effectiveness of maintenance decision making (Ahmad and Kamaruddin 2012). Its development was driven by the fact that 99% of machine failures are preceded by certain signs, conditions, or other indications that a failure will occur (Zhang 2014). Analyses of some study results have shown that, in most cases, the goals of the model are reached by choosing the predictive maintenance policy (Bertolini and Bevilacqua 2006). Owing to the potential advantage of predictive maintenance, many studies have served to develop a predictive maintenance model. Moreover, the growth of a prediction methodology has accelerated the development of predictive maintenance.

In predictive maintenance, condition data and performance data are matched. From that point, the relation between them is identified. This approach provides an opportunity for improving failure predictability and machine reliability (Elwany and Gebraeel 2008). Several studies focused on building a prediction model for bearings, gears, shafts, pumps, and alternators using various algorithms, such as the Fourier transform, Wavelet energy, Principal component analysis, Logistic regression, Kalman filter, and Neural network (Lee et al. 2014). However, researchers have tended to emphasize building a predictive model, not selecting a predictive maintenance policy and target component. On account of high data collection costs (Ahmad and Kamaruddin 2012), it is impossible to collect all data from all components. Therefore, target component identification should precede predictive maintenance. In this paper, a selection method is proposed for selecting and prioritizing components to which predictive maintenance is selectively applied.

3 Appropriate Component Identification for Predictive Maintenance

Predictive maintenance is not always the best strategy when strategic and data analysis aspects are considered. Therefore, before applying predictive maintenance, it is important to find appropriate component that is better to apply predictive maintenance than corrective maintenance or preventive maintenance. Applying predictive maintenance requires an additional investment in machines (e.g., sensors, gateways, and servers). Furthermore, data should be in adequate form to build predictive maintenance. Thus, depending on the condition, a suitable maintenance strategy should be selected before applying any kind of maintenance strategy. When the maintenance objective is not operating well, but is enabling the machine to merely function—or, if alternate machines are adequate so that a machine failure is not a critical issue—predictive maintenance is not required. Consequently, strategic decision making should be first performed. If the strategic aspects of the maintenance do not indicate adopting a predictive maintenance strategy, then other maintenance strategies should be considered.

When determining through strategic decision making that predictive maintenance should be applied, additional decision making should be performed in terms of data analysis. Lee et al. (2014) suggested use of a maintenance transformation map to guide appropriate maintenance strategies for data analysis (Fig. 1.). As shown in Fig. 1, predictive maintenance can be applied to systems in which complexity is intrusive and uncertainty is continuous. Depending on the machine component, the system can differ and increase in size, including with additional components. Thus, the complexity is non-intrusive and uncertainty is dynamic.

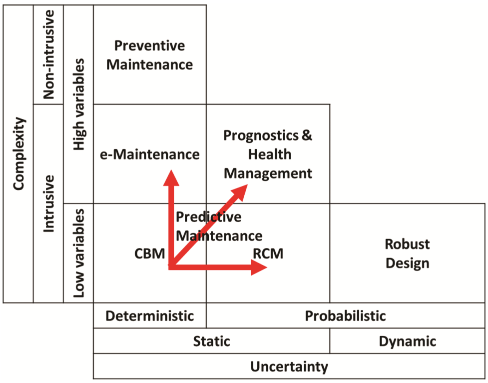

Fig. 1. Maintenance transformation map.

If a component is strategically identified and the related data are analytically appropriate to applying predictive maintenance, then component prioritization follows. Figure 2 summarizes the steps of applying predictive maintenance.

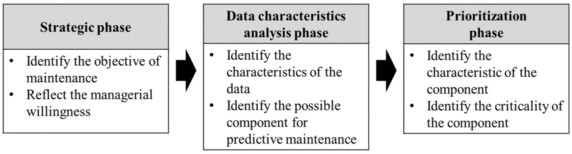

Fig. 2. Decision-making process for applying predictive maintenance.

4 Components Failure Criticality Measurement

To prioritize components, criticality analysis for each component's failure should be conducted. Criticality analysis is based on the component characteristics. In the manufacturing industry, the component criticality may relate to the cost incurred by the component's absence. However, it is difficult to quantify the cost that reflects the component absence itself (Zha et al. 1998, Kennedy et al. 2002). Thus, the criticality measurement is conducted in terms of severity, frequency of occurrence, and detectability. These three criteria—severity, occurrence, and detectability—are widely used to measure criticality in failure, mode, effect, and criticality analysis (FMECA). (Bowles and Peláez 1995) Using the same criteria, component criticality analysis can be performed to prioritize the components.

4.1 Severity

According to (Department of Defense USA 2012), "severity" is defined as "death, injury, occupational illness, damage to or loss of machine or property, damage to the environment, or monetary loss." From the definition, we can recognize that, if the severity is high, the result of the component failure leads to a significantly negative impact. Therefore, if the severity is high, predictive maintenance should be first applied. The definition includes three issues: cost, time, and regulation. We determined the characteristics of components related to the above three issues through a literature review.

4.1.1 Cost

One of the most important characteristics relating to component failure severity is the cost. Many studies that addressed spare components management or machine prioritization used cost as a decision variable for developing an optimal procurement and management policy (Hamdi et al. 2012, Taghipour et al. 2011). The cost related to component severity can be classified into four types, which are outlined below.

Repair cost refers to the cost required to return a component to normal condition. This cost is only incurred when the component can be repaired, and it is better in terms of cost and time than replacing the component. Repair is a widely accepted concept to managing a component. To minimize the total cost of inventory (Allen and D'Esopo 1968), components are classified as repairable or non-repairable (Gross and Pinkus 1979). If the repair cost of a certain component is higher than the repair cost of another component, it is better to monitor the component with the higher associated cost. The component for which the repair cost increases if degradation occurs should be monitored before the repair becomes impossible or the repair cost remains low.

Replacement cost is the second type of cost that affects the component criticality. Replacement is needed when the component no longer can be used because of degradation or a random incident. As mentioned above, the replacement cost should be considered with the repair cost for estimating criticality. In addition, replacement is inevitable; hence, it is necessary to consider the replacement cost to measure the component criticality.

Ordering cost (regular/emergency) is the expense involved in processing an order to suppliers. Depending on the order type, the ordering cost can be classified as a regular or emergency ordering cost (Zohrul Kabir and Al-Olayan 1996). The regular ordering cost is lower than the emergency ordering cost. Therefore, if the gap between the two different costs is high, the severity of an unexpected component failure increases and the positive effect of the predictive maintenance will be greater.

Spare component cost/holding cost affects decisions of whether the company should have a spare component, and, if so, how many spare components the company should hold. In practice, it is difficult to maintain expensive spare components, especially when the spare component requires extra care in its holding. On the other hand, inexpensive components, such as bolts, nuts, screws, and cables, which do not require extra care, are not burdensome to the manufacturer. In this case, it is reasonable to hold an adequate amount of spare components because the holding cost is much lower than the ordering and shortage costs. Thus, if spare components of this type exist, the severity of the component failure is limited.

4.1.2 Time

Time has a strong relation with productivity, and productivity is the main indicator of performance in the manufacturing industry. Therefore, time can be used to measure the severity of the component failure. In the same manner as the cost, time can be classified into four types, as outlined below.

Repair/replace time refers to the time required to repair and replace the component when the repair/replacement component ready for use. That is, it does not include delivery time. As mentioned above, the repair and replacement are inevitable and require a certain amount of time to return the component to a normal condition. Before the component repair or replacement is completed, the machine cannot operate; it remains in an idle time, for which the manufacturer incurs a monetary loss.

In practice, if component alternatives exist, a temporal repair or replacement with an alternate component is possible. For example, a key switch has a similar structure as a selector switch. If a key switch fails, a selector switch is used as a temporary alternative. Thus, the cost of a *temporal repair or replace with an alternative* is another cost that is not common.

Delivery time is the time that should be employed to receive the new component for replacement. If no spare component exists, a wait time for the component delivery is involved and a monetary loss from the component failure can also occur. Moreover, in the manufacturing industry, the delivery time can be lengthy if the machine is discontinued or the machine manufacturer is far from the factory.

4.1.3 Regulation

Safety is another key aspect. Workers should be protected from the conditions that can cause any hazardous outcome, such as injury, death, or illness. If the component failure is directly related to a safety problem, it should be maintained in the best possible condition to fulfill the safety requirement and maintain worker safety.

In terms of the *environment*, when the failure of a component results in costs required for cleanup and environmental liability, fines or penalties can be imposed. Hence, it is desirable that environmental aspects are measured.

4.2 Occurrence

4.2.1 Frequency

The *failure rate* is the frequency in which failure events occur in a given time period (Ostrom and Wilhelmsen 2012). It is a widely used concept in reliability engineering. If the failure rate is high, the frequency of the component failure is likewise high. Thus, the appropriate monitoring system should be installed to manage the component.

Mean time between failure (MTBF) is another representation of frequency. It is calculated by the sum of the time operation normally divided by the number of observed failures. Unlike the failure rate, if the value of MTBF is low, the frequency of the component failure is high. With same logic, *mean time to failure (MTTF)* can be another candidate.

4.2.2 Life Time

Desired life time is the expectation of the amount of time the component will last once installed. For components that have short life times, and frequent replacements are needed, the predictive maintenance should be reconsidered. In contrast, if the durability of the component is retained over a long time, and the desired life time is semi-permanent, then predictive maintenance may not be needed.

Of the characteristics compared for assessing component failure criticality, *remaining life time* is a good measurement. It is the estimated remaining time until a failure occurs (Finkelstein 2008). Depending on the metric use, it can be an alternative to the desired life time or they can be used in combination.

4.3 Detectability

4.3.1 Ease of Prediction

Before the component fails, if the machine state or any *prior signal* from the machine indicates the future failure of the component, it is not severe to assign a priority to a certain component.

In PHM research, for some components, common features applied for PHM are identified. In this case, detectability of that component (*probability to success)* is high, and the risk of applying predictive maintenance is low.

5 Component Prioritization Method

In this section, a method for component prioritization in predictive maintenance metrics is presented (see Fig. 2 and Table 1). As shown in Fig. 2, the appropriate component for predictive maintenance should be selected first in terms of the strategic and data analyses. After the candidate components are selected, prioritization is conducted by comparing component failure criticality. The criteria for measuring component criticality are severity, occurrence, and detectability. Each criterion has a sub-category (see Table 1). The component characteristic presented in Table 1 may not apply to all machines in all industries. However, the data shown in Fig. 2 and Table 1 are only a starting point. This method can hopefully assist researcher efforts in assessing the component criticality for sequential application of predictive maintenance.

Table 1. Characteristics for measuring component failure criticality.

Severity			Occurrence		Detectability
Cost	Time	Regulation	Frequency	Lifetime	Ease of prediction
Repair cost Replacement cost Ordering cost Spare part (holding) cost	Repair time Replacement time Temporal - Replacement time Delivery time	Safety Environment	Failure rate MTBF MTTF	Desired lifetime Remaining lifetime	Prior signal Probability

6 Conclusions

Before applying predictive maintenance, the primary issues to be addressed include determining which maintenance strategy is appropriate for a certain component, and which component should be prioritized if predictive maintenance is applied. Thus, the strategic phase and data analysis phase are suggested for identifying the appropriate component for predictive maintenance. In addition, three criteria—i.e., severity, occurrence, and detectability—are used to identify the component failure criticality. With these three criteria and their sub-categories, the component characteristics—i.e., cost, time, regulation, frequency, lifetime, ease of prediction—that affect each criterion are identified. For component prioritization in predictive maintenance, the characteristics are comprehensively considered. However, if the quantitative approach is adopted, then the usability of the method will be enhanced.

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Collaborative Operations Using Process Alarm Monitoring

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Abstract. We discuss alarm monitoring in process control supported by best practice used and standards implemented into recently developed engineering tools. Our paper describes aspects of a joint project development in the specific engineering company and VSB-Technical University of Ostrava. Our work focuses on monitoring assets and viewing status of conditions with help of data files acquired during commissioning process implementing the technology into practice. Alarm and event data received from technology process were analyzed according to standardized approaches with the aim to point out further limitations of alarm reports and develop an engineering tool for configuration of event and alarm limits of monitored variables in a control system during the commissioning phase under operation conditions.

Keywords: Alarms · Commissioning · Data · Monitoring · Project · Process

1 Introduction to Collaborative Operations

In many engineering systems, the ability to anticipate and provide well-defined alarm of an impending critical event is of great importance. Various critical events can have different degrees of severity and in fact may occur during normal operation of the system. According to (Rodney 2004) "An alarm may be given for any number of thermal sensation complaint events that occur over a specified time period. As such, an optimal alarm system can be designed to warn facility managers of impending complaints that might occur within a specified time period, to aid them in making critical decisions about building operations."

Diagnostics, error detection and its further processing bring other points of view at the critical state or situation monitoring. Errors or failures can occur on hardware parts of control systems, as well as in the software operating systems and programming logic controllers (PLCs), user application software or the behavior of a controlled process. Standardized procedures (Tiegelkamp 2010) provide reports indicating system response to various conditions of error or malfunction. The new generation PLC has standardized basic functionality and engineers use highly sophisticated tools to program it for a variety of applications. Standardization also supports ability to integrate systems assembled from standardized software components such as editors, compilers, and export and import utilities, with open interfaces for repeated functionality. Tools that were

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previously provided as separate and distinct modules, for example, human-machine interfaces (HMIs), simulation and/or visualization modules are now standardized interfaces of control systems, see the photo in Fig. 1 showing the control room with operators and their workstations.

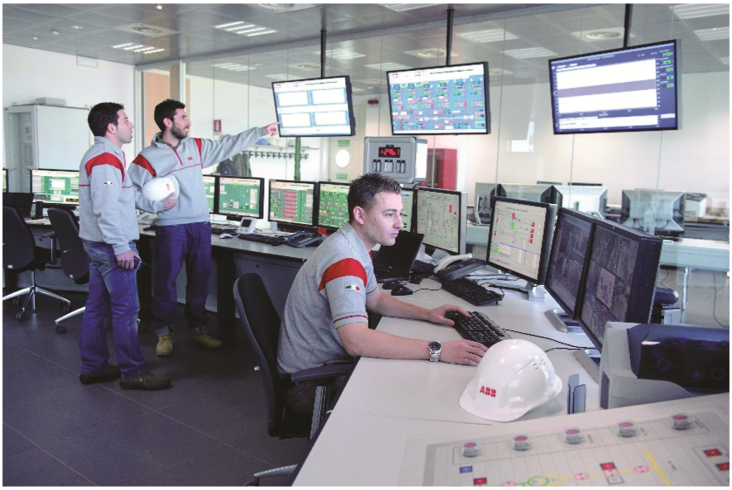

Fig. 1. Illustrative photo of a control room with operators and their workstations running applications with HMI (Source: A photo from a project)

During engineering practice, new knowledge constantly comes from the observed phenomena during operation and production, and the observation shows that events in many cases repeat. By storing information about these events into database allows us to access those records later and process historical data files through familiar and proven methodologies for data processing. The standardized steps ensure that the data is accurate and relevant in order to validate the data processing. Furthermore, these steps correct the data processing and organize it in sequence and/or in different files, then sort the data or put them into categories (classification), reduce the details of data into their main points (summarization), combine multiple pieces of data (aggregation), collect, organize, analyze, interpret and present data into reports. This is the way, in which the knowledge is born from data (Hýl and Wagnerová 2016).

Knowledge Discovery and Data Mining (KDD) is an interdisciplinary field focused on methodologies for extracting useful knowledge from data. These methodologies further develop mainly due to the rapid growth of online data access and due to the widespread use of the Internet and databases. The role of extracting knowledge from data originated from research. The further development is supported, among others, by the field of statistics, but the pattern recognition, machine learning, and data visualization earns its importance as well. Areas of monitoring and control, scheduling and diagnostics represent the increasing availability of large amounts of sensor data, due to different sensors or connection to processes, its high dimensionality and variety, and complete nature of manufacturing optimization problems (Wuest 2015).

Knowledge which comes from processed data measured during repeated observations, and evaluate common patterns, carries the added value to any development of reporting tools. The limitations of traditional Statistical Process Control (SPC) used in quality problem detection are well recognized. According to (IBM 2012): "*Specifically, traditional SPC is largely reactive in nature, results in a large number of cumulative defects produced before alerting, and suffers from high rates of false alarms*". Assuming the subject of observation is a control system operation, its evaluation focuses on the part of the data emerging during configuration of alarm limit states of monitored variables. Then a wide area of knowledge opens, which combines the knowledge and experience in the field of industrial automation, statistical process control, and knowledge and experience of people, operators, who work with these processes and in this operation (Grabot et al. 2014).

2 Standardization in Integrated Process Control Systems

The compliance with standards and principles during design of operator workstations and supervisory control system configuration process have a direct impact on innovation processes and reflect development of new requirements for control system functionalities (Brand 2010). The shift occurred when a standardized means of communication and technology started to be dominated by the industrial Ethernet followed by IEC 61850 standard.

Capacity of today's communication networks allows us to work with current and voltage in the so-called digital world of zeros and ones by sensors directly at the measuring element of the system, at the switch. The measured and monitored value is heading as a data entry with its time stamp directly to plants processing this item.

Although IEC 61131 standard prescribes to every PLC programmer to follow standardized procedures (Karl-Heinz and Tiegelkamp 2001), another area that must be taken into consideration when designing the control system is the functional safety of machinery, equipment and its units. In terms of production process, this part is implemented in the machine and process control with the use of control algorithms and is performed automatically. Therefore, with large and distributed control systems, the role of supervision at operator workplaces gets much higher attention and growing importance than in the past.

Data acquisition from production and technological units along with the monitored values of variables set to reporting their limits expand sources of information used in decision-making and production management. This binds the now standardized aspects of the safety of people and the environment in the area, according to the standards IEC 61508 and EN 61511, and thus generally increases complexity of control systems connected to the aspect of human behavior.

Data acquired from the technology system with system architecture structured according to ISA95 Standard (Khedher et al. 2011) during commissioning phase provides us with data log files that contain items that hold information about each triggered alarm, see also Fig. 3. The ISA95 organizes individual parameters of specific equipment, on which alarm settings are configured for process control, and these show the information from the log files divided accordingly (MESA 2013).

3 Real Time Data Acquisition from Control System Operation

As an example of supervisory control, we describe here the area of an alarm management system. Such system is dealing with alarm logs giving a feedback for better understanding at the level of the human-machine interface in order to improve and support the engineering work on the design, configuration and implementation of the system for an operator supervising the production and managing alarms (Fig. 2).

1	Priorit	State	ActiveTime	ObjectName	ObjectDescription	Message	Conditio	SubConditio	Class	Severity
2	1	ACT	07 17:08:26:771	7430Q07511	SCRUBBER 1 GAS NOX	HIGH HIGH LEVEL	HH	HH	27	900
3	1	ACT	07 17:07:10:166	6414V06415	ME 4 FUEL OIL FEED VISCOSITY	HIGH HIGH LEVEL	HH	HH	18	900
4	2	ACT	07 17:03:54:268	6514L06501	ME 1 LO SYSTEM TANK LEVEL	HIGH HIGH LEVEL	HH	HH	12	650
5	2	ACT	07 17:03:29:563	6111U01734	ME2 COMMON ENGINE ALRM	ALARM	VALUE	VALUE	7	650
6	1	ACT	07 17:03:24:266	6414V06413	ME 3 FUEL OIL FEED VISCOSITY	HIGH HIGH LEVEL	HH	HH	18	900
7	2	ACT	07 17:02:33:037	8241P08124	BT1 LUB OIL PRESS LOW	ALARM	VALUE	VALUE	11	650

System | MAS | MasDataOnlyAlarm | MASdata | MASgrafy | HVAC | HVACdata | ...

Fig. 2. Data fragment directly exported from a log file used for the alarm data analysis: Priority, State, ActiveTime, ObjectName, ObjectDescription, Message, Condition, Subcondition, Class, and Severity (Source: Authors' data processing files)

The alarms as well as other data are acquired during the data acquisition process with data collection functions. The data acquisition functions determine the data acquisition processing functions. Those are the function, which are consequently applied for consolidation and the identification of the data source(s).

The database provides consistent and always up-to-date data and must be optimized in order to minimize the waiting time for the data retrieval from database into reports for the user. Process data is automatically acquired from the process as real time raw data - the primary logs - acquisition of data entries of the same time base pertaining to one specific item, the stop logs and maintenance counters. Stop logs and maintenance counters are needed for downtime management, for troubleshooting and maintenance, and they are not further compressed or consolidated. Primary logs are compressed to save space when archived, and to speed-up trend graphical display.

The compressed data is stored in the database as compressed logs. In addition, primary logs are used to create secondary logs for hourly, shift, daily, weekly, monthly and yearly data. The creation of secondary logs is referred to as data consolidation process.

As described above, the control systems save readings and history about monitored variable courses into logs, events and alarms. An **event** is recorded when the variable changes its value within the defined working interval, while **alarm** is identified as a change regarding the exceeding limit of the working interval.

The alarm logs inform us about the time, value, frequency of reaching or exceeding maximum or minimum limits set for the monitored variable during the observed time interval. Both the maximum and minimum limits can be defined at levels of severity, for example high (H) and very high (HH), low (L) and very low (LL).

In our work we dealt with system modules determined for alarm handling and alarm management and focused on operator performance, when alarm is raised, what actions need to be done, metrics and benchmark values for design principles. The files with data regarding the time, values, set limits, acknowledgment status, frequency of events, date of last reset interval, alarm log creation, and similar information were acquired from the exported data from the control system alarm logs and elaborated as described further.

4 Implementing Control Systems in Operation with the Support of Human-Machine Interface

The problems occurring during implementing control systems into operation will show and can be identified based on looking into data from the control system during the commissioning phase of a project and talking to the operators of the technological process at the customer site. Discussions with the operators about the system implementation and further alarm performance analysis from the real time operation is also supported by using methodology from approved standards, such as the ISA 18.2 and EEMUA 191 (ANSI/ISA–18.2 2009). These two standards prescribe the function of alarm systems and recommend their design (Emerson Process Management 2015). Together with the definition for specific areas, they also set the average number of alarms per day, and the maximum number of received alarms per 10 min period. The operator should not be overloaded with more than 1 or 2 alarms within 10 min. The overloaded operator is then defined as the operator working under condition, when more than 10 alarms are received and displayed at an operator workstation within a 10 min time period. According to the EEMUA 191 standard, alarm performance parameters, such as:

- Average alarm intensity
- Maximum alarm intensity
- Percentage of alarm intensity beyond reasonable target

can be set for each 10 min period. The ISA 18.2 Standard further recommends not using more than 3 or 4 types of alarm priorities and more than 5% of alarms set for the highest priority (Honeywell Process Solutions 2011).

Having these parameters defined and standardized in a process industry, it is possible to analyse data logs in several ways. For example, looking at the problems occurring during implementing control systems into operation and during the Functional Acceptance Test (FAT), the acceptance testing conducted at the site determines if the requirements of a specification or contract are met, which involve performance tests.

By acquiring data from the control system during this phase of a project, the commissioning engineers realize that the same data logs indicate and provide much more information about the real time operation. This motivated us to analyze alarm logs from different technological processes and corresponding operator responses from the supervisory control system in plants, where the control system was implemented (Urban and Landryová 2016).

5 Designing and Testing the Engineering Tool for HMI Part of the Control System

The first step to design the analysis procedure was the data preparation by calculation done with the data files with the aim to determine time intervals for logs according to the Alarm Rate definition.

For example, the time difference between the last reset of the equipment *L21/00*, date in *Reset date* column, and the log creation, date in *Create log date* column of Table 1, was 154115 min. For this equipment data log, 854 alarms correspond to the given time interval; The average time calculated for events logged into the equipment was 180 min., the result was written to the Table 1 and this step was applied for other equipment and their data logs.

Table 1. The example of calculated frequency of alarms for each equipment and defined interval (Source: Authors' data processing files)

Equipment	Different time [min]	Time of generation one alarm [min]	10 [min]	20 [min]	30 [min]	….	….	160 [min]	170 [min]	180 [min]
L21/00	154115	180,00	0	0	0			0	0	1

The Fig. 3 shows a flowchart for the code, based on which the engineering tool was built. The results were tested and compared with the manual calculations and verified the correct function. The commissioning engineer can now import the log file from a control system into this tool, and the program code will prepare the alarm model with the help of its Array Mapper according to the standards described above. The algorithm will then create the time intervals and will process the alarm data into form ready for graphical format according to the EEMUA 191 standard.

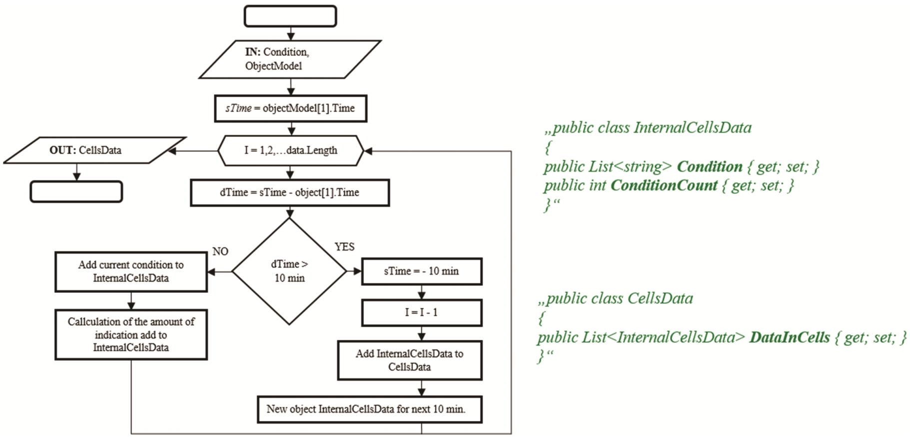

Fig. 3. A flowchart and a part of the code for the design of the engineering tool algorithm (Source: Authors' design of algorithm)

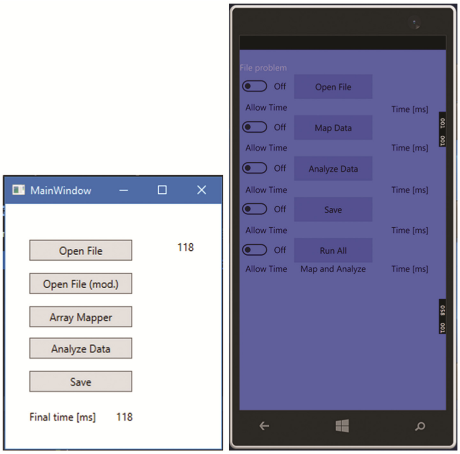

Fig. 4. Engineering Tool was tested as a console application for PC user interface and a smart phone user (Source: Authors' scan and a photo of a mobile phone)

6 Conclusion

The main objectives of this work were to address the extensive amount of analyzed data logs and develop and provide a tool for engineering, which will help project commissioning engineers and process systems operators to manage alarms in control systems and meet the standards. The engineering tool developed for the purpose of alarm system analyses enables now a commissioning engineer to analyze the newly configured control system before it runs in full operation on various technology and protects the operators from alarm overload defined in the EEMUA 191 standard (Fig. 4).

The engineering tool now joins the group of tools used in the practice and enables interoperability of control systems and human operators, defined as the component of an intelligent production company management communicating by IoT (Internet of Things) and IoS (Internet of Services). Using this tool provides the "virtualization", as it gives the ability of interconnecting the physical systems and a virtual model with a simulation during commissioning phase before the system is in a full time operation. Furthermore, the tool supports the decentralization idea for decision-making in subsystems and the ability of working in real-time, which is the key factor for any communication, decision-making and control of process systems. Finally yet importantly, the newly developed tool configurability and modularity comprehend the Industry 4.0.

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Assessment of Counter-Measures for Disturbance Management in Manufacturing Environments

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Abstract. With big data-technologies on the rise, new fields of application appear in terms of analyzing data to find new relationships for improving process understanding and stability. Manufacturing companies oftentimes cope with a high number of deviations but struggle to solve them with less effort. The research project BigPro aims to develop a methodology for implementing counter measures to disturbances and deviations derived from big data. This paper proposes a methodology for practitioners to assess predefined counter measures. It consists of a morphology with several criterions that can have a certain characteristic. Those are then combined with a weighting factor to assess the feasibility of the counter measure for prioritization.

Keywords: Counter measures · Deviations · Disturbance management

1 Introduction

The amount of data generated in production companies is continuingly growing. One reason for this development is the advancing integration of system control and measurement utilities within the production, due to new cost-efficient, high-performance information technologies. Whereas the number of applications for isolated optimization problems is continuously growing, the analysis of complex processes as found in production systems require suitable data models representing the real world [1].

The research project BigPro addresses this issue by creating a Big Data driven, pro-active disturbance management system, capable of processing various data from the manufacturing environment. Within a platform, data will be analyzed for data patterns that indicate possible disturbances in the production system. The results of the analysis is matched with a set of predefined counter-measures and then forwarded to responsible stakeholders. Additionally, generic counter-measures are proposed, if no specific one is available.

This paper deals with a systematic approach to asses counter measures for disturbances in a manufacturing environment. The remainder of this paper is organized as follows: First, we give a literature overview of existing approaches to disturbance

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management and classification of measures in Sect. 2. Next, we introduce the concept of the proposed methodology to evaluate counter measure in Sect. 3 describe the underlying calculation scheme. Finally, we conclude in Sect. 4 and highlight future work.

2 Literature Review

Before describing the developed assessment model, the terms of disturbance and deviation in context of manufacturing environments are explained. Furthermore, existing concepts of disturbance management are reviewed.

2.1 Disturbance Variables in Operations Management

In manufacturing practice as well as in research the concepts of disturbances and deviations are often used as a synonym. Disturbances interrupt or at least affect a running production or logistics process [2]. Deviations are unexpected differences between the actual and the planned state, which must not lead to failure but could be indicators for disturbances [2, 3].

To measure such disturbances a set of disturbance variables is necessary, which are recorded and observed through time. Disturbance variables are distinguished by their relation to a process, a temporal progress, an impact and a reason [4]. Furthermore, deviation variables are divided into exogenous and endogenous depending on the sphere of influence of the affected company [5]. Research has shown that less than 30% of disturbances in manufacturing are exogenous [4]. Since the project scope lies on process-related disturbances on the Shopfloor, exogenous disturbances are no longer considered.

2.2 Disturbance Management

To cope with the high number of possible deviations in an ever-complex production environment disturbance must be handled systematically. Simon defines the disturbance management in the context of production control. It is task of the disturbance management to initiate appropriate reactions to significant deviations between logistics aims and conclusion from feedback data [6]. Fischäder extends the definition by considering the purpose of disturbance management from an economical perspective. Therefore, goal of the disturbance management is the minimization of costs of the disturbance itself and the taken measures [7].

The disturbance management consists of three different steps. Firstly a disturbance is indicated by a deviation e.g. of a defined indicator. Secondly, the derivation is analyzed and decided if a counter measure has to be taken. Depending on affected object and type of derivation a corresponding counter measures has to be selected and implemented. Afterwards it is determined, if the measure has been successful and the disturbance is remedied. Otherwise another measure hast to be taken [4, 7].

Fischäder's approach focusses on the design of production systems and adaptions of the capacities. Those adaption measures are implemented in several models and directly related to logistics KPIs. Although this is very precise depiction of possible options, it stays on a rather theoretical level [7].

Leitão develops a holonic architecture for disturbance management for flexible manufacturing systems. It comprises of holons for resources, maintenance, quality control, products and the supervisor. The chosen approach allows the detection and diagnoses of disturbances. The taken measure is always a re-scheduling of orders under consideration of available resources, which are evaluated by their price, location and reputation. In addition a prediction of disturbances is described [8].

Pattig and Thorhauer present a disturbance management for rescheduling production orders based on the availability of material and potential factors (machines, equipment and personal). The approach focuses on a methodology for the production control and makes the order release depend on the availability of aforementioned production factors. Disturbances within a production process are not addressed explicitly [9].

Meyer develops a "disturbance variable management", that allows a precise description of disturbances [10]. Measures are stored in a database and linked manually to a disturbance. Thereby the measures mostly are of conceptual character, e.g. doing a 5 Why Analysis or carrying out an FMEA. The measures are linked to the necessary qualification of staff, which is stored separately [11].

2.3 Systemization of Measures in Disturbance Management

Disturbance management includes different types of measures to cope with upcoming disturbances. Those haven been classified by several characteristic (see Table 1).

Table 1. Systemization of measures in disturbance management [2]

	preventive measures		reactive measures	
	analytical	statistical	repulsive	withdrawing
cause-related measures		X		X
impact-related measures				

First of all measures can be classified into preventive and reactive measures [9]. Preventive measures aim at the identification and elimination of possible deviations or disturbances. Whereas analytical approaches can lead to the cause of a disturbance, statistical methods only apply to the observed effects and therefore the impact [2]. Applying preventive measures in most cases is associated with financial expenses and personal expenditures [4]. Therefore, it has to be clearly determined, if the consequences of the disturbance justifies the costs or if it is more favorable to react. Furthermore, preventive measures should only be taken when a possible scenario concluding of description of the disturbance and the time is available [4].

On the other hand, a measure taken after the disturbance has occurred is called reactive measure. Compared to preventive measures the effectivity is decreased.

Nevertheless, these can be sensible when the costs of remedy are lower than the cost effects of the disturbance or the disturbance cannot be predicted at all or with the necessary precision. Reactive measures can be divided further into repulsive measure, which aim for a remedy or decrease of impact and so-called withdrawing measures when the only option is to reduce the spread of the effects [4]. Furthermore, the measures can be classified into cause-related and impact-related. Whereas the former aim for the remedy, the latter can only reduce the effects [4].

2.4 Conclusion

Whereas the proposed systemization for measures allows the assignment of any real-world measure to one of the fields, the presented approaches lack a detailed evaluation concept. This can be explained with the strong focus on production planning and control [9] as well as supply chain planning problems [2, 7]. In these areas, the impact of single measures on indicators often is hard to describe. Another approach deals with the implementation of several solution concepts [12]. For the proposed disturbance, management based on big data an assessment for specific and even more general measures is necessary.

3 Assessment of Counter-Measures for Disturbance Management in Manufacturing Environments

BigPro focusses on disturbance management in manufacturing environments relying on BigData analytics. Therefore, several information sources on the shop floor are connected to a universal messaging bus. Predefined patterns, which are supplemented during operation, lead to error messages. A combination of error messages then is mapped to a disturbance. Based on a list of possible failures derived from FMEA and other process analytics approaches possible counter measures are selected. In many cases, there is more than one counter measure, depending on the level of criticality or only a few can be initiated, since not all prerequisites are met. For a further description of the platform and the integration of the counter-measures see [13].

In the following, the morphology to describe counter measures is presented before explaining the assessment methodology in detail. The application is shown with a real world example from an industrial partner.

3.1 Morphology of Counter Measures

To assess counter measures, a set of description criterions has been developed. The research follows a desk research approach, combining several aspects of existing work in disturbance management. The results are presented in Table 2 and explained in detail in Sect. 3.3.

Table 2. Relevant criterions to asses counter measures in BigPro disturbance management

I	Criterion	Explanation	Ref.
1	Duration of measure	Time from detection until recovery	[4]
2	Cost of measure	Necessary expenses to perform the measure	[14]
3	Presumed/Actual impact of measure	Impact of the measure in terms of fixing the symptoms or the reason	[15]
4	Standardization of m.	Current degree and quality of documentation to perform the measure	[4, 11]
5	Organizational escalation level	Implementation level of the measure (e.g. machine, plant, supply network)	[16]
6	Degree of qualified staff available	Share of staff, which is qualified to perform the counter measure	[11]

3.2 Mathematical Model to Assess Counter Measures

To find appropriate measures and to bring them in an order, a numerical calculation is necessary. Table 3 provides an overview of the proposed evaluation scheme to asses counter measures in disturbance management.

Table 3. Evaluation scheme for characteristics of measures

I	Criterion	Characteristic c				
		0	1	2	3	4
No.	Description	Not feasible	Partly feasible	Mainly feasible	Very feasible	Optimal

Each criterion i is subdivided into five different characteristics c. Each possible characteristic is represented by a value, starting from 0 for not feasible at all up to 4 representing the optimal condition. To adapt the criterions to disturbance-specific cases, a simple weighting formula is introduced.

$$M = \frac{\sum_{i=1}^{F} \omega_i \cdot c_i}{\sum_{i=1}^{F} \omega_i} \tag{1}$$

Let M be the priority of the measure, F the number of features (6) w_i a weighting factor within a range from 0 (irrelevant) to 4 (highly relevant) and c_i the valuation of the feasibility of the feature i. The minimum of M can be 0, whereas the maximum is 4. In the following exemplary characteristics are assigned to any criterion.

3.3 Explanation and Application

The developed morphology and evaluation scheme was applied at an industrial partner of the research project. The use case deals with an assembly of pedelec carts with manual assembly tasks. The disturbance is a scratched type plate provided by a supplier and labeled in-house. Table 4 provides an overview of possible characteristics, which are explained in detail below.

Table 4. Possible criterions with characteristics derived from the industrial use case

I	Criterion	Characteristics c_i				
		0	1	2	3	4
1	Duration	>1 month	1 week–1 month	1 day–1 week	1 h–1 day	<1 h
2	Costs [€]	>100.000	>10.000	>1.000	>100	<100
3	Impact of measure	None	Dev. impact decreased	Dev. impact eliminated	Dev. impact resolved, cause decreased	Cause eliminated
4	Standardization of m.r	None	Roughly documented	Moderately documented	Well documented	Fully documented
5	Organizational escalation level	Supply chain	Plant	Shopfloor	Machine group	Work place
6	Coverage rate of qualified staff	0%	<5%	[5%; 25%)	[25%; 50%]	>50%

For the presented approach, the **duration of measure** is defined as the timespan between the observation of a disturbance and the (noticeable) effect of the initiated counter-measure. Since the disturbance management foremost handles short-term disturbances, a short duration of measure is desired. A long time span indicates mid- or long-term measures such as process redesign. The given characteristics have to be adapted to the company's requirements. A duration of less than an hour can lead to significant waste and is not acceptable, whereas other processes allow a relative long time for corrections.

As mentioned before, the disturbance management deals with the minimization of costs [7]. Therefore, the trade-off is between costs of the disturbance and **costs of a measure**. It is up to the company to define the exact bounds of the characteristics; the given values only serve as an example and are derived from the use-case.

The **impact of the measure** relates to the effect of the measure on the deviation variable or the cause of the disturbance. The more sustainable, the higher the stage. Examples for the solely elimination of the effects of a deviation is the implementation of a 100% quality control. Hereby it is ensured, that no waste is processed any further without addressing the causes. The reason for the fault remains unknown at the first glance and needs further examination.

For an efficient and effective disturbance management, counter-measures should be **standardized** and therefore documented in a way that allows employees to take the best actions possible. This accounts for extensive measures, especially [4]. It is further distinguished between certain degrees of documentation, e. g. it has to be checked, if the documentation consist of visualizations like flow diagrams, illustrations etc. or is only a short summary and difficult to comprehend if never done before.

A measure can either relate on a certain work place (e.g. a disturbed machine with a defined problem state and solution) or affect the whole supply chain. This is taken into account with the **organizational escalation level**. Later oftentimes requires additional efforts and resources. Therefore, the former option (a local solution) is preferred in any case the desired level impact of measure (see criterion 3) can be achieved.

Whereas the documentation of a feasible solution is always the best option, the desired resolution can only be achieved if qualified staff is available [11]. This requires an appropriate personal capacity planning and a certain **degree of qualified employees**. The characteristics therefore take into account the mean degree of qualified personal available to fix the considered disturbance.

Table 5 shows a possible application after setting the characteristics of counter measures within a workshop with the industrial use case partner. Weightings have been set as well as the specific value for each criterion. In the result, the measure scores at 1.7 out of 4 and therefore is comparable to other measures for the specific or similar disturbances.

Table 5. Exemplary calculation of general feasibility of a measure

i	criterion	characteristic					weighting	
		0	**1**	**2**	**3**	**4**	**w**	$c_i \cdot w_i$
1	duration of measure		■				3	3
2	costs of measure [€]			■			4	8
3	impact of measure		■				2	2
4	standardization of measure				■		3	9
5	org. escalation level				■		1	3
6	coverage rate of qualified staff					■	4	4
						∑	17	29
						M		1.7

4 Conclusion and Outlook

The paper presents an approach to assess pre-defined counter-measures. Therefore, characteristics from existing approaches have been combined. The weighting component enables companies to specify borders in context of their processes and requirements. Once the characteristics for each criterion are defined, new measures can easily be evaluated and connected to newly occurring disturbances. This is a crucial step to increase the automation level of the desired disturbance management. Further research is needed for finding ideal types for several kinds of measures (e.g. logistics measures, maintenance tasks, production re-scheduling).

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Operations Planning, Scheduling and Control

Solving a Discrete Lot Sizing and Scheduling Problem with Unrelated Parallel Machines and Sequence Dependent Setup Using a Generic Decision Support Tool

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Abstract. In any manufacturing systems, planning and scheduling are not intuitive. Some dedicate tools may exist to help some specific companies to daily plan and assign their activities. Our purpose is to develop a generic decision support tool to solve any planning or scheduling problems. To do so, we use a hybridization between a metaheuristic and a list algorithm. The metaheuristic is generic to any studied problems. The list algorithm needs to be specific to the considered problem. The use of our tool needs a minimum work development. In this paper, our proposal is illustrated by the case study of a textile company which intends to schedule its production, by assigning it resources and dates. This problem can be seen as a Discrete Lot Sizing and scheduling Problem (DLSP).

Keywords: Lot sizing and scheduling problem · Discrete · Sequence dependent setup · Metaheuristic · List algorithm · Hybridization

1 Introduction

One key point of the organization of a manufacturing system is the planning of its production. Each enterprise has several customers, with their specificity and delivery dates. The enterprise has a given quantity of resources (human and/or material, for example machines) that it has to occupy in order to have the best possible return and to satisfy as best as possible customer demand.

When an enterprise is selling only one type of product, planning may be easy. But when the number of product types, customers or resources is increased, planning becomes more complex. Finding an optimal solution may be difficult.

Enterprise Resource Planning (ERP) is an informatic tool which can manage every departments in an enterprise. Information about departments are stored

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in an unique database, all data are shared, that avoid unnecessary re-entry of information. When a customer makes a new order, ERP is able to check the stock level, to buy raw material and to launch fabrication order if applicable. But ERP is used at a macro level. According to the demands, it plans month by month or week by week the activity of the company. From our knowledge, it does not exist any generic tool that can interpret ERP fabrication order to make an assignment and scheduling used on the shop floor. There are some software packages specifically dedicated to scheduling, but there are dedicated to a specific situation.

Usually, one experienced worker is making the detailed scheduling of fabrication order every day, and assigns them the required resources. But what could happen if this worker is missing? The aim of our work, is to propose a tool which solves scheduling and assignment problems. This tool has been developed in a generic way, so it should be used to solve many problems. In this paper, this tool is applied to a textile problem, previously studied in 2006 [1].

2 Analysis of the Studied Problem

The considered company is producing acrylic fiber used in the textile industry. These fibers are made following three steps. Dope preparation: a polymer is dissolved in an organic solvent to make the dope. Spinning: dope is going through a spinneret (a tool which is a metal plate with holes from different diameters) to obtain the synthetic filaments. After this step the fiber is called “tow”. Cutting and packing: the tow obtained in the previous step can suffer two different types of operation: it can simply be packed before being send to the warehouse or, it can be cut in small segments, originating a new kind of fiber called raw, which is also packed before expedition.

Our study focuses on the spinning area. There are 10 non-identical spinning machines on the shop floor. Machines are dedicated, all products can not be produced on all machines. A compatibility machine-product is defined. All machines do not have the same production rate: some of them can produce more tons of product per hour than others.

Fibers can be made from different diameters, within three colors: shiny, mat and black. There are two types of fiber: tow and raw. In total, the company can make 60 different products. A change of color may induce the stop of the machine for its cleaning. Transition shiny-shiny and shiny-mat/black does not induce a stop, but transition mat/black-shiny does. If there is a setup (change of tool), change of color is made in the meantime. A tool can produce fibers from different diameters by changing the used tensity during the production. Moreover, each tool has a lifetime, from 8 to 45 days. When its lifetime is over, a new tool has to be used. A setup lasts 2 h. Lifetime of tools depends on the type and the color of the product, and depends on the used machine. Constraints have to be respected:

- All or nothing: if a product is planned, production lasts 24 h even if the needed quantity is less. Over-quantity is stocked and used next month, it will be deduced from the next orders.

– Possible setup between two products:
  - Setup between two products,
  - Cleaning of the machine (transition mat-shiny or black-shiny),
  - Setup if lifetime is over.

The company wants to plan products within a planning horizon of one month, by periods of 24 h. Customers orders are analyzed to make a production plan. Our objective is to schedule these fabrication orders on the different machines and the different periods during the considered month. The result will be a schedule over 28 days by periods of 24 h. Two criteria have to be minimized:

– The quantity of products not produced during the considered month. This quantity would be produced next month,
– The number of setups.

3 State of the Art

This problem can be seen as a Discrete Lot Sizing and scheduling Problem (DLSP). The fundamental assumption of the DLSP is the so-called "all-or-nothing" production: only one item may be produced per period, and, if so, production uses the full capacity [2]. Some papers refer DLSP as a Dynamic Lot Sizing Problem, which is not the problem considered in this paper.

The first resolution of this kind of problem seems to be done in 1971 [3]. The authors developed an efficient algorithm to solve a multi-item scheduling problem with identical parallel machines. This paper is referenced in a chronology of lot sizing and scheduling problems [4], used as an example of multiproduct small bucket problem. A problem is said with small bucket if only one item can be done per period, in opposition to large bucket problems, where several items can be done per period. DLSP is a small bucket period. This acronym is quite recent. Its first apparition is made in 1990: after having defined the problem, [5] solved it with a branch and bound used with Lagrangian Relaxation. In 1991, a classification of DLSP extensions were proposed and complexity was discussed [6]. According to this classification, our problem can be denoted: P (parallel unrelated machines)/M (positive integer number of machines)/N (positive integer number of items). Without setup consideration, this kind of context has a NP-Complete feasibility problem and a NP-Hard optimization problem [6]. In 1994, the two-stages consideration is introduced [7]. All these historical articles consider problems with an unique resource, or several identical resources. Most of them propose some algorithms inspired by exact method such as branch and bound or Lagrangian decomposition.

More recently, some papers propose new methods to solve the DLSP. In 2011, an exact solution approach is proposed to solve medium-size instances, in the case of identical parallel machines [8]. Mixed Integer Programming (MIP) formulation are proposed and used with a commercial solver. This method solves instances up to 20 products, 100 periods and 5 resources. The Proportional Lot-sizing and Scheduling Problem allows processing of two products within a single period, one before and another after the setup operation, while for the DLSP, the setup is made at the beginning of the period. It has mainly been solved with identical resources, for example using MIP procedures [9]. Instances considering 10 products and 5 machines are not solved in less than 30 min. As a perspective, the author proposed to use these procedures to unrelated parallel machines.

In 2017, a classification and review about simultaneous lot sizing and scheduling problems, including DLSP, has been done [10]. While trying to find analogies with our current problem in that recent review, it was noticed that three terms can be used to define when all machines can not treat all products. Machines can be called as not-identical, heterogeneous or unrelated. Among the 175 referenced articles, 59 are one of the kind, in all scheduling and lot-sizing problem. According to the DLSP, 34 papers are referenced, 7 of them dealing with non-identical machines. Only 3 of them take into account the setup: 2 with sequence independent setup and 1 with sequence dependent setup [11] using Lagrangian Relaxation.

Our problem is a DLSP with unrelated parallel machines due to compatibility restrictions, considering sequence dependent setup. [1] used a heuristic approach to solve that specific problem: the list of products is sorted, and then products are assigned to resources. In the following, our generic method, which will be used to solve our problem, is presented.

4 Proposed Method

The used method to solve this problem has previously been applied. First the method has been developed in a hospital context: exams planning and resources assignment [12]. Then it has been used to solve a lot sizing and scheduling problem for the injection industry, identified as a Capacitated Lot Sizing Problem (CLSP) [13]. Our main objective is to show that our tool is sufficiently generic. It is used with a minimum work development to solve the current problem, identified as a DLSP.

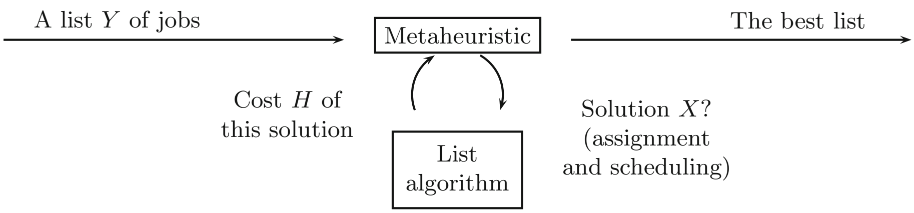

Fig. 1. Hybridization metaheuristic - List algorithm

4.1 General Description

The method can be summarized as Fig. 1. It is a hybridization of a metaheuristic and a list algorithm. The list algorithm L has to be specified for any considered problem. It is applied on a list $Y \in \Omega$, to schedule and assign all jobs Y_i, $i \in \{1,$ number of products$\}$, respecting all constraints of the problem. This builds the solution $X \in S$. The list algorithm must consider the list order while building solution X, it must not sort the list in any way. The order of the list is determinated by the metaheuristic, by applying a neighborhood system. An objective function H evaluates the quality of the solution X, by computing the number of remaining quantity at the end of the month or the number of setup. The whole method is illustrated by Eq. (1), with Ω the set of all lists of products and S the set of all admissible solutions. A solution is admissible if it is a schedule and assignment which respects all constraints of the system.

$$Y \in \Omega \underset{Heuristic\ L}{\longrightarrow} L(Y) = X \in S \underset{Criterion\ H}{\longrightarrow} H(X) \tag{1}$$

The metaheuristic is the generic part. Algorithm 1 illustrates the method, using the stochastic descent as a metaheuristic. Any metaheuristics can be used. The stochastic descent is working on a list Y of jobs. Metaheuristic browses the set Ω of lists Y by applying a neighborhood system V. V is the permutation between two products in the list Y. Other neighborhood system may be used. Solution are compared thanks to the objective function H. According to the value of H, the best solution becomes the current one.

Algorithm 1. Principle algorithm of stochastic descent

Data: Initial solution Y
$X = L(Y)$
while *necessary* **do**
    Choose uniformly and randomly $Y' \in V(Y)$
    $X' = L(Y')$
    if $H(X') \leq H(X)$ **then**
        $Y := Y'$

4.2 List Algorithm *L*

When solving such a problem using our method, the main thing to do is to develop a list algorithm which schedules the products assigning them to machines, respecting the constraints previously described in Sect. 2. Because it must be a list algorithm, the algorithm is considering jobs one by one respecting the order defined by the list. The used list algorithm is summarized in Algorithm 2. The list algorithm needs to be efficient to find a solution (good or not) in a small computation time. It does not need to be effective because a good solution will be found after having tried some neighbors thanks to the metaheuristic.

The hypothesis is made that at the beginning of the month, all machines are empty, there is no tool on them, no raw material. This hypothesis is not restrictive. Maybe, the needed tool at the beginning of the month was already on the machine at the end of the previous month, so a setup is avoided.

Algorithm 2. Principle algorithm of the list algorithm

```
Data: Initialize all variables at zero
forall JOB in the list do
    while all quantity of JOB has not been scheduled do
        MACHINE = first machine
        while Next machines can be considered do
            DAY = first day
            while Next days can be considered do
                if MACHINE is compatible with JOB then
                    if MACHINE is available then
                        Assign JOB, the needed tool, and the needed color to
                          MACHINE during DAY
                        Update the lifetime of the tool, change the tool if needed
                          with a new tool (lifetime = 100%)
                        Update the number of setups if needed (change of tool,
                          transition from black to shiny, transition from mat to
                          shiny)
                        Update the remaining quantity of JOB to produce
                DAY = Next day
            MACHINE = Next machine
```

4.3 Objective Function *H*

The objective function is used to compare solutions in the metaheurisitic. The main used criterion is the remaining quantity of all products at the end of the month, written C_q. To provide all customer demands, our system must produce as many quantities as possible in a month. Another used criterion is the number of setup (caused by a change of tool, a change of color, or an exceeded lifetime), written C_s. A hierarchy of both criteria is used.

5 Experiments and Results

To make our experiments, instances have been created, representing the data used by the company. Each instance is made by:

- A list of jobs to be done, with the needed quantity, the type and color and the used tool.
- A matrix representing the effectiveness of the machines to produce the jobs, which can be null if the machine and the job are not compatible.
- The lifetime of each tool on each machine, depending on the type and color of made product.

Table 1. Results of our method

Instance	[1]: $(C_q; C_s)$	Our method: $(C_q; C_s;$ Time)
22 products	(552; 17)	(522.6; 17; 13 s)
25 products	(232; 16)	(68.0; 21; 8 s)
33 products	(387; 17)	(196.0; 19; 11 s)

Our experiments are made on a computer powered by an i7 CPU running at 2.6 GHz with 16 Gb RAM. Table 1 summarizes the results of our method giving the remaining quantity C_q and the number of setups C_s, with the needed computational time. The number of products is assigned to 10 machines over 28 days. Results are compared to the ones found by using the method presented by [1]. The results show that our method gives better results than the ones from the previous method. Indeed, the previous method finds a solution given by a constructive heuristic while our method browses a set of solutions and gives the best one among all tested solutions.

6 Conclusion and Further Work

This paper presented an application of our generic decision support tool to an application of lot sizing and scheduling in a textile industry. The results given by our method are better than the previous known results. Because our tool is generic, it is easy to use with a minimum work development. The only things to do are to build a list algorithm, to compute an objective function, and to transform the real data in usable instances. Many problems can be solved as long as a list algorithm can be used to provide a solution to the considered problem.

As a first perspective, our tool could be used connected with the Information System of the company. Internet of Things may collect data on the shop-floor to better describe the system. Scheduling and assignment solution could be transformed to Fabrication Orders directly transmitted to the shop-floor via the Manufacturing Enterprise System. Thanks to a connection to the Enterprise Resource Planning, when a customer gives a new order, our tool could simulate when this customer will be delivered, thanks to our criteria.

Our tool could be improved by using other metaheuristics such as population based metaheuristics, for example particle swarm optimization. Using this, our tool could be performed using parallel computation on GPUs. Then, we could implement a database of our industrial problems we already solved, to better solve the next ones.

To assess the quality of our result, we should find some benchmark in the literature. By solving the available data, we will be able to position the quality of our tool among all other existing methods. Existing methods are dedicated, so the fact that our tool is generic is already an originality.

All problems we already solved are about tactical and operational levels. They deal with planning and assignment problems, lot-sizing and scheduling problems. As future work, we intent to solve problems at a strategic level, about sizing of the system, sizing of resources, according to the future demand. Nowadays, because of the way of consuming, products lifecycle becomes shorter and shorter, so demands are unpredictable. Reconfigurable manufacturing systems should now be considered. Manufacturing systems need to be agile and flexible to be adaptable to the variety of product and quantity. Our next step is to size and maintain such a system with our generic decision support tool.

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Decentralized Vs. Centralized Sequencing in a Complex Job-Shop Scheduling

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Abstract. Allocation of jobs to machines and subsequent sequencing each machine is known as job scheduling problem. Classically, both operations are done in a centralized and static/offline structure, considering some assumptions about the jobs and machining environment. Today, with the advent of Industry 4.0, the need to incorporate real-time data in the scheduling decision process is clear and facilitated. Recently, several studies have been conducted on the collection and application of distributed data in real-time of operations, e.g., job scheduling and control. In practice, pure distribution and decentralization is not yet fully realizable because of e.g., transformation complexity and classical resistance to change. This paper studies a combination of decentralized sequencing and central optimum allocation in a lithography job-shop problem. It compares the level of applicability of two decentralized algorithms against the central scheduling. The results show better relative performance of sequencing in stochastic cases.

Keywords: Decentralization · Centralization · Allocation · Sequencing · Job-shop scheduling · Industry 4.0

1 Introduction

In the last decade, studies on distributed data collection and decentralized decision making in manufacturing research has been intensified and promoted [1]. The underlying reason lies on the upcoming surge in e.g., the complexity of operations, individualization of products, and the needs for higher flexibility and responsiveness in manufacturing [1] [2]. Consequently, industries are experiencing a digitalization era of producing products and providing services at the presence of the fourth industrial revolution, namely, "Industry 4.0" (I4.0) [3], see BMBF (Germany). Development in and facilitation of the modern information and communication technology (ICT), being capable of collecting and processing data in a distributed and decentralized manner, supports this ambition. The quick changes in manufacturing necessitate explorations and definition of a comprehensive reference framework for adopting I4.0. This paradigm shift alternates the classical (central and offline) structure of decision making based on aggregated data collection for global optimization. In contrast, the new trend supports a decentralized and distributed structure aiming at simplicity [1]. However, more explorations for applicability is due. Whereas the aggregated data collection and

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offline decision making assumes authenticity of all assumptions and available data, the process of decentralized data collection in real-time always varies along the time horizon, so that it necessitates a modern approach for dynamic-based decisions. Today, the research question is: where is the best application scenario in manufacturing to adopt this structure?. At this level, a coalition between both structures (hybrid centralized and decentralized) seems practical. Scholars need to introduce ways to practitioners for experiencing this paradigm shift. Generally, the shift toward decentralization of control reflects the needs of improvising higher flexibility and responsiveness at the presence of dynamics, [4]. The facilitation of real-time monitoring and control from (days to seconds) is causing this shift. Among all hierarchical decision making levels (strategic, tactical, and operational), scheduling and control at the shop-floors are very sensitive to real-time data collection [5]. The classical scheduling problems leverage assumptions in theory, which are not realistic in practice. The lack of real-time data collection and relatively few dynamics in the operations has supported the success of the classical solutions, whereas the upcoming circumstances, e.g., cyber-physical systems [6], necessitate scheduling and control decisions closer to real-time. The job scheduling problem can be divided into two parts. First is the allocation of jobs to a set of machines, concerning the specifications of both jobs and machines. Second is the sequencing of jobs for processing on each given machine, accomplished by the permutation of them based on relevant parameters, e.g., processing times, dependent setup times, etc. [7]. Job-shop scheduling problems with sequence dependent setup is severely NP-hard [8]. The broad applicability and variety of job shop scheduling problems in practice makes it an interesting environment for conducting research about decentralized data collection and real-time decision making. Meanwhile, some trade-offs between the pure decentralization of decision (heterarchical structure) and classical central optimization (hierarchical structure) have to be analyzed [9], based on the application level of technologies, dynamic operations, and efficiency of the developed algorithms. This paper studies a combination of central and decentralized approaches in scheduling of a complex job-shop problem at lithography operations. However, the aim is to explore the decentralized vs. central approaches in a three levels of spectrum, as the three options in Fig. 1 (c1–c3). Here only the sequencing task is run by the decentralized structure as in option 1 and the rest are kept for future work. The rest of the paper is structured as follows. An introduction to the scheduling problem and the case study is given. Then the mathematical model for the problem with centralized solution is explained. Later, the decentralized algorithms are discussed and alternative scenarios are experimented. The results are discussed afterwards and the paper ends with the conclusions and research opportunities.

2 Problem Framing and Case Study

Job scheduling is a combinatorial optimization problem with varieties [10]. The current problem is a job shop scheduling with alternative routes that require the allocation to machines (choose the route) as well as the sequencing of jobs, according to the set objective function(s), in the most optimized/efficient way, see also [11]. However, solving the centralized mathematical programming with exact algorithm or heuristics cannot always lead to an optimum solution, because of the underlying complexity. Furthermore, the required assumptions for centralized solutions, e.g., the availability of all jobs at time zero or deterministic parameters, are mostly impractical [12]. A scheduling case out of lithography manufacturing processes for producing various canes with alternative applications, sizes, and content is considered. The complexity of operations and abundant changeover (times) makes it a suitable case for I4.0 experiments. Varnishing for coating and printing for coloring are the major processes to be scheduled in this slice of the manufacturing processes, see Fig. 1a.

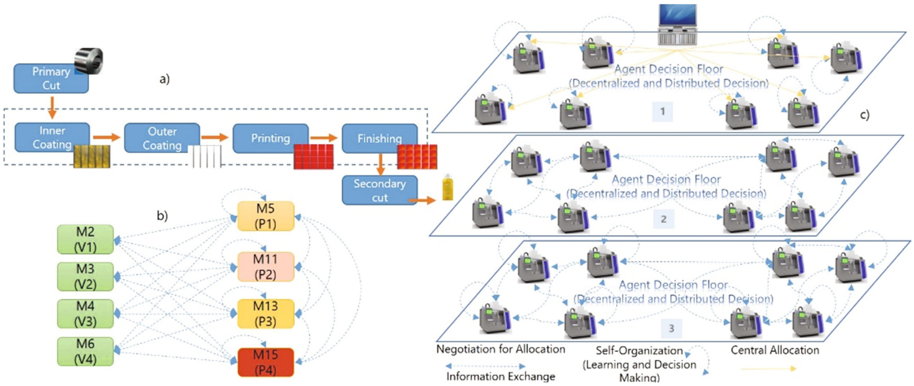


Fig. 1. (a) The manufacturing processes for scheduling. (b) Arrangement of the flexible job shop with flow possibilities. (c1) Decentralized sequencing and central allocation. (c2) Decentralized sequencing and allocation based on negotiation and real-time data. (c3) Decentralized sequencing and allocation based on real-time negotiation and historical knowledge of agents.

This shop-floor consists of eight machines with four varnishing (*V*) and four printing machines (*P*). For the sake of simplicity, all machines are named as *M = {M2, ..., M15}*, see Fig. 1b. The varnishing machines are capable of doing all types of operations, whereas the printing machines have alternative ink capacities not for all types. On this basis, the scheduling environment does neither resemble a pure job-shop nor a pure flexible job-shop. However, it can represent a flexible job-shop problem, with machine eligibility restrictions (M_i), recirculation ($rcrc_i$), setup-dependent (s_{ik}) jobs, and makespan (Cm) as the objective, i.e., machine environment is $FJ_8|M_i, s_{ik}, rcrc_i|Cm$. This lithography scheduling has complex constraints, e.g., precedence severity, drastic setup times, limited combination of colors (the CMYK color model), and recirculation, see [13]. However, this is much simplified to comply with the limitation of a conference. To solve this, the problem is split into the allocation and sequencing sections. A global mathematical model is initially developed to statically model this scheduling and help to its comprehension. However, it is solved by two approaches. First is the centralized solution with allocation and sequencing. This uses the classical optimization with mathematical programming and using the exact algorithm of branch and bound (BB) for allocation [14] and then using constructive heuristic [15] for sequencing. This is solved by the IBM ILOG Cplex solver. Second is the decentralized sequencing in real-time by developing a discrete-event simulation model, using the Anylogic program. The decentralized approach at this level presents a pure decentralization of sequencing in real-time of the centrally allocated jobs.

3 Centralized Allocation and Sequencing

Initially, the MRPs planning derives the jobs (in an aggregated manner and a longer time-horizon) to be scheduled. To do the allocation for this study, the characteristics of the jobs regarding the combination of colors, the capacity of the machines and the coating operations, and the objective function are decisive. These specifications of the jobs are given in a master data as the parameters (inputs) of the mathematical model. The consideration of these simply results in one to few alternative operation-routes for each job as (L_i). A generic mathematical model can represent the problem as follows.

Indices and Sets:		Parameters:	
$i \in I$	Jobs	$pt_q =$	Processing time of operation q
$m \in M$	Machines	$st_{\acute{q}q} =$	Setup time of operation $\acute{q}$ after process of operation q on same machine
$l \in L_i$	Sequence id of job i	$G =$	Big value
$q \in Q_l$	Operation id of sequence l	$gap =$	a gap time (transport time) between machine switch
$n \in N$	Operation number in sequence		
m_q	Operation q on machine m		
Variables:			
Cm = makespan			
$x_l = 1$ if sequence l is performed, 0 otherwise (allocation)			
$y_{\acute{q}q} = 1$ if operation $\acute{q}$ is performed before operation q, 0 otherwise (sequencing)			
S_q = Starting time of operation q.			

$$Minimize\ (Cm) \tag{1}$$

St.

$$\sum\nolimits_{l \in L_i} x_l = 1; \forall i \in I \tag{2}$$

$$S_q \geq S_{q'} + pt_{q'} + st_{q'q} - \left(1 - y_{q'q}\right) \times G - (1 - x_l) \times G - \left(1 - x_{l'}\right) \times G; \quad \forall q', q \in Q : q' > q, m_q = m_{q'}, l = l_q, l' = l_{q'}, l_q = l_{q'} \tag{3}$$

$$S_{q'} \geq S_q + pt_q + st_{qq'} - \left(y_{q'q}\right) \times G - (1 - x_l) \times G - \left(1 - x_{l'}\right) \times G; \quad \forall q', q \in Q : q' > q, m_q = m_{q'}, l = l_q, l' = l_{q'}, l_q = l_{q'} \tag{4}$$

$$S_q \geq S_{q'} + pt_{q'} + gap - (1 - x_l) \times G; \forall q', q \in Q : n_q = n_{q'} + 1, m_q \neq m_{q'}, l_q = l_{q'} \quad (5)$$

$$Cm + (1 - x_l) \times G \geq S_q + pt_q; \forall i \in I, l \in L_i, q \in Q_l \quad (6)$$

Later, by splitting this model into allocation and sequencing ones, BB chooses the best route (among alternatives) for each job (allocation task). This part is relatively simple and can reach more than 99.9% optimality within 10 min. The sequencing model is an NP-hard problem. For the instances of the case study, it was not even able to solve the linear re-laxation. Therefore, a heuristic approach was used. The sequencing method consists of a multi-start constructive heuristic, which generates thousands of solution and keeps only the best. The procedure to construct a solution is probabilistic, i.e., the next operation to sequence is chosen based on some probability that assigned to each operation. This probability is higher for operations with lower setups, considering the operation that is on the machine at that moment. The level of greediness of the algorithm can be parametrized, by using a scoring function such as $u_q = \left(\frac{1}{st_{q'q}}\right)^k$, where q' is the operation at the machine, q is the one being considered, u_q its score and k the greedy factor. The higher the k, the greedier the algorithm will be, since it will be amplifying the differences between operations. The probability is then obtained by dividing each score by the sum of all the scores.

4 Decentralization in Real-Time Sequencing

Decentralization of the sequencing decisions in real-time is an extreme case of the spectrum of decentralization scenarios. At this instance, a combination between central allocation and decentralized sequencing is made to witness the cooperation level of both approaches in practice. Here, each machine decides about the sequence of its own queue in real-time status. Two major decentralized algorithms for sequencing are considered to be compared against the purely central (optimum) solution for the allocation and sequencing. Makespan is the objective function. The first algorithm, Setup rule, purely considers the dependent setup times of the operations in the queue It is equivalent to the constructive heuristic described previously, but in its deterministic form and executed only once (no multi-start). However, this simple process is repeated each time a product is to be processed. The algorithm is as follows:

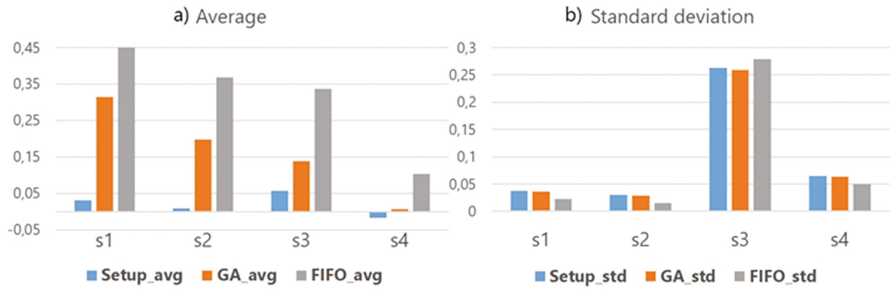
1. While $\exists\ q$ in the queue
   $F_q = \left(s_{0q}^m \times (sum\ of\ setups)\right)^2 \Big/ \sum_q^Q \left(\left(s_{0q}^m \times (sum\ of\ setups)\right)^2\right);\ \forall q \in Q$
2. Sort the queue in descending order of F_q and send the first operation to the machine.

The second algorithm has a broader view to each entire queue and follows the Little´s Law [16] in analyzing the entire queue, by calculating the queue-length (QL) at each new instances. It considers several possible permutations (of the *n!* possibilities) for the arrangement of the products in the queue and, for each of them, it calculates the QL. Given this, the best permutation is selected regarding the least QL. However, this algorithm is not necessarily beneficial in purely sequencing decisions, but in real-time allocation. Since the queue arrangement changes dynamically in every entrance instance, the permutation with the least QL at an instance does not necessarily lead to the least makespan of the same machine or the global makespan. Also, the least QL does not guarantee the product with the least setup time as the next one to be processed. Knowing that the permutation instances can be very large, a simple genetic algorithm (GA) constructively covers a certain number of the permutations. The GA considers only mutation and crossover operators for producing 2 child out of 2 parents. The number of individuals in each generation varies between 5 to 10 and the termination is after 5 generations. The GA is as follows:

1. $Z \leftarrow (popSize - 1)$ random queue permutations
2. Z←Z {current queue}
3. while
   - Take Fitness Function $f = QL + (Localavg.throughputtime + globalavgthroughputtime)/2$ of each $indiv \leftarrow Z$, where $QL = \lambda_t^m \cdot \left(\sum_{q_t < \acute{q}_t = 1}^{Q_t} \left(s_{\acute{q}_t q_t}^m + pt_{\acute{q}}^m\right) \times y_{\acute{q}_t q_t}^m\right)$ based on Little´s Law
4. Use Roulette Wheel selection $P_t = f_{rt} / \sum_{r=1}^{R} f_{rt}$ for choosing the Best (#) Individuals
5. Select the Best Individuals by Descendingly sorting their P_t
6. Apply GA operators (Mutation and Crossover) to the Best Individuals to breed Children; add the Best Individuals (from parents list) to the Children list in next Generation if (#BestInd<Z)
7. Sort the Best Individuals in the new Generation and Repeat up to the Termination #
8. Take the first Individual of the List BestInd as the queue for performance!

5 Simulation Results and Discussion

Both decentralized algorithms as the Setup rule and GA are evaluated against the centralized solution and FIFO in the simulation model. For comparing their performances, five scheduling instances based on real data are experimented. To integrate the results and save space only the average values (avg.) of all instances are demonstrated. Then, four scenarios (1 deterministic and 3 stochastics) for processing times are comparing the avg. of the other algorithms relative to the avg. of the central solution, as the reference with the value = 0, see Fig. 2. It is observed that the average performance of the central solution mostly outperforms the decentralized algorithms in makespans. However, in each scenario this relativeness was changing. In the deterministic scenario, this was fully expected, whereas in the scenario 4 central solution was not the best. In s3 the performance deviation between the instances was noticeable. This is because of the broad spread of the normal distribution. Nonetheless, in most stochastic cases the decentralization showed a reasonable performance relative to the central one. It was witnessed that the decentralization in some other measures like average throughput time (ATPT) could hit the record of the central one in several single tests. However, for the makespan it was even not expected to hit the record of the central solution, since it is a global measure. The Setup rule was easy to implement, but showed pretty good results. The GA as expected was not specifically suitable for sequencing, while it is expected to operate much better in case of decentralized allocation in future works. In decentralization the focus is on local awareness, so as the dynamics of the global system may negatively influence the global objective of the system. However, having local overview, while being comparable with the global measure, achieved by the central solution, shows the potential of the decentralization in sequencing.



	Scenarios for Processing Time							
	s1) pt		s2) $N\sim(\mu = pt, \sigma = pt/2)$		s3) $N\sim(\mu = pt, \sigma = pt)$		s4) $Exp(x = pt, \lambda = 1/pt)$	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
Setup	0.0305	0.037	0.0081	0.030	0.0565	0.262	-0.0166	0.064
GA	0.3150	0.036	0.1974	0.029	0.1385	0.259	0.0061	0.063
FIFO	0.4489	0.022	0.3680	0.015	0.3372	0.278	0.1034	0.050

Fig. 2. Comparing the divergence of the 3 algorithms, in 4 scenarios, from the centralized sequencing as reference 0, (a) avg. (b) standard deviation.

6 Conclusion

To gradually adopt the I4.0, more explorations in manufacturing and shop-floor operations are required. Scheduling must adapt itself to this opportunities by employing real-time data for planning the flows. This issue was the concern of this study. The outputs are supposed to help practitioner to smoothly experience the transformation phase. The simplicity, yet comparable, of the algorithms in decentralization presents a promising application of that in practice, though for a verification more experiments are required. The central solutions are usually very limited, sensitive, and have less flexibility in several aspects. For instance, the assumptions are fixed at the run of the solutions and global overview of the entire system is necessary. In case of static models, no urgent order can intervene the system and rescheduling is required. Any changes in the model (e.g., changing deterministic processing time to stochastic one) requires several modifications and solution efforts. In contrast, these all dynamics can easily happen in a decentralized and real-time system without requiring any changes in the structure of the running system (no disturbance in the performance of material flow control). In implementing I4.0, (intelligent) agents (e.g., machines) with simple algorithms can deal with the complexities and still deliver good results. The extension of this work with considering all color combinations for machines (routes + the printing capacities) and the experiments of other decentralization levels and algorithms are still due.

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A Dynamic Approach to Multi-stage Job Shop Scheduling in an Industry 4.0-Based Flexible Assembly System

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Abstract. Industry 4.0 technology is based on the concepts of flexibility and dynamic assembly system design. This enables new production strategies and creates new challenges for job shop scheduling. In particular, manufacturing processes for different customer orders may have individual machine structures whereas the flexible stations are able to execute different functions subject to individual sets of operations within the jobs. This study develops a control approach to job shop scheduling in a customized manufacturing process and job sequencing of operations within the jobs. The developed approach presents a contribution to flexible distributed scheduling in the emerging field of Industry 4.0-based innovative production systems.

Keywords: Assembly system · Scheduling · Dynamics · Industry 4.0 · Control

1 Introduction

Individualization of products frequently requires different technological chains of operations in the manufacturing processes. Industry 4.0 technology enables new production strategies with the use of cyber-physical system principles based on highly customized assembly systems with flexible manufacturing process design (Erol et al. 2016; Battaïa et al. 2015; Oesterreich and Teuteberg 2016; Kumar et al. 2016; Nayak et al. 2016). Such innovative production strategies represent new challenges and opportunities for scheduling. In particular, manufacturing processes for different customer orders may have individual station structures whereas the flexible stations are able to execute different functions subject to individual sets of operations within the jobs (Weyer et al. 2015; Ivanov et al. 2016; Nayak et al. 2016; Zhong et al. 2017).

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Practical environments for applications of scheduling and sequencing models and algorithms to customized assembly systems are multi-facet. With the help of smart sensors and plug-and-produce cyber-physical systems, the stations in the assembly system are capable to change the operation processing and setup sequences according to actual order incoming flows and capacity utilization (Otto et al. 2014; Theorin et al. 2017). In the front opening unified pods technology in semiconductor industry, robots are used in real-time operation sequencing. Robots read the information about the products from sensors and tags and decide flexibly where to forward a wafer batch next (Mönch et al. 2012).

Recent literature constituted principles and approaches to design and scheduling of flexible reconfigurable assembly systems with the focus on balancing, scheduling and sequencing (Boysen et al. 2007; Chube et al. 2012; Delorme et al. 2012; Battaïa and Dolgui 2013; Battaïa et al. 2017; Dolgui et al. 2009). In these studies, models and methods for solving problems related to the optimization of assembly system performance intensity for sets of flexibly intersecting operations have been presented. The studies by Ivanov et al. (2012, 2016) showed a wide range of advantages regarding the application of control-theoretic models in combination with other techniques to scheduling.

It can be observed that in previous studies the selection of the process structure and respective station functionality for operations execution have been considered in isolation. In many real life problems such an integration can have a significant impact on process efficiency (Bukchin and Rubinovitz 2003). The problem of simultaneous structural-functional synthesis of the customized assembly system is still at the beginning of its investigation (Levin et al. 2016). Previously isolated gained insights into job shop scheduling, scheduling and sequencing with alternative parallel machines can now be integrated in a unified framework. Three most important prerequisites for such an integration, i.e., data interchange between the product and stations, flexible stations dedicated to various technological operations, and real-time capacity utilization control are enabled by Industry 4.0 technology.

2 Problem Statement

Consider an assembly system that is able to react flexibly at customer orders and produce individualized products. Customers generates orders (jobs) each of which has an individual sequence of technological operations. Each station is dedicated to a set of technological operations. Since multiple stations may perform the same operations, a number of alternatives of job scheduling and sequencing exist subject to actual capacity utilization, machine availability, time-related and cost-related parameters.

The independent jobs consist of a chain of operations whereas the station sequence can differ from different jobs. All jobs are assumed to be available for processing at time zero. Each station is capable of handling only one operation at a time. Processing speed of each station is described as a time function and is modelled by material flow functions (integrals of processing speed functions) and resulting operation processing time is, in general, dependent on the characteristics of the station. The following performance indicators (objective functions) are considered: Throughput, Lead-time, Makespan, Total lateness, Equal utilization of stations in the assembly line.

The first task is to assign the operations to stations at each stage of the technological process. The second task is to sequence the operations at the stations. Note that both tasks will be solved simultaneously.

Consider the following sets:

$\overline{B} = \{\overline{B}^{(i)}, i \in \overline{N}, \overline{N} = (1, \ldots, \overline{n})\}$ is the set of customer orders (jobs)
$D = \{D^{i}_{\mu}, \mu \in \overline{S}, \overline{S} = (1, \ldots, s_i)\}$ is the set of manufacturing operations
$M = \{M^{j}, j \in N, N = (1, \ldots, n)\}$ is the set of stations

In terms of scheduling theory, we study a multi-objective, multi-stage job shop scheduling problem with alternative machines at each stage of the technological process with different time-dependent processing speed, time-dependent machine availability, and ordered jobs where job splitting is not allowed. Examples of such problems can be found in the studies by Kyparisis and Koulamas (2006) and Tahar et al. (2006). The peculiarity of the problem under consideration is the simultaneous consideration of both process design structure selection and operation assignment. On one hand, an assignment problem is discrete by nature and requires the introduction of binary variables, i.e., discrete optimization techniques can be correctly used here. At the same time, a non-stationary operation execution can be accurately described in terms of continuous optimization. An additional peculiarity of such simultaneous consideration is that both the machine structures and the flow parameters may be uncertain and change in dynamics and are, therefore, non-stationary.

3 Dynamic Approach to Job Shop Scheduling

This section considers the principles of the modelling approach. The first principle is to use fundamental results gained in the optimal program control theory for modelling the scheduling decisions. The second principle is the computational procedure based on the maximum principle and Hamiltonian maximization.

3.1 Modelling Approach

Lee and Markus (1967) and Moiseev (1974) proved optimality and existence control conditions for linear non-stationary finite-dimensional controlled differential systems with the convex area of admissible control. We formulate the scheduling model in the form of such a system.

A particular feature of the proposed approach is that the process control model is presented as a non-stationary dynamic linear system while the non-linearity will be transferred to the model constraints. This allows us to ensure convexity and to use interval constraints. Equations (1)–(8) exemplify process control models, constraints, and objective functions.

$$\frac{dx_{i\mu}^{(o)}}{dt} = \dot{x}_{i\mu}^{(o)} = \sum_{j=1}^{n} \varepsilon_{ij}(t) u_{i\mu j}^{(o)}(t) \tag{1}$$

$$\frac{dx_{i\mu j}^{(f)}}{dt} = \dot{x}_{i\mu j}^{(f)} = u_{i\mu j}^{(f)} \tag{2}$$

$$\sum_{i=1}^{\bar{n}} \sum_{\mu=1}^{s_i} u_{i\mu j}^{(o)}(t) \leq 1, \quad \sum_{j=1}^{n} u_{i\mu j}^{(o)}(t) \leq 1 \tag{3}$$

$$\sum_{j=1}^{n} u_{i\mu j}^{(o)} [\sum_{\alpha \in \Gamma_{i\mu_1}^{-}} (a_{i\alpha}^{(o)} - x_{i\alpha}^{(o)}) + \prod_{\beta \in \Gamma_{i\mu_2}^{-}} (a_{i\beta}^{(o)} - x_{i\beta}^{(o)})] = 0 \tag{4}$$

$$0 \leq u_{i\mu j}^{(f)}(t) \leq c_{i\mu j}^{(f)} \cdot u_{i\mu j}^{(o)} \tag{5}$$

$$\sum_{i=1}^{\bar{n}} \sum_{\mu=1}^{s_i} u_{i\mu j}^{(f)}(t) \leq \tilde{\tilde{R}}_j^{(f)} \cdot \xi^{(f)}(t) \tag{6}$$

$$J_1^{(o)} = \frac{1}{2} \sum_{i=1}^{\bar{n}} \sum_{\mu=1}^{s_i} (a_{i\mu}^{(o)} - x_{i\mu}^{(o)}(T_f))^2 \tag{7}$$

$$J_2^{(o)} = \sum_{i=1}^{\bar{n}} \sum_{\mu=1}^{s_i} \sum_{j=1}^{n} \int_{T_0}^{T_f} \alpha_{i\mu}^{(o)}(\tau) u_{i\mu j}^{(o)}(\tau) d\tau \tag{8}$$

The processing dynamics of an operation is presented in Eq. (1). In the case of station availability (i.e.,$\varepsilon_{ij}(t) = 1$) and control $u_{i\mu j}^{(o)}(t) = 1$ at the time point t, the operation $D_{\mu}^{(i)}$ is assigned to the machine $M^{(j)}$. The continuous time allows to represent the execution of the operations at each time point, and therefore, to obtain additional information about the execution of the operations. The state variable x(t) accumulates the executed (processed) volume of the considered operation. Constraints (3) and (4) determine the precedence relations in the manufacturing process and assignment rules (i.e., how many operations may be processed at a station simultaneously), respectively. Constraints (3) determine the "*and*" and "*or"* precedence relations by blocking the operation $D_{\mu}^{(i)}$ until the previous operations $D_{\alpha}^{(i)}$, $D_{\beta}^{(i)}$ have been completed.

Equation (2) consists in the dynamic representation of the material flows resulting from the execution of the operations on the machine $M^{(j)}$. The meaning of Eq. (2) is very close to a system dynamics model to balance the flows in a system. However, the proposed approach also considers the strictly defined logic of the execution of the operations (Eq. 4). Moreover, the models of operations control (Eq. 1) and flow control (Eq. 2) are interlinked linearly by Eq. (5) and the conjunctive system (see Ivanov et al. 2016).

The control variable $u_{i\mu j}^{(f)}(t)$ is not a binary variable like $u_{i\mu j}^{(o)}(t)$, but it is equal to the processed flow volume $x_{i\mu j}^{(f)}$ at each time point t. The model (2)–(5) and (6) uses the assignment results from the model (1)–(3) and (4) in the form of the control variables $u_{i\mu j}^{(o)}(t)$ and extends them by the actual processing speed of the machines subject to the constraints (5) and (6). Inequalities (5) use the assignment decisions $u_{i\mu j}^{(o)}(t)$ and consider the actual processing speed $c_{i\mu j}(t)$ of the stations $M^{(j)}$. Constraints (6) reflect that the processing speed is constrained by $\tilde{\tilde{R}}_{j}^{(f)}$ taking into account the lower and upper bounds of some perturbation impacts $0 \leq \xi^{(f)}(t) \leq 1$ which may decrease the capacity availability.

The objective function $J_{1}^{(o)}$ (Eq. (7)) characterizes the on-time delivery subject to accuracy of the accomplishment of the end conditions, i.e., the volume of the completed operations by the time T_f. The objective function (8) minimizes total maximum lateness using penalties. The penalty function $\alpha_{i\mu}^{(o)}(\tau)$ is assumed to be known for each operation. Note that the constraints (3)–(6) are identical to those in mathematical optimization models. However, at each t-point of time, the number of variables in the calculation procedure is determined by the operations, for which precedence and machine availability conditions are fulfilled. This allows us to start description of the second principle of the developed approach, i.e., the computational procedure.

3.2 Computational Principle

The calculation procedure is based on the application of Pontryagin's maximum principle. The modelling procedure essentially reduces the problem dimensionality at each instant of time due to connectivity decreases. The problem dimensionality is determined by the number of independent paths in a network diagram of manufacturing operations and by current constraints. In its turn, the degree of algorithmic connectivity depends on the dimensionality of the main and the conjugate state vectors at each point of time. If the vectors are known, then the schedule calculation may be resumed after the removal of the "inactive" constraints.

First, on the basis of the Pontryagin's maximum principle and corresponding optimization algorithms, the original problem of optimal control is transformed to the boundary problem. The maximum principle permits the decoupling of the dynamic problem over time using what are known as adjoint variables or shadow prices into a series of problems each of which holds at a single instant of time. Second, the optimal program control vector $\mathbf{u}(t)$ and the state trajectory $\mathbf{x} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t)$ should be determined so that the desired values of the objective functions are obtained as an analogy to goal programming.

At each time instant, the assignment decisions consider only the gray colored operations subject to some available ("competing") machines, i.e., the large-scale multi-dimensional combinatorial matrix is decomposed. The assignment of a machine $M^{(j)}$ to the execution of the operation $D_{\mu}^{(i)}$ can be described by the piecewise continuous function $u_{i\mu j}^{(o)}(t)$ that becomes equal to 1 in the case of an assignment. As such, the constructive possibility of discrete problem solving in a continuous manner occurs.

Besides this, the required consistency between optimal program control and linear programming or integer programming models is ensured – although the solver works in the space of piecewise continuous functions, the control actions can be presented in the discrete form.

In the proposed dynamic scheduling model, a multi-step procedure for scheduling is implemented. At each instant of time while calculating solutions in the dynamic model with the help of the maximum principle, the linear programming problems to allocate jobs to resources and integer programming problems for (re)distributing material and time resources are solved with mathematical programming algorithms.

1. Initial solution $\bar{\mathbf{u}}(t),\ t \in (T_0, T_f]$ (a feasible control, in other words, a feasible schedule) is computed with a heuristic algorithm.
2. As a result of the dynamic model run, $\mathbf{x}(t)$ vector is received. Besides, if $t = T_f$ the objective function values are calculated.
3. The transversality conditions are evaluated.
4. The conjugate system is integrated subject to $\mathbf{u}(t) = \bar{\mathbf{u}}(t)$ and over the interval from $t = T_f$ to $t = T_0$. For the time $t = T_0$, the first approximation of the conjunctive vector is obtained as a result.
5. From the time point $t = T_0$ onwards, the control $\mathbf{u}(t)$ is determined for different iterations. In parallel with the maximization of the Hamiltonian, the main system of equations and the conjugate one are integrated. The maximization involves the solution of several mathematical optimization problems at each time point.

The assignments (i.e., the control variables) are used in the flow control model by means of the constraints (5). At the same time, the flow control model (2), (5) and (6) influences the operations execution control model (1), (3) and (4) through the transversality conditions, the conjunctive system, and the Hamiltonian function. A methodical challenge in applying the maximum principle is to find the coefficients of the conjunctive system which change in dynamics. One of the contributions of this research is that these coefficients can be found analytically (Ivanov et al. 2016). The coefficients of the conjunctive system play the role of the dynamical Lagrange multipliers as compared with mathematical programming dual formulations.

4 Conclusions

Industry 4.0 technology enables new production strategies that require highly customized assembly systems. The ultimate objective of those systems is to facilitate flexible customized manufacturing at the costs of mass production. Such innovative production strategies represent a number of new challenges and opportunities for short-term job scheduling. In particular, manufacturing processes for different customer orders may have individual machine structures whereas the flexible stations are able to execute different functions subject to individual sets of operations within the jobs. Therefore, a problem of simultaneous structural-functional synthesis of the customized assembly system arises.

This study develops an optimal control model and an algorithm for job shop scheduling in an Industry 4.0-based flexible assembly line. In contrast to previous studies which assumed fixed process design, our approach is capable of simultaneously designing manufacturing process in regard to available alternative stations, their current capacity utilization and processing time, and sequencing jobs at the stations.

The developed framework is also a contribution to scheduling theory. The formulation of the scheduling model as optimal program control allows including into consideration a non-stationary process view and accuracy of continuous time. In addition, a wide range of analysis tools from control theory regarding stability, controllability, adaptability, etc. may be used if a schedule is described in terms of control.

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Genetic Algorithms with Simulation for a Job Shop Scheduling Problem with Crane Conveyance

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Abstract. In this paper, a genetic algorithm (GA) and GA with diversification generator (DG) for solving scheduling problems with crane conveyance are proposed. It becomes very difficult to obtain an optimum or near optimum schedule under consideration of restrictions to avoid crane interference in addition to many restrictions on operation of each machine. GA-based algorithms are applied to obtain high quality crane assignment which successfully leads to few working hour delays caused by crane interference. Effectiveness of this algorithm is confirmed by numerical experiments.

Keywords: Scheduling · Genetic algorithm · Diversification generator · Crane interference

1 Introduction

Scheduling problems of the manufacturing industry generally have a large number of variables and constraints. It is difficult to find an optimal schedule that satisfies all constraints within the practical time. Especially when the products are conveyed by two overhead cranes (hereafter crane), it is necessary to avoid interference of crane conveyance (hereafter crane interference) in addition to restrictions on operation of each machine. In the previous studies, authors proposed an enumeration tree search method [1] and an enumeration tree search method with perturbation [2]. These methods can solve the scheduling problem in a short time, but the search of crane assignment depends strongly on the initial assignment at the beginning of the methods, which fails to explore the solution space widely.

In order to solve this problem, we develop a new solution method using GA and GA with DG for crane assignment in which DG was proposed by Glover [3]. Effectiveness of the proposed method is shown through some numerical experiments.

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2 Problem Description

2.1 Production Process with Crane Conveyance

The process for this research is a job shop process with two cranes (Fig. 1) [2]. The products to be produced are carried in from the left side, and are carried out to the right side after processing at any machine.

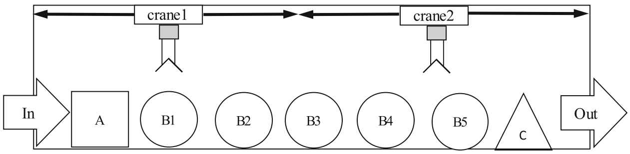

Fig. 1. Production process with crane conveyance

This production process is consist of following three steps.

(a) First step—A
(b) Second step—B1–B5 (There are multiple machines)
(c) Third step—C

Both cranes can move in the left and right direction. Due to the mutual positional relationship, interference may occur and the operating range may be limited. The conveyance speed and the required time for hoisting and lowering are fixed.

2.2 Objective Function and Constraints

The objective of this problem is the minimization of the total time from carrying-in to carrying-out of all products. Constraints are as follows:

(a) There is no division/integration of products. Weight does not increase or decrease.
(b) Each machine cannot process on two or more products at the same time.
(c) Process machines, process sequence, processing times of each machine are given.
(d) Cranes can be selected.
(e) Adjacent crane keeps a certain interval or more.
(f) The possible start time for the third step is given. Delay of start time for third process is avoided as much as possible.
(g) The first carried in time is the start time of the first step.
(h) There is no stock place between machines. If the next machine is in operation, the product to be produced stands by at present machine or at crane.

3 Proposed Solution Method

The decision variable of the problem is the assignment of cranes 1 and 2, which is represented as a binary variable taking 1 and 2 if each task of conveyance between machines is assigned to crane 1 and crane 2, respectively. In this paper, the decision vector of the crane assignment is called a solution which is obtained by the proposed GA-based solution method. The proposed method involves backward simulation (Sect. 3.1) and forward simulation (Sect. 3.2) to avoid machine conflicts and crane interference. For diversification of solutions explored, GA with DG is constructed by integrating diversification generator (Sect. 3.3) into GA.

3.1 Backward Simulation

The determination of the latest process starting/ending time of each machine begins from the third step in the order of due date, and then is continued by tracing back to the second step and the first step. This time is obtained by subtracting processing time of the machine and conveyance time of crane from the latest ending time of that machine. If machine conflicts occur, processing times are ahead of schedule. Also, without considering the crane interference, conveyance time is calculated moving distance/conveyance speed + lifting/hoisting time.

3.2 Forward Simulation

The crane assignment by GA for conveying the product is performed in order of earlier process ending time determined by backward simulation. If crane interference or machine confliction occurs, the process starting/ending times of crane and machines are shifted backward to avoid them (Fig. 2). The gene required for applying the GA is the assignment of crane (Fig. 3). The number of genes at locus is the number of crane conveyance. Forward simulation algorithm is as follows.

S.1 Initial value setting
  Set the number of individuals and the number of generations.

S.2 Initial parent solution generation
  Generate initial parent solutions randomly for the number of individuals. Generate 1 or 2 is set as a gene randomly.

S.3 Operation simulation and Objective function value calculation
  Execute operation simulation. Determine process time and calculate objective function value by the following S.3.1 to S.3.3. Repeat this procedure for the number of individuals.
  - S.3.1 Assign crane using genes. Determine process starting/ending time of crane so as to avoid crane interference.
  - S.3.2 As a result of S.3.1, if a delay occurs at the latest process starting/ending time of each machine, the delay time is shifted backward. Furthermore, propagate the delay to process time of the subsequent machines and jobs.
  - S.3.3 Apply S.3.1 and S.3.2 to all genes in the locus. Calculate objective function value.

S.4 Child solution generation (GA)
  Using GA for the parent solutions, generate the child solutions for the number of individuals by the following S.4.1 to S.4.4.

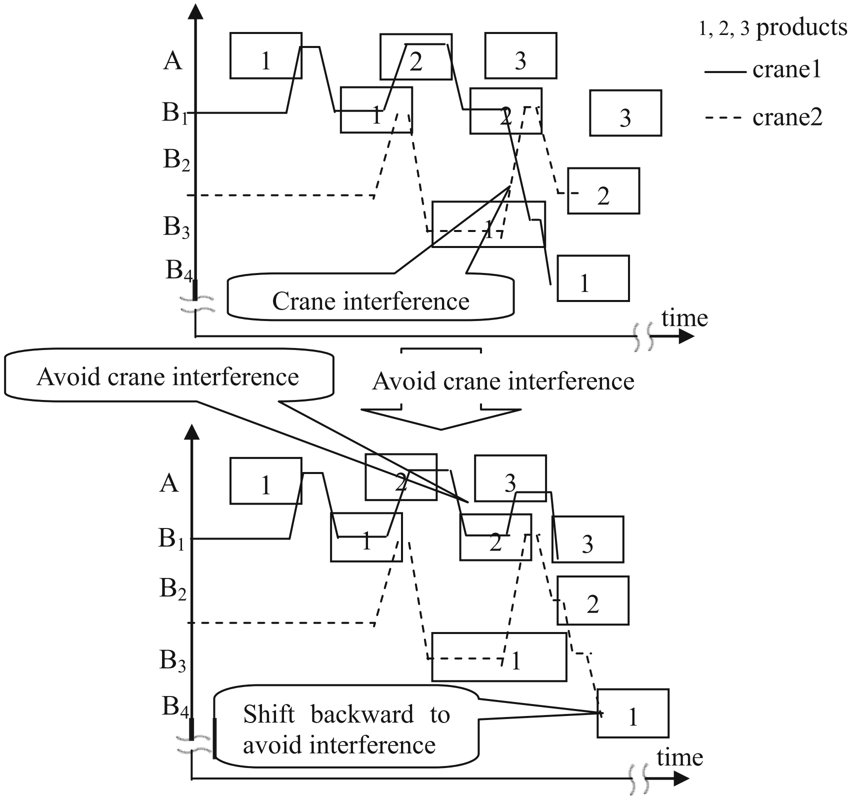

Fig. 2. Avoidance of crane interference and shifting backward processing time

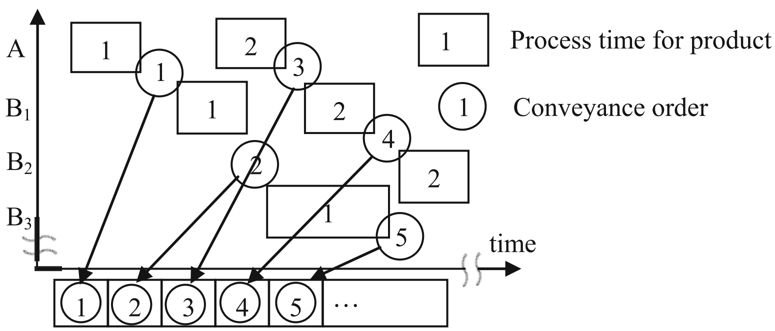

Fig. 3. Gene locus

S.4.1 Extract two parent solutions randomly from the parent solution group.
S.4.2 Perform two-point crossover to generate two solutions. Crossover points are chosen randomly.
S.4.3 Change the genes of the two solutions generated in S.4.2 to 1 or 2 with a probability of 5% and make them a child solution.
S.4.4 If the solution group becomes an empty set, it ends. Otherwise return to S.4.1.

S.5 Operation simulation and Objective function value calculation
Execute operation simulation in the same way as in S.3 for the generated child solution, and calculate objective function value.

S.6 Survivor selection
Select the top half solutions that have good objective function value in the parent and child solutions. Make them the next generation parent solutions.

S.7 End judgment
If it repeats as many times as the number of generations set in S.1, it ends. Otherwise return to S.4.

3.3 Diversification Generator

There is a possibility that bias will occur in the initial solution generated randomly. Therefore, we develop a solution method to use DG for generating initial solution.

DG is a method of generating a new solution sequentially so that the Hamming distance becomes the maximum with respect to the base solution [3]. By using DG as the initial solution of crane assignment, we aim to diversify the initial solution and explore the solution space widely. Algorithm of DG for S.2 in forward simulation is as follows.

S.1 Initial value setting
Let gene locus be $x = (x_1, x_2 \cdots, x_m)$. Let n = 2.

S.2 Initialize x and m
Let be m the number of genes and initialize the element of gene with 1 (i.e. crane 1 is assigned).

S.3 Generate element $x_i^{'}$
Let $h = n$. Generate element $x_i^{'}$ by following expression. Store the generated $x_i^{'}$ in gene locus.

$$x_i^{'} = 3 - x_{1+hk} (\text{for } k = 0, \ldots, m/h)$$

S.4 Generate 1–2 inversion $x_i^{''}$ of $x_i^{'}$
Generate 1–2 inversion $x_i^{''}$ by following expression. Store the generated $x_i^{''}$ in gene locus.

$$x_i^{''} = 3 - x_i^{'}$$

S.5 Generate right rotation shift x_i''' of x_i'
If $h \geq 3$, generate x_i''' by rotating k to the right relative to x_i'. Store the generated x_i''' in gene locus (for $k = 1, 2, \ldots, h - 1$).
S.6 Generate right rotation shift x_i'''' of x_i''
If $h \geq 3$, generate x_i'''' by rotating k to the right relative to x_i''. Store the generated x_i'''' in gene locus (for $k = 1, 2, \ldots, h - 1$).
S.7 End judgment
When the number of stored gene locus reaches the number of individuals, it ends. Otherwise, return to S.2 with $n = n + 1$.

4 Numerical Experiment

In order to verify the effectiveness of proposed solution, we solve scheduling problems shown in Tables 1, 2 and 3 for the previous research [2] and proposed method, and compare objective function values and solving time.

Table 1. Processing times and machine positions

Machine	A	B1	B2	B3	B4	B5	C
Processing time	28	20	16	21	30	15	20
Position	20	35	55	80	120	150	220

Table 2. Experimental data setting

Individuals	Generation	Jobs	Interval	Simulation
512	100	20	25	10

4.1 Numerical Experiment Condition

Processing times and machine positions from left side are shown in Table 1. Many machines are arranged on the left side of process, because there are few equally installed machines in the factory layout. Experimental data settings are shown in Table 2. The number of individuals of GA is set to 512 from the capacity limit of our computer. The number of generation is set to 100, in which the update of the solution almost disappears from experiment result. The delivery time interval is set to 25, because the operation was not established from crane interference if it was shorter than 25 in the experimental results of the previous research. We categorized the tendency of machine selection in the second process (uniform machine selection, alternate jobs with different machine selections, high operating load of the first ten jobs, etc.) are and set the operation pattern in Table 3.

Table 3. Operation pattern

Pattern	Job sequence	Characteristic
1	A → B1 → B2 → B4 → C	All the same machine
2	A → B1 → B2 or B3 → B4 or B5 → C	Machine of B2 and B3, B4 and B5 is Unevenly processed
3	A → B1 → B3 → B4 → C A → B1 → B2 → B5 → C	Machine of B2 and B3, B4 and B5 is alternatively processed
4	A → B1 → B4 → B5 → C A → B2 → B4 → B5 → C A → B3 → B4 → B5 → C	Operation with allowance in the first half of the job
5	A → B1 or B2 or B3 → B4 → B5 → C	Machine of B1, B2 B3 is unevenly processed
6	A → B1 → B2 → B3 → B4 → C A → B1 → B2 → C	The first half job has 6 machines The second half job has 4 machines
7	A → B1 → B2 → B3 → B4 → C A → B1 → B5 → C	
8	A → B1 → B2 → C A → B1 → B2 → B3 → B4 → C	The first half job has 4 machines The second half job has 6 machines
9	A → B1 → B5 → C A → B1 → B2 → B3 → B4 → C	
10	A → B1 → B2 → B3 → B4 → C A → B1 → B2 → C	The number of machine is 6 → 4 → 6 → ...
11	A → B1 → B2 → B3 → B4 → C A → B1 → B5 → C	
12	A → B1 → B2 → C A → B1 → B2 → B3 → B4 → C	The number of machine is 4 → 6 → 4 → ...
13	A → B1 → B5 → C A → B1 → B2 → B3 → B4 → C	

4.2 Results of Numerical Experiment

Average objective function value and the best value of 10 numerical experiments are shown in Table 4. Calculation time is average value of 10 numerical experiments. The following were confirmed from Table 4.

(a) Objective function values (average) of proposed solution (GA or GA + DG) are improved by about 5 to 15% compared with that of previous research except pattern 1. They are within 5% of the lower limit of 10 cases in 13 cases. In many cases, the results of GA are somewhat better than GA + DG.
(b) Objective function values (best) of proposed solution (GA or GA + DG) are improved by about 8 to 18% compared with that of previous research except pattern 1. They are within 5% of the lower limit of 10 cases in 13 cases. In many cases, the results of GA are somewhat better than GA + DG.
(c) Calculation time of proposed solution (GA or GA + DG) is 10 to 16 times that of previous research.

Table 4. Result of numerical experiment

pattern	objective fanction value (average)			objective fanction value (best)			Lower limit
	PR	GA	GA + DG	PR	GA	GA + DG	
1	2702.0	2712.7	2708.9	2700.0	2710.2	2707.0	2700.0
2	2987.3	2649.1	2649.0	2952.0	2646.8	2645.8	2600.0
3	3099.6	2666.8	2666.3	3030.0	2666.0	2665.5	2600.0
4	3010.1	2672.1	2671.4	2993.5	2670.0	2670.3	2658.0
5	3020.5	2679.0	2680.4	3019.3	2678.0	2678.0	2658.0
6	3007.5	2641.4	2645.3	3001.5	2638.7	2638.8	2610.0
7	3093.0	2630.3	2633.4	3080.8	2625.0	2625.0	2600.0
8	3393.4	3246.7	3051.3	3388.5	3052.3	3046.8	2610.0
9	3706.2	3322.3	3357.9	3694.5	3278.3	3281.0	2600.0
10	3207.3	2766.6	2769.0	3172.8	2765.5	2767.3	2610.0
11	3206.7	2645.3	2645.3	3175.0	2645.3	2645.3	2600.0
12	2892.4	2623.9	2627.3	2869.3	2622.2	2626.2	2610.0
13	2972.8	2600.0	2600.0	2887.8	2600.0	2600.0	2600.0

pattern	calculation time		
	PR	GA	GA + DG
1	47.5	766.1	660.4
2	56.3	794.9	805.2
3	57.6	772.8	781.2
4	51.6	711.0	713.2
5	51.9	698.2	697.2
6	54.7	750.9	737.5
7	54.9	704.7	711.0
8	56.5	864.4	877.2
9	57.4	792.5	791.2
10	56.1	766.3	760.6
11	56.5	626.9	633.9
12	54.6	717.6	751.4
13	56.0	585.2	596.1

PR : Previous research
GA : Genetic Algorithm
GA + DG : GA with Diversification Generator for initial solution generation
Lower Limit: Sum of operation time and crane movement time (without machine conflict and crane interference)

In the case where the number of jobs is 20, there are 2^{80} possible candidates for crane assignment, which is a very large optimization problem. Previous research could solve in a short time, but it was not able to sufficiently search solution space. As improving the above problems using GA or GA with DG, the proposed method can derive better solutions. Calculation time is about 15 min. It was possible to apply to the shift plan that was planned once/8 h.

5 Conclusions

A scheduling method for production process with crane conveyance using GA and GA with DG has been proposed. The proposed method has been successful in searching a wider range of solution space than that of previous research, and it is confirmed that objective function value improved by about 10%. In the future, we plan to develop a solution method that realizes solution concentration and diversification.

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A Proposal of Production Scheduling Method Considering Users' Demand for Mass Customized Production

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Abstract. The main goal of this study is to make a production schedule considering users' demand about due date and price in mass customization. For minimizing the total tardiness, a proposed method using Combinatorial Auction is applied to develop an optimal plan in planning phase. In operational phase, a technique for inserting additional orders at idle time is proposed using Single Auction approach. To evaluate effectiveness of the proposed approaches, computer experiments are conducted.

Keywords: Production scheduling · Combinatorial Auction · Single Auction · Mass customization

1 Introduction

The aim of this paper to propose a production scheduling method considering user needs to realize mass customization. Mass customized system can respond variety of users' demands, and achieve high production efficiency with low cost [1]. To implement a mass customized system, manufacturers are required to achieve an optimal production scheduling, inventory planning and so on. Among them, focusing on the production scheduling, we have proposed a method applying Combinatorial Auction [2] to planning phase for making the production schedule over multiple periods, and Single Auction [3] to operational phase for updating the production schedule quickly in response to new additional orders such as received orders [4].

In this study, "users' demand" is defined as the users' demand about due date and price, and we propose a method of making the production schedule considering the users' demand by weighted tardiness according to the price paid by users.

2 Model

In this study, we focus on mass customization of the sole part of running shoes [5]. The shoes are composed of a sole part and an upper part. The sole part consists of three parts: inner sole, mid sole, and outer sole. The upper part is supposed to have sufficient

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inventory anytime and is not subject to planning in this study. The user can select each sole part from either standard parts or tailor-made parts. Standard parts are parts with shape and material standardized, and tailor-made parts are parts considering user needs manufactured by tailor-made machine (3D printer). Each part for inner, mid, outer is manufactured by the standard machines and/or tailor-made machines. Then, the parts are assembled by assembly machine, and the shoes are completed. In each machine (excluding assembly machine), a setup time occurs when the type of parts is changed.

3 Proposed Scheduling Method

3.1 Notation

The notations used in this model are shown as follows:

I : Order number ($i = 1, \cdots, I$)
j : Work number ($\{j = 1, \cdots, J \mid j \in standard, tailor, assembly\}$)
k : Bid number of bidder ($k = 1, \cdots, K$)
t : Time slot number ($t = 1, \cdots, T$)
te : Manufacturing term number ($te = 1, \cdots, TE$)
RT_i : Arrival time of order i
$MT_{i,j}$: Production time of work j of order i
AT_i : Assembly time of order i
$PS_{i,j,k}$: Starting time of processing of bid k of work j of order i
$MN_{i,j,k}$: Machine number of bid k of work j of order i
DP_i : Number of time slot of the tardiness of order i
AP_i : Amount of additional price of order i
w_i : Weight factor of order i for the tardiness with additional price (AP_i)
λ_{te} : Constraint violation penalty per term te
α : Weight factor for constraint violation penalty per term te (λ_{te})
$U_{i,j,k,t}$: A dependent variable that is 1 if the bid k of work j of order i is being manufactured at time slot t, and otherwise 0
$UA_{i,j,k,t}$: A dependent variable that is 1 if the bid k of work j of order i is being assembled at time slot t, and otherwise 0
C_j : Setup time of work j ($C_j = Co(j \in standard), C_j = CoT(j \in tailor)$)
TS_{te} : All time slots included in term te
OR' : Target machine operating rate
$term$: Number of time slots per a term
$T_{i,j,k,te}$: A dependent variable that is 1 if the starting time of processing of bid k of work j of order i $\left(PS_{i,j,k}\right)$ is included in term te, and otherwise 0
$rand$: A random variables following the uniform random number
$direct$: The threshold for neighborhood search operation

3.2 Planning Phase

3.2.1 Proposed Method Based on Combinatorial Auction

A Combinatorial Auction (CA) [2] is known as social contract based optimization approach and used to develop optimal scheduling and stock allocation planning. CA first shows the information of goods to the bidders, and the bidders make bids (Bid determination problem). Then the auctioneer decides winner bids which make objective function maximum or minimum (Winner determination problem).

In this study, manufacturer hosts auction and the bidder is the order requested by the user and goods included in the bid are the right to use the machine (machine number to be manufactured ($MN_{i,j,k}$), starting time of processing ($PS_{i,j,k}$)).

3.2.2 Bid Determination Problem

Bid Value

Equation (1) expresses bid value $B_{i,j,k}$ of bid k by bidder (i,j). Parameter w_i is a weight factor for the tardiness determined by the additional price paid by the user (AP_i), and the relationship between weight factor and price is shown in Fig. 1. By increasing w_i of the user who pays the high additional price (AP_i), the order ordered by the user is preferentially manufactured.

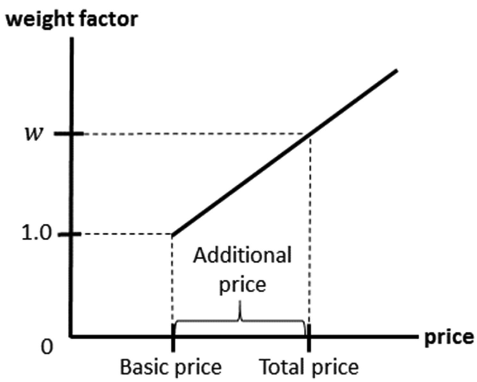

Fig. 1. Relationship between weight factor and price

$$B_{i,j,k} = \begin{cases} \max\{0, (PS_{i,j,k} + AT_i - DP_i) \times w_i\} & (\text{if } j \in assemby) \\ 0 & (\text{otherwise}) \end{cases} \quad (1)$$

Bid Constraints

Each bidder avoids to make the bid including infeasible combination. Then bidding rules in conjunction with the bid are set as shown in Eqs. (2) and (3).

$$PS_{i,j,k} \geq RT_i(\forall k) \tag{2}$$

$$PS_{i,j,k} \geq \max\left(PS_{i,j,k} + MT_{i,j}\right) \tag{3}$$

$$(j \in standard, tailor, j' \in assembly, \forall k)$$

Equation (2) expresses that the order i is manufactured after the arrival time of order i (RT_i). Equation (3) expresses that assembly work is started after completion of all parts is determined.

3.2.3 Winner Determination Problem

Objective function and constraints are formulated as follows:

$$\min \sum\nolimits_{i=1}^{I} \sum\nolimits_{k=1}^{K} \left(B_{i,j,k} \times x_{i,j,k}\right) + \sum\nolimits_{te=1}^{TE} \lambda_{te}(j \in assembly) \tag{4}$$

$$\text{s.t} \sum\nolimits_{k=1}^{K} x_{i,j,k} = 1(\forall i, \forall j) \tag{5}$$

$$\sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J} U_{i,j,k,t} \times x_{i,j,k} \leq 1(\forall k, \forall t, j \in standard, tailor) \tag{6}$$

$$U_{i,j,k,t} = \begin{cases} 1 & \left(\text{if } PS_{i,j,k} \leq t \wedge t \leq PS_{i,j,k} + MT_{i,j}\right) \\ 0 & (\text{otherwize}) \end{cases}$$

$$\sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J} UA_{i,j,k,t} \times x_{i,j,k} \leq 1 \quad (\forall k, \forall t, j \in assembly) \tag{7}$$

$$UA_{i,j,k,t} = \begin{cases} 1 & \left(\text{if } PS_{i,j,k} \leq t \wedge t \leq PS_{i,j,k} + AT_i\right) \\ 0 & (\text{otherwize}) \end{cases}$$

$$x_{i,j,k} + x_{i',j,k'} \leq 1 \tag{8}$$

$$(\{\forall i, \forall i', \forall j, \forall k, \forall k' | i \neq i' \wedge j \notin assembly \wedge PS_{i,j,k} + MT_{i,j} \leq PS_{i',j,k'} \wedge PS_{i',j,k'} \leq PS_{i,j,k} + MT_{i,j} + C_j\})$$

$$PS_{i,j,k} \times x_{i,j,k} + MT_{i,j} \leq PS_{i,j',k'} \times x_{i,j',k'} \tag{9}$$

$$(\{\forall i, \forall j \,|\, j \in standard, tailor, j' \in assembly\})$$

$$\lambda_{te} = \max\left\{0, \left(\sum\nolimits_{i=1}^{I} \sum\nolimits_{j=1}^{J} \sum\nolimits_{k=1}^{K} \left(MT_{i,j,k} \times x_{i,j,k} \times T_{i,j,k,te}\right) - TS_{te} \times OR'\right) \times \alpha\right\} \tag{10}$$

$$T_{i,j,k,te} = \begin{cases} 1 & \left(\text{if} \, term \times (te - 1) \leq PS_{i,j,k} \wedge PS_{i,j,k} \leq term \times te\right) \\ 0 & (\text{otherwise}) \end{cases} (\forall \text{te})$$

$$x_{i,j,k} \in \{0, 1\} \tag{11}$$

The decision variable is $x_{i,j,k}$, expressed by Eq. (11). When this value is 1, the bid bearing bidding number k of work j of order i becomes the winner. When this value is 0, the bid becomes the loser.

Objective function is expressed by Eq. (4), which is intended for minimizing the total tardiness and constraint violation penalty per term (λ_{te}).

Equation (5) guarantees that only a bid per bidder becomes winner. Equation (6) is constraint equation related to the rights on standard and tailor machine at a time slot. Equation (7) is constraint equation related to the rights on assembly machine at a time slot. Equation (8) is constraint equation related to the rights on processing machine under considering setup time at a time slot. Equation (9) guarantees that a product can be assembled after the completion of parts. Equation (10) is constraint on the level of the machine operating rate, which means that if the machine operating rate in each term exceeds the value of the target machine operating rate $\left(OR'\right)$, a constraint violation penalty (λ_{te}) will occur for each term.

3.2.4 Bidding Rule

Initial Bid

When auctioneer establishes an upper bound of the number of bids per bidder to obtain the solution in a short time, sometimes feasible solution of winner determination problem is not obtained. Therefore, all bidders make an initial bid in accordance with the dispatching rules for getting the practicable solution.

Bidding by Neighborhood Search Operation

Except for initial bid, bidders make the bid that won the last auction and its nearby value. By the neighborhood search operation, all bidders always get the practicable solution and prevent from worsening of the objective function value. The detail of the bidding by neighborhood search operation is as follows:

STEP 1 Make a bid of the same goods combination as the bid of the winner of the last auction.

STEP 2 Other bids are made by shifting the starting time of processing $\left(PS_{i,j,k}\right)$ of the bid that was the winner of the last auction. Equation (13) determines the direction of shift. Parameter ε is a random variable following the uniform distribution.

$$PS_{i,j,k} := \begin{cases} PS_{i,j,k} + \varepsilon & (\text{if } rand < direct) \\ PS_{i,j,k} - \varepsilon & (\text{otherwise}) \end{cases} \tag{13}$$

STEP 3 If the bid made in **STEP 2** overlaps $PS_{i,j,k}$ of another bid, the process returns to **STEP 2**. Otherwise, the process ends

3.3 Operational Phase

3.3.1 Proposed Method Based on Single Auction

A Single Auction [3] is an auction that can make an efficient schedule in a short time. In the Single Auction used for this study, the bidder is tailor-made machine and bidding goods are received orders. The bid value is the residence time of received order i' expressed by the Eq. (14). Bidding with the minimum the residence time $(ReT_{i'})$ is the winner and the order is assigned to the machine.

$$ReT_{i'} = PS_{i',j,k} + AT_{i'} - RT_{i'} \tag{14}$$

3.3.2 Flow of Received Order Assignment

At operational phase, the received order is allocated to the machine for each term and the schedule is updated. The flow of received order assignment is as follows:

STEP 1 The orders included in the term *te* of the production schedule made in planning phase are left-aligned in consideration of setup time.

STEP 2 Using the Single Auction shown in Sect. 3.3.1, received orders are allocated to machine in order of early due date. If due delay occurs, go to **STEP 3**. Otherwise go to **STEP 4**.

STEP 3 Perform the received order inserting operation. The received order inserting operation is to reinsert the received so that the total tardiness becomes minimum. The time slot to be reinserted is decided by considering w_i shown in Sect. 3.2.2.1.

STEP 4 If $te = TE$, then finish. Otherwise, $te \coloneqq te + 1$ and return to **STEP 1**.

4 Computational Experiments

In order to evaluate the proposed method, the computational experiments were performed. The evaluation criteria are as follows:

- DD [TS]: Total tardiness (DP_i)
- NOD: The number of order that delays due date
- NOD_A: The number of order with additional price (AP_i) that delays due date
- NOD_N: The number of order with no additional price that delays due date
- OR [%]: Overall machine operating rate
- $OR_{1,2,3}$ [%]: 1st, 2nd, 3rd term machine operating rate
- CT [sec]: Calculation times

4.1 Experimental Conditions

The experiments are performed with the following conditions:

- The number of order (Order set 1): 45 (Additional price payment: 22, No: 23)
- The number of order (Order set 2): 35 (Additional price payment: 17, No: 18)
- The number of received order: 10 (Additional price payment: 5, No: 5)
- Arrival time of orders (RT_i): 0[TS]
- The number of standard parts varieties: 3
- The number of tailor-made parts varieties: 7
- The number of standard machine: 3 (1 inner sole, 1 mid sole, 1 outer sole)
- The number of tailor-made machine: 5
- The number of assembly machine: 1
- Production time of standard machine ($\{MT_{i,j} \,|\, j \in standard\} \,|$): 1[TS]
- Production time of tailor-made machine ($\{MT_{i,j} \,|\, j \in tailor\} \,|$): 10–20[TS]
- Assembly time (AT_i): 1[TS]
- Setup time of standard machine (Co): 3[TS]
- Setup time of tailor-made machine (CoT): 4[TS]
- The number of time slots per term ($term$): 50[TS]
- The number of term (TE): 3[term]
- Weight factor for the tardiness (w_i): $w_i = 1 + AP_i \times 1000$
- Weight factor for constraint violation penalty (α): 10
- Target machine operating rate (OR'): 61 (order set 1), 77 (order set 2)
- Threshold for neighborhood search operation *direct*: 0.5
- The number of bid per bidder (K): 10
- The number of iteration (Ite): 500
- The number of trial: 50

This study uses CPLEX 12.6 [6] and Inter(R) Xeon(R) CPU E5 1650 3.50 GHz 16.0 GB memory computer to solve bid determination problem.

4.2 Experiment 1: Evaluation at Planning Phase

Computer experiments at planning phase were conducted to evaluate the constraints on the level of machine operating rate (OR_1, OR_2, OR_3) and the weight by price (w_i). The results are shown in Tables 1 and 2. Order set 1 was used for the experiments.

Considering the results in Table 1, the average values of the difference between OR and (OR_1 or OR_2 or OR_3) are smaller with the proposed method (with constraints), and machine operating rates are about the same. DD of the proposed method (61.28) was reduced by 1% compared with DD of No-Constraint (61.74). CT increased in proposed method with the introduction of the constraint. From these results, it was confirmed that it is possible to level the machine operating rate of each term without a large change in the total tardiness by introducing the constraint, and that the constraint is effective for leveling the machine operating rate.

Considering the results in Table 2, NOD_A of the proposed method was 0, which was greatly improved compared to No-Weight. On the other hand, DD of the proposed method (99.5) was increased by 56% compared with DD of No-Weight (63.74). NOD_N

Table 1. Results of experiment 1 (for evaluating the constraint)

	Proposed		No-Constraint	
	Avg.	S.D.	Avg.	S.D.
OR	77.6	0	77.6	0
OR_1	77.82	0.834	81.44	0.999
OR_2	77.34	0.405	78.0	1.31
OR_3	77.26	0.751	73.3	1.26
DD	61.28	6.30	61.74	6.51
CT	119.04	2.94	106.61	2.81

Table 2. Results of experiment 1 (for evaluating the weight by price)

	Proposed		No-Weight	
	Avg.	S.D.	Avg.	S.D.
DD	99.5	18.81	63.14	6.43
NOD	6.12	0.84	7.8	0.693
NOD_A	0	0	4.44	0.983
NOD_N	6.12	0.84	3.36	0.768
CT	112.91	3.46	120.04	2.89

of the proposed method (6.12) was increased by 82% compared with NOD_N of No-Weight (3.36). From these results, it was confirmed that it is possible to make a schedule considering the price by weighting on the tardiness by the price, but the tardiness of the user who does not pay the additional price (NOD_N) is increasing.

4.3 Experiment 2: Evaluation at Operational Phase

Computer experiments were conducted to evaluate the effectiveness of the received order inserting operation considering price at operational phase. The results are shown in Table 3. Order set 2 was used for the experiment.

Considering the results in Table 3, DD of the proposed method (with Insert) was greatly improved to 17.3% of DD without inserting operation. Furthermore, NOD of proposed method became smaller than NOD of No-Weight. Therefore, by using inserting operation, it was found that it is possible to insert received order without

Table 3. Results of experiment 2 (for evaluating the received order inserting operation)

	Proposed		No-Insert	
	Avg.	S.D.	Avg.	S.D.
DD	27.45	16.81	158.75	32.38
NOD	4.2	0.98	6.75	2.12
NOD_A	0.9	0.83	2.6	1.11
NOD_N	3.3	1.05	4.15	1.35
CT	78.51	2.95	83.43	1.82

increasing the tardiness. In addition, the ratio of NOD_A (2.6) to NOD (6.75) was 38.5% in the case of No-Insert, while the ratio of NOD_A (0.9) to NOD (4.2) was 21.4% in the proposed method, and the number of order with additional price that delays due date was decreasing. From these results, it was suggested that the schedule acquired by using the proposed method is able to be updated with priority given to users who paid the high price, and it is confirmed that insertion of received order considering price is effective.

5 Conclusion

In this study, the production scheduling method considering user needs with auction methods – CA and Single Auction, for mass customization was proposed, and we evaluated its effectiveness by computer experiments. From the obtained results, it was found that by using the proposed method, it is possible to greatly improve the tardiness and the value of NOD_A. Therefore, it was confirmed that it is possible to make a schedule considering the users' demand about due date and price by using the proposed production schedule method.

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Production Capacity Pooling in Additive Manufacturing, Possibilities and Challenges

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Abstract. Industries such as aviation tend to hold large amounts of capital tied to spare parts inventories to insure a high availability [1]. One effective approach to increase the efficiency in inventory management has been resource pooling [2]. However, the emergence of additive manufacturing (AM) enables the new paradigm of production capacity pooling, which varies from current ones. AM's inherent characteristics may realize capacity sharing among distinct industries, alleviate the need for high safety stock levels and enable better customer service through the reduction of transshipments for spare parts. The advantages can be extended to the broader fulfillment reach of the firm in other geographical areas without expanding its existing production capacity or inventory (and other benefits from a distributed production setting). However, issues with inter-organizational agreements, testing and production reliability may slow down the pooling process while the required facilities are in place. This paper aims to extend the existing literature on implications of this growing phenomenon on inventory management practices. Study methodology is conceptual analysis.

Keywords: Additive manufacturing · Capacity pooling · Inventory management

1 Introduction

Spare parts supply chains are profitable for the business but inherently complex and potentially wasteful. The root problem is in the stochastic and uncertain nature of spare parts demand and different service levels required to satisfy and retain customers. In industries where availability is essential and downtime is very costly; operators tend to hold a high level of safety stock on hand. For instance, according to Harrington [19] the monetary value of spare parts stock in commercial aviation industry is about 44 billion dollars. To improve the situation, researchers have utilized other technologies (such as Information and communications technology) to introduce various tools and inventory management strategies. Among those, inventory pooling strategy [25, 26] which is based on the resource sharing has been effective on various implementation levels (intra/inter organizational). However, the difficulties regarding the cost sharing in inventory pooling has led to limited use of this method to reduce the costs for instance among the airlines [2].

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Currently, digitalization of manufacturing enabled by additive manufacturing (AM) methods has the potential to affect a major improvement throughout supply chains [5, 6, 24]. Therefore, a detailed impact investigation of this phenomenon on current supply chain practices will provide a better understanding among the managers in this field. Hence enabling them to make more informed decisions and take advantage of the possibilities while staying away from the possible threats.

The paper is structured in five sections; Introduction, literature review on resource pooling and additive manufacturing, Methodology, Results and Conclusions. Capacity pooling in this research refers to the pooling of the production capacity.

2 Description of Basic Concepts

2.1 Resource Pooling

According to Yu et al. [11], "capacity pooling refers to the consolidation of capacity that resides in multiple facilities into one. In a system without pooling, each facility fulfills its own demand relying solely on its capacity." Inventory pooling is described in same manner by Wong et al. [20] as "inter-company cooperation where the cooperating companies share their inventories, is an effective strategy to improve a company's logistical performance without requiring any additional cost. Cooperation usually takes the form of lateral transshipments (LT) from a location with a surplus of on-hand inventory to a location that faces a stock-out". As understood from Yu et al. description, pooling of resources including inventory may also be implemented in an intra-organizational setting, where a company reduces its variety of products (e.g. iPhone which works both for AT&T and Verizon) or centralizes its warehousing to reduce its safety stock (cost) and simultaneously improve its response time (however, according to literature the simultaneous cost cutting and improved response time is not always the case). Introduction of a centralized location imposes the additional transportation in case of inventory pooling which might increase the response time [15].

The literature on the subject of inventory and capacity pooling is extensive. Since Eppen [13] introduced benefits of a centralized inventory pool, the body of knowledge around it expanded ever since. Various papers are dedicated on solving the issues regarding the cost sharing in inter-organizational context while others studied the potential benefits of inventory and capacity pooling in different demand settings and demand correlations impact the pooling outcome [17]. Moreover, studies have been conducted to enable the airlines to take advantage of this concept and reduce their inventory costs [2]. A comprehensive review of literature regarding the capacity and inventory pooling is presented in Yu et al. [11] work.

Reviewing the literature regarding the benefits of pooling policies in operations management, suggests that gained benefits are improved customer response time, reduction in total system cost (reduced safety stock and lower overheads) and simplification of inventory control and production process [13, 15].

Among the companies which have implemented resource (inventory or production capacity) pooling, we can refer to KLM, SAS, Swissair, UTA (as KSSU consortium) and Air France, Alitalia, Iberia and Lufthansa (as Atlas consortium) in commercial aviation industry; Amazon, Google intra-organizational cloud services, Fujitsu and AMD flash memory production, Acer, IBM, Compaq assembling their computers in same plant in 1990's; Isuzu, General Motors diesel engine plant. Moreover, organizations such as hospitals and public sector also take advantage of resource pooling in their operations [2, 14].

Resource pooling in an inter-organizational setting is rather more challenging because of two reasons. First, all parties attending the pool should benefit in a balanced manner from their participation; otherwise taking part in the pool will not be rational [28]. Competitive behavior of pool partners will likely derail this effort. Second, cost sharing in a pool needs to be sorted out through an initial agreement to keep the pool functioning [1]. For instance, literature suggests that sizable airlines tend to keep their own inventory management operations and not taking part in spare parts inventory pools consisting of smaller companies [2].

2.2 Additive Manufacturing

A growing branch of direct digital manufacturing technologies which implements layers deposition or solidification technics to objectify theoretically any intended item. AM is increasingly being used as final parts production system [24]. Currently, main obstacles for a wider industrial implementation are related to limitations in the range of raw material availability, production phase, product finish and physical size limitations (especially for the metal AM). On the other hand, AM offers several unique features which are the forces behind its growth. According to Holmström et al. [5] geometrical complexities are not costlier to produce nor difficult, which means enabling design for performance concept (is highly valuable for industries such as aerospace that extra weight equals extra lifecycle costs). In AM, the economies of scale does not hold as there is no need for tooling therefore producing individually customized parts is not more resource intensive than producing batches of standard parts (the main cost drivers while calculating the parts' value are time and material expenditure).

2.3 Literature Gap

There exist various studies which explore the benefits and limitations of production capacity pooling. Jain [10] studied the impact of varieties of demand on the value of capacity pooling. Benjaafar et al. [12] investigated the differences between benefits of capacity pooling and inventory pooling.

Holmström et al. [5] in their study, briefly pointed out the benefits and shortcomings of capacity pooling while AM is implemented. The fact that AM capacity is not limited to specific use and might be utilized to produce any part if the material requirements are matched is pointed out. Moreover, concerns regarding the quality of produced parts and availability of pooled capacity when is needed, has been discussed. Khajavi et al. [6], provides an example of distributed AM implementation and illustrates the feasibility of high excess capacity in that setting. In this work, we investigate this matter more in-depth. Answering the following research questions will help us fulfill this goal. "What are the advantages and limitations of AM production capacity pooling?"

3 Methodology

The methodology chosen for this research is conceptual and theoretical analysis through the study of similar phenomenon in other industries [23]. We chose airlines industry and cloud computing as two of the fields where practice of capacity pooling has been implemented before. The main sources of our data are secondary data in the form of journal articles, books and websites which provide relevant material on inventory pooling practices as well as production capacity pooling instances and AM. The search keywords that used to find the research material in the library and internet data bases are as follows; Inventory pooling, capacity pooling, production capacity pooling, pooling benefits, AM pooling, rapid manufacturing pooling.

The main reason for the selection of conceptual and theoretical methodology is the current lack of empirical case data in this specific field. This is due to the position of AM at early stages of its lifecycle as a functional parts production technology.

4 Advantages and Limitations of AM Capacity Pooling

4.1 AM Capacity Pool Types

An AM enabled capacity sharing may take place as companies with implemented machines starting to share their unused capacity under different types of agreement. Or it might take place as an OEM or A third party service provider configures a network of 3D printing machines to provide production capacity as a service [5]. The former concept is similar to peer to peer (P2P) network concept which users utilize their peers' excess bandwidth for sharing data among each other without utilizing servers as their connection nodes [29]. On the other hand, the latter concept of AM capacity sharing is comparable to Amazon company business model of providing cloud services (computing, storage and bandwidth) to many customers through its pool of datacenters.

In P2P capacity pooling, companies with excess AM production capacity, tend to participate in the pooling network if they get compensated for that or they require more capacity in geographical locations which other members are present in [6]. Moreover, the size and reach of a company will potentially be effective in inter-organizational agreements. In this scenario, as for the inventory pooling in airline industry, the biggest players tend to acquire or construct their own networked capacity pool and not get involved into pooling arrangements with smaller players [2, 27] (e.g.: GE aviation acquisition of Morris technologies and Rapid Quality manufacturing AM facilities [24]).

In a third-party capacity provision setting, each client company might be active in a different industry and a distinct geographical location which makes it difficult for the service provider to establish a centralized production facility trying to serve all the locations from there. Thus, it can take advantage of production distribution [5] and locate the AM machines in optimal proximities to customers' facilities in order to be profitable and provide high service levels, quicker [6]. This strategy requires the firm to be agile and reconfigure its network or add new machines to the network while adding new clients.

4.2 Higher Flexibility

In general, one of the advantages of AM capacity pooling over inventory pooling is flexibility of use. Meaning that, it can be dedicated to produce any part as long as the material and quality requirements of machines and parts are matched [21]. In traditional inventory pooling companies tend to share their excessive resources including the fast or slow-moving parts. Hence inventory pooling is just limited to surplus units in same industries and often exact same stock keeping units (SKUs). However, in an AM enabled capacity pooling scenario, not only companies in different industries can cooperate to form the pool, also the need for companies to hold high safety stock levels for slow moving parts will vanish. This means that companies will be able to take advantage of postponement strategy by delaying the production of required parts until there is a need for them [22]. In the latter strategy, capacity pool reduces spare parts inventory carrying cost while increasing raw material holding, possible post production process and testing expenses.

In an AM enabled spare parts supply chain for F-18 Super Hornet airplanes, simulation showed while current AM machines are not ideal for a distributed production, future developments might trigger cost efficiency with high level of spare capacity in decentralized setting. In F-18 aircraft case, centralized production of spare parts yielded about 5% excess capacity while the distributed production resulted in excess capacity of 75% [6]. The numbers are large and illustrate how local manufacturing of parts save time and consequently cost in an aerospace spare parts provision, while at the same time resulting in a buffer available for pooling.

4.3 Reduced Transportation

Another advantage of this technology which was concisely discussed, is the reduced necessity for transshipments [5]. In contrast to a centralized inventory capacity, this strategy is more similar to virtually centralized inventory pool but with obvious advantages. In a virtual inventory if the part does not exist at the inventory branch near the market there is a need for transshipment of the part from the other closest branch which possesses the part [16]. However, in AM capacity pool, this transshipment will not exist if all of the parts and machines are compatible and the pool (among peers or provided by third party) is located in various geographical locations close to markets [6]. This may translate to independent operation of each network node and higher focus on local responsiveness.

4.4 Division of Cost

Cost allocation strategy is an important matter which needs to be aligned before the implementation of a pooling policy [1]. Obviously, all parties involved in the pool intend to alleviate their inventory costs lower than the scenario in which they solely manage their inventories. However, existence of competitive or cooperative tactics leads to different outcomes. Situations which a company puts its own interests on higher priority at the expense of others [3]; or in cooperative scenarios that all of the companies tend to reduce their costs to a lower level than their individual operation levels, while also keeping the other players cost reduction intentions in-check [4]. These characteristics in a pooling scheme bring up two major types of inventory pooling decision making polices: centralized and decentralized. In AM capacity pool, a decentralized decision making on cost allocation might prove to be more effective as each node of the network is more accurately possesses its production schedule [9]. The cost sharing for AM capacity also might be based on machines' production hours and consumed raw materials [18]. A pooled capacity might happen to be one slot among a number of parts produced at once in a production chamber.

4.5 Matching Material, Process, Skill

AM advantages come with its costs and limitations. The availability of exact same material and production process as well as testing requirements (which were briefly discussed before) are among the obvious issues [18]. For instance, since there exist various AM production methods, and each method differs from others in the utilized raw material and output properties [21], therefore, pool should possess a balanced number and types of machines as well as inventory of required materials. Moreover, for the testing process, suitable machinery or skilled workforce might become a bottleneck.

4.6 Intellectual Property Rights

Another concern over AM capacity pooling comes from intellectual property rights aspect. While acquiring parts from a capacity pool of an original equipment manufacturer (OEM) might not touch on this subject, spare parts production through third party AM providers or P2P networks is more complex. The IPR and reliability complexities is related to an OEM reluctance to provide the customers with the products' spare parts digital blue prints [27] or the warranty and also realization of liable party in case of part or system failure. From this perspective AM enabled capacity pooling is more difficult to establish than inventory pools. One obvious solution might emerge from OEMs licensing third party service providers and simplify the process for the customer.

5 Conclusions

As AM is slowly gaining foothold as a final parts production method, illustration of its potential managerial implication becomes essential. In this research, we compared the traditional inventory and capacity pooling benefits and limitations to an AM enabled capacity pooling in spare parts provision context. The traditional pooling has proved to be effective in improving companies' efficiencies in many cases. Reducing safety stock which leads to lower costs and commonly (but not always) improved service levels has been observed by the researchers as the positive benefits of pooling strategies. However, one of the important challenges realized to be cost sharing strategies among pool members. In this article which is a conceptual paper based on literature case reviews, we described peer to peer type AM capacity pooling and third-party pools and illustrate their differences. Consequently, the major advantages of AM pooling were explained.

Flexibility of AM capacity which enables production pools among companies in different industries as the parts are not limited by forms long as the print is not started. In a distributed AM capacity pool, this will lead to reduced transshipments and safety stock for slow moving parts. On the other hand, the need for raw material inventories, material and process matching, post production activities and IPR complexities are the most important challenges in front of AM capacity pooling.

This is important to be pointed out that, AM currently is most suitable while the parts are small and have complex geometries and also needed to be produced in limited production batches. The production configuration of choice is centralized since machines are expensive, labor intensive and provide rather low production rates. However, the potential for a distributed AM production systems in the future is irrefutable. Hence this study provides the stepping stone for the research in AM distributed production configuration to prepare managers for probable changes.

This article's limitations have their roots in the discussed facts regarding the lack or handful number of available cases in AM final products implementations; however, we utilized the literature to close the gap to the reality. For future research, cost analysis comparing AM enabled capacity pooling to inventory pooling, empirical study of the findings and also IPR strategizing in AM pooling context are worthwhile topics. Moreover, as an arena for the future research we also propose four scenarios to be compared with one another in an empirical setting which are as follows: Inventory pooling managed by participants (Base case scenario 1), inventory pooling managed by third party (Scenario 2), capacity pooling by the participants (Scenario 3) and third party managed capacity pool (Scenario 4).

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Modeling Lateness for Workstations with Setup Cycles

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Abstract. Sequence-dependent setup times force companies to bundle similar products to avoid setup efforts. While this increases the output rate the schedule reliability tends to decrease due to the sequence deviations enfaced by this sequencing policy. Our paper presents a model to predict the impact of different strategies for setup-optimized sequencing and their actuating variables on the sequence deviation. Through this it enables a positioning in the trade-off between a high output rate and a high schedule reliability.

Keywords: Sequence-dependent setup times · Manufacturing control · Production planning and control · Schedule reliability

1 Introduction

An important objective of manufacturing companies is the reduction of setup efforts since high setup times negatively influence a workstation's productivity and flexibility. Two scenarios of setup times can be distinguished. In the first one, the setup time of the next order is independent from the currently processed order. In the second case, setup times depend on the predecessor of the currently processed job and are hence called sequence-dependent setup times [1].

Independent from the industry, companies often face the challenge of sequencing with sequence-dependent setup times at some of the workstations. Bundling similar orders in setup families and defining a repetitive pattern for a cyclic production of these families has become common practice. A changeover between orders within a setup family requires only minor setup efforts, while the changeover between setup families causes major setup efforts. Whereas the bundling of orders increases the output rate of the workstation, the production schedule is mixed up, as orders are either accelerated or delayed. Delayed orders negatively influence the delivery reliability which is the logistic objective mainly perceived by the customer. Orders which are finished too early increase inventory costs of the company [2].

Figure 1 shows exemplarily the principle of building setup cycles. A FIFO (First-In-First-Out) processing sequence would require five major setups while the bundling reduces the amount to two major setup efforts. The potential for building setup families is also influenced by the WIP (work in process) level at the workstation: The higher the WIP level, the higher is the potential for bundling but also the resulting turbulences in the production schedule. Thus, companies with sequence-dependent setup times are in

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a trade-off between a high output rate, low WIP levels and a low variance of output lateness at the same time.

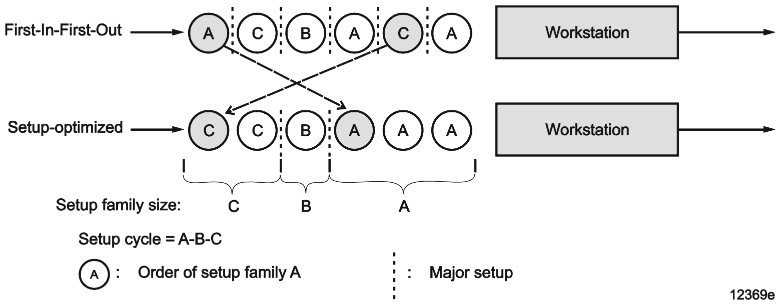

Fig. 1. Principle of building setup cycles

This paper is structured in five sections. After an introduction, we present the current state of research, on which the model presented in section three is based. Section four gives recommendations for a logistic positioning in the before mentioned trade-off. The last section gives a brief summary of the paper and an outlook on planned research.

2 Current State of Research

2.1 Modeling Output Lateness

Output lateness is the deviation of the actual and the planned end of order processing [3]:

$$L_{out} = EDO_{act} - EDO_{plan} \tag{1}$$

where L_{out} is the output lateness (shop calendar days (SCD)), EDO_{act} the actual end of order processing (SCD) and EDO_{plan} the planned end of order processing (SCD).

Hence, a positive output lateness indicates a late completion of an order and a negative lateness an early completion. Schedule reliability is defined as the percentage of orders that is manufactured within a defined lateness tolerance [4]:

$$SR = \frac{NO \text{ with } L_{out,ll} \leq L_{out} \leq L_{out,ul}}{NO} \cdot 100 \tag{2}$$

where SR is the schedule reliability (%), NO the number of orders (−), $L_{out,ll}$ the lower limit for permissible output lateness (SCD), L_{out} the output lateness (SCD) and $L_{out,ul}$ the upper limit for permissible output lateness (SCD).

There are mainly two factors influencing schedule reliability: backlog and sequence deviation [2]. Backlog influences the mean value of output lateness while sequence deviation determines its standard deviation [5, 6]. The mean lateness is the ratio between the mean backlog and the mean output rate [4]:

$$L_{out,m} = \frac{BLO_m}{ROUTO_m} \tag{3}$$

where $L_{out,m}$ is the mean output lateness (SCD), BLO_m the mean backlog (−) and $ROUTO_m$ the mean output rate (orders/SCD).

By definition, the mean lateness does not reflect the effect of sequence deviations of single orders on output lateness. Sequence deviations are defined as [7]:

$$SDO_i = rankO_{act,i} - rankO_{plan,i} \tag{4}$$

where SDO_i is the sequence deviation of order i (−), $rankO_{act,i}$ the actual rank of order i (−) and $rankO_{plan,i}$ the planned rank of order i (−).

The rank of an order is determined by sorting the orders by their completion date and ranking them with consecutive numbers. The orders are sorted by their planned completion date to define the planned rank and by their actual completion date for the actual rank. Sequence-dependent lateness is then calculated by dividing the sequence deviation of an order by the planned output rate [5]:

$$L_{out,SD} = \frac{SDO_i}{ROUTO_{plan}} \tag{5}$$

where $L_{out,SD}$ is the sequence-dependent output lateness (SCD), SDO_i the sequence deviation of order i (−) and $ROUTO_{plan}$ the planned output rate (orders/SCD).

2.2 Modeling Output Lateness due to Setup-Optimized Sequencing

As mentioned in Sect. 2.1, lateness can be partitioned in the two parts lateness due to sequence deviations and lateness due to backlog. In preliminary studies we focused on the forecast of the output rate resulting from setup-optimized sequencing [8]. Thus, we assume that output rate is forecast reliably. The only remaining influence on lateness is the sequence deviation and hence the standard deviation of lateness. The mean value of output lateness is zero.

Literature basically differentiates between class exhaustion and truncation rules for sequencing. Class exhaustion means the workstation will not change to another setup family as long as there are orders of the currently processed setup family in the queue. Truncation rules permit the changeover to another family while there are still orders of the currently produced family in the queue [9].

Eilmann et al. investigate different setup-optimized sequencing rules and their influence on productivity and standard deviation of throughput times. Scheduling with constant throughput times means the standard deviation of throughput times equals the standard deviation of output lateness. A FIFO sequencing results in the lowest productivity but also the lowest standard deviation of throughput times. Class exhaustion leads to the highest productivity but also increases standard deviation of throughput times. The authors also investigate the productivity of a truncation rule but do not show its effect on standard deviation of throughput times [10].

Bertsch investigates the effect of setup-optimized sequencing on output lateness. His strategy is to prioritize the setup family with the lowest ratio of setup effort and number of orders in the queue. To forecast the standard deviation of lateness due to setup-optimized sequencing he uses the same model as for a random sequence. The standard deviation increases with a higher WIP level and a higher number of setup families. The applied model works well as an approximation but the lower the number of setup families and the higher the WIP level at the workstation is, the higher is the difference between the forecast and simulated standard deviation [11].

Sawicki compares different class exhaustion rules with truncation rules in terms of tardiness. He also investigates the application of different setup family sequences. His results suggest that usually class exhaustion performs best while specific values for parameters of truncation rules outperform class exhaustion [12].

All above mentioned authors explain the effects of certain setup-optimized sequencing rules on lateness mostly based on simulation experiments. The authors neither model the influence of sequence-dependent setup times nor do they give recommendations for a positioning in the trade-off. Also most authors did not analyze the interdependency between the WIP level and configuration of the sequencing rules.

3 Sequence Deviation due to Setup Cycles

3.1 Strategies for Setup-Optimized Sequencing

The heuristic of class exhaustion is often suggested by literature for sequencing at workstations with sequence-dependent setup times. Its application is easy and for the sake of a higher output rate scattering throughput times are usually accepted. Class exhaustion, as it is referred to in this paper, means that a setup family will be produced until there is no order belonging to this family left in the waiting queue of the workstation.

Another strategy for setup-optimized sequencing is a truncation rule that fixes a maximum number of bundled orders without preventing the workstation setting up for the next setup family. A cyclic order is fixed for both strategies (e.g. A–B–C) to decide which setup family is produced next without taking due dates into account.

3.2 Sequence Deviations

Figure 2 left shows how the maximum sequence deviation is caused when applying class exhaustion with the help of an example. In the worst case, order A arrives when the workstation has just begun the setup for family B. Hence, the order has to wait until all the other setup families have been produced. Due to a random distribution of setup families in the WIP, the time for the production of all families, which is denoted as the setup cycle time in the following, varies for each setup cycle. As a consequence, also the waiting time varies for each setup cycle. The figure shows a situation with 6 orders in the waiting queue of the workstation. A new order will arrive at the workstation each time the processing of an order is completed.

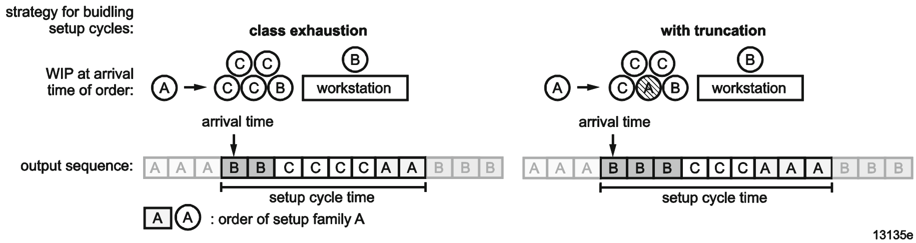

Fig. 2. Sequence deviation caused by setup cycles

Figure 2 right shows the effect of the truncation rule on sequence deviations. If an order of setup family A arrives when the workstation just started producing setup family B the order will wait at least until all other setup families have been produced. The upper limit causes the workstation to stop producing a setup family although further orders of the currently produced setup family could be present in the waiting queue (shaded order A in Fig. 2). In this case the waiting time for this order increases steeply by at least one setup cycle while the throughput times of orders of the other setup families are slightly reduced. With an upper limit maximum sequence deviations are not only defined by the length of one setup cycle but also by the amount of orders present in the waiting queue.

The assumption is that in a job shop production the production schedule is made with constant planned throughput times which are independent from a setup-optimized sequence. This FIFO scheduling considers the WIP level and thus the planned rank of an order is increased by orders in the waiting queue which, according to the plan, would be processed before. If an order is processed within one setup cycle the maximum sequence deviation is only determined by the amount of orders processed until its respective setup family is produced. This equals the time of the current setup cycle less the size of the order's setup family in the current cycle. The setup cycle time is counted from the last production of the respective setup family. Thus, the maximum sequence deviation is:

$$SDO_{max,i} = TSC - SSF_i - WIPO \tag{6}$$

where $SDO_{max,i}$ is the maximum sequence deviation of an order belonging to setup family i (–), TSC the setup cycle time (–), SSF_i the setup family size of setup family i in current setup cycle (–) and WIPO the work in process in number of orders (–).

Since the setup cycle length increases with a higher WIP level, the maximum sequence deviation increases simultaneously. In contrast, the *minimum* sequence deviation is only determined by the WIP level at the workstation. An order is able to overtake maximally the whole WIP:

$$SDO_{min,i} = 1 - WIPO \tag{7}$$

where $SDO_{min,i}$ is the minimum sequence deviation of an order belonging to setup family i (–) and WIPO the work in process in number of orders (–).

The absolute value of the minimum sequence deviation linearly increases with the WIP level. As arriving orders are randomly distributed beneath the setup families, the setup cycle time highly varies depending on the amount of bundled orders. As a consequence, the maximum possible delay of an order scatters. Simulation experiments with class exhaustion have been conducted to evaluate the relationship between setup cycle time and sequence deviation. Figure 3 shows the results of a simulation run with a WIPO of 20 orders. All measured sequence deviations are located within the limits determined by Eqs. 6 and 7.

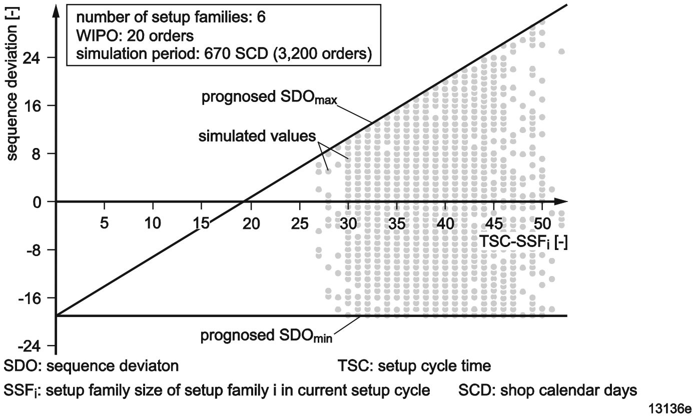

Fig. 3. Sequence deviation for setup cycles with class exhaustion

4 Recommendations for a Logistic Positioning

4.1 Output Lateness due to Setup Cycles

Assuming a random input sequence of orders, the setup family size depends on the WIP level at the workstation. The higher the WIP level the higher is the mean setup family size and thus, the higher the output rate of the workstation [8].

Figure 4 left shows the output rate for the two investigated strategies. With class exhaustion, the output rate constantly increases with a higher WIP level while the truncation rule cuts the output rate increase as soon as the maximum setup family size is reached. The standard deviation of output lateness linearly increases with the WIP level. The reason is that the absolute value of both the maximum and the minimum sequence deviation increase with a higher WIP level (Eq. 7). Class exhaustion results in a slightly lower standard deviation than truncation rules since orders are never delayed beyond one setup cycle. The truncation rule leads to the effect that an order is occasionally delayed beyond one setup cycle.

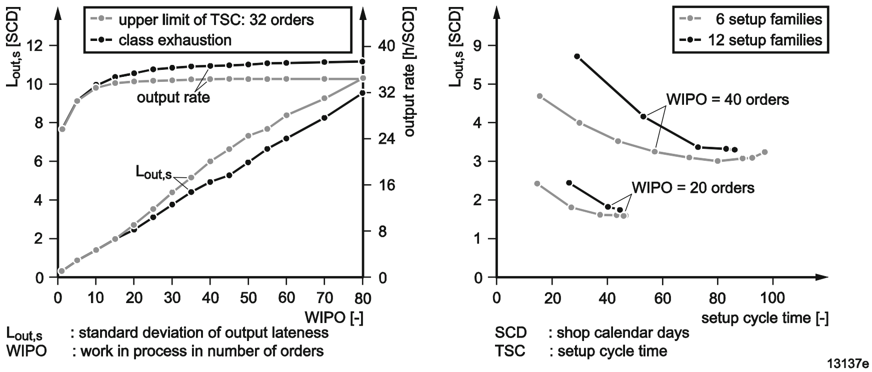

Fig. 4. Standard deviation of output lateness with setup cycles as a function of WIPO (left) and as a function of setup cycle time and number of setup families (right)

Figure 4 right shows the influence of the number of setup families on the standard deviation of output lateness when the truncation rule is applied. With the same setup cycle time a higher number of setup families causes a higher standard deviation of output lateness. With 12 families the sizes of the single families are lower than with 6 families so the production is cancelled earlier and orders have to wait while 11 other families are processed. Depending on the WIP level, the maximum setup cycle time converges towards a certain value which equals the setup cycle time reached by class exhaustion. With a WIP level of 20 orders the setup cycle time of approx. 46 orders cannot be exceeded.

4.2 Recommendations for a Logistic Positioning

Results show that an active planning is required to limit the standard deviation of sequence deviation and thereby avoiding the delay of orders beyond one setup cycle. A higher WIP level results in a higher standard deviation of sequence deviation for both investigated strategies for setup-optimized sequencing. Although results imply that class exhaustion leads both to a higher output rate and a lower standard deviation, the sequence deviation cause by class exhaustion is often still too high to declare it a systematic sequencing rule.

Applying class exhaustion means that mean setup cycle times only depend on the prevalent WIP level at the workstation. The higher the WIP level, the higher is the reached output rate but also the resulting standard deviation of sequence deviation (see Fig. 4 left). In contrast, the truncation rule has two control parameters: the WIP level and the upper limit for the setup family size. In general, increasing the WIP level offers the potential for a longer setup cycle time. However, if low values for the maximum setup family sizes are fixed, the production of a setup family is cancelled early. This leads to high waiting times for some orders of one or even two setup cycles.

Setup-optimized sequencing has the advantage of increasing a workstation's output rate. Nevertheless, sequencing heuristics not considering the orders' due dates increase the standard deviation of output lateness and thereby deteriorate schedule reliability.

Applying simple sequencing rules as presented in this paper and investigated by above mentioned authors [10–12] has a rather negative influence on schedule reliability.

However, if one of the two investigated sequencing rules should be applied, class exhaustion is the more preferable rule as it reaches a higher output rate with a lower standard deviation of output lateness (Fig. 4 left).

5 Summary and Outlook

This paper explains the influence of two different setup-optimized sequencing rules on output lateness: class exhaustion and sequencing with a truncation of setup family sizes. These rules affect the standard deviation of sequence deviation or output lateness respectively.

Standard deviation caused by class exhaustion linearly increases with the WIP level because a higher number of orders is bundled and thus the potential of mixing up the schedule increases. Sequencing with truncation leads to a disproportionately high increase of the standard deviation with the WIP level. The reason is that the production of a setup family is stopped although orders of the respective family are waiting in the queue. These orders will thus wait at least one whole setup cycle until being processed.

In summary, the application of sequencing heuristics to increase output rate or productivity of a workstation with sequence-dependent setup times without taking due dates into consideration crucially worsens schedule reliability.

Currently, it is planned to develop an easily applicable sequencing rule which takes not only the increase of output rate but also the orders' due dates into account. Thereby, it is guaranteed that setup-optimized sequencing has a positive influence on the output rate while only insignificantly worsening the schedule reliability.

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A Nested Configuration of POLCA and Generic Kanban in a High Product Mix Manufacturing System

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Abstract. The work presented in this paper is part of a project aimed at streamlining and improving the process flow at a leather furniture manufacturing company. The manufacturing throughput time is highly variable, and this makes planning difficult for the assembly of components at the downstream stages. Throughput time predictability at the upstream stages where the components are manufactured would facilitate the planning of their assembly according to their expected arrival times for specific product models. Research conducted in a previous phase of the project showed that the application of the CONstant Work In Progress (CONWIP) control mechanism to regulate inventory yielded significant improvements in the throughput time's mean and variation. However, as it is the case with tighter control of inventory in manufacturing, previously unrealised problems were exposed in relation to the selection of the product model to release into the CONWIP loop. This has significant impact on the balance of the distribution of workload across the system's workstations and among the multi-skilled teams at one of the workstations.

This research implements a nested configuration of the Paired-cell Overlapping Loop Of Cards with Authorisation (POLCA) and the Generic Kanban control mechanisms to achieve a balance of the workloads. This ensures a synchronised flow of the different product mix through the entire manufacturing system.

Keywords: POLCA · Generic Kanban · High-mix manufacturing

1 Introduction

The research presented in this paper is part of a project titled SØM4.0, which is aimed at streamlining and improving the process flow at a furniture manufacturing company. The manufacturing throughput time is significantly higher than the value adding time, and it is highly variable, which makes planning difficult for the downstream assembly of the components produced. In a previous phase of the project, in which CONWIP control mechanism was applied to regulate system inventory and a sequencing rule to control production at the workstations, significant improvements were achieved in the throughput time's mean and its variation [1, 2]. However, as it is the case with tighter control of inventory in manufacturing, previously unrealised problems were exposed in

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relation to the selection of the product model to release into the CONWIP loop. This has significant impact on the balance of the distribution of workload across the system's workstations and among the operator teams at one of the workstations.

The aim of the research reported here is to implement a production control mechanism that would provide a balance of workload, both across the system's workstations and among the operator teams. This would ensure a synchronised flow of the different product mix through the system. The rest of the paper is organised as follows. In the next section (Sect. 2), the case study company's challenges are described in more detail. In Sect. 3, related production control mechanisms that have been applied to address similar challenges are reviewed and discussed. Section 4 will describe a concept for achieving workload balance through a nested configuration of control mechanisms in the case study system. Finally, Sect. 5 will provide insights and discussions on the nested configuration concept, by presenting its potential benefits and establishing grounds for future work to investigate the concept further.

2 Overview of Case Study System

The case study company is a typical example of high-mix production. The product line consists of 36 different models, most of which are offered in two or three different sizes (small, medium and large). Additionally, each model size is offered in fabric or leather material, which can also come in different variety of colours and material textures. The product differentiation starts right from the first production step, where the model design and materials are configured specifically for a product.

The materials for the furniture are cut in Step 1 (S1) followed by them undergoing variety of sewing operations between Steps 2 and 10 (i.e. S2 to S10). S1 is the cutting section, while S2-S10 constitute the sewing section. Semi-finished items from the sewing section undergo subsequent finishing processes, followed by assembly with foam, wood and steel components to derive the finished furniture. This work focuses on the sewing section, which has the most labour intensive and value-adding processes of the whole production. The routing possibilities through these processing steps differ from one product model to another, as shown in Fig. 1.

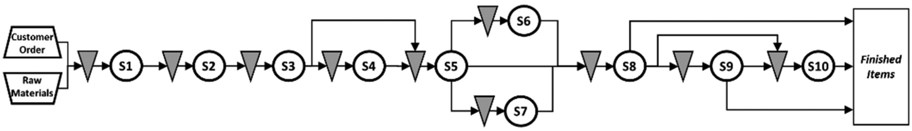

Fig. 1. Process flow chart

2.1 Background

The company previously applied a Push control mechanism to release items from the cutting into the sewing section, followed by applying a first in first out (FIFO) rule to sequence their processing at the workstations. Barring any capacity constraints, this should ensure that the products are completed as planned in the production order.

However, the direct release of semi-finished items from the cutting section into the sewing section created a constant need for human intervention to re-sequence and reshuffle the in-process items. A person had to monitor the workloads at the different operator teams and redistribute waiting items to balance the workload.

To overcome the problem highlighted above, a CONWIP control was implemented in the sewing section to limit the volume of work in progress (WIP) in the section, with an intermediate buffer also created between the two sections. The lower amount of WIP, judging by Little's law [3], reduced the throughput time [1, 2]. The intermediate buffer served decoupling purposes between the flow of items out of the cutting section and their release into the sewing section. As a result, the resequencing of items became easier, as the number of items that had to be re-sequenced reduced, and the level of *chaos* in the sewing section reduced.

However, although the lower WIP level reduced the effort needed for reshuffling, it did not ensure a balanced workload distribution among the operator teams at S8. The release of items from the intermediate buffer into the sewing section did not consider the current workload for the operator teams, as the logic of the CONWIP mechanism does not entail this information. Prior to the implementation of the CONWIP, there were excessive items in the sewing section which ensured that the workstations and operator teams were consistently utilised. With the CONWIP, it became necessary to ensure that the limited number of items released into the sewing section consisted of a balanced distribution of workload across the workstations and among the operator teams at S8.

Making use of additional information, such as the capacity availability and the level of inventory downstream, can significantly improve item release decisions. And, as reported in a previous study, the release method into a system is more crucial than the sequencing or prioritisation rule at individual workstations, such that if the release rule functions well, the setting of sequencing rules for individual workstations becomes less effective or even counterproductive [4]. Hence, the aim of the current work reported here is to implement control mechanisms that will synchronise the release of items into the sewing section with the current state of the downstream workstations, particularly the operator teams at S8. This shares some of the objectives of existing production control mechanisms which are going to be discussed in the next section.

3 Review of Literature on Related Control Mechanisms

The card-based mechanisms that are available in literature can be categorised into unit-based or load-based, depending on if their signal card represents the physical inventory implication or the workload impact of releasing an item for processing. The original card-based mechanism was the traditional Kanban control strategy of Toyota Production System, and it was unit-based [5]. Other unit-based mechanisms are the CONWIP [6], the Generic Kanban [7], the POLCA [8] and many others. Load-based mechanisms adapted workload control concepts [4, 9] into card-based mechanisms. As such, some of the existing load-based mechanisms have retained the same control logic of previously existing unit-based mechanisms, but with load-based interpretation of their cards. Examples of such load-based mechanisms are the Constant Load

(CONLOAD) [10], Control of Balance by Card Based Navigation (COBACABANA) [4] and Load-based POLCA [11], which can be said to be the load-based versions of the CONWIP, Generic Kanban and the POLCA respectively. The aim of these load-based implementations was to take into account that different products might have different workload impacts on a manufacturing resource, especially in high-mix systems in which the processing time requirements of the system's products vary significantly. Unit-based mechanisms, on the other hand, would not quantify the difference in the workload impacts of releasing a unit of a short processing time and a high processing time product into a system.

However, load-based mechanisms are generally less used than unit-based mechanisms, because of challenges that have to do with accurate quantification of the load impact of released item units, as well as the complexity of their software and hardware requirements for implementation and execution [12]. As evident in the COBACABANA, for which two methods of representing workload have been reported [4, 13], it can be difficult to find a trade-off between requiring many cards to precisely represent different product workload ranges and reducing the number of cards with the implication of a less precise load representation.

In addition to the adaptation of workload regulation concepts in card-based mechanisms, modifications have been made to their card transmission logics in order to overcome their limitations in non-repetitive, dynamic environments. This is because it is often easier to adapt a control mechanism to an environment – even if it results in some loss of effectiveness – than to adapt the environment to the mechanism [7]. Some of the common modifications are the use of generic (or centralised) control of cards as found in the Generic Kanban and the Generic POLCA, which are adaptations from the traditional Kanban and POLCA respectively. In the original control mechanisms, an item obtains the authorisation cards for processing at the workstations one at a time; while in the generic adaptations, an item must obtain all the authorisation cards it requires for its processing steps before it is released into the system. The aim is to ensure that there is available capacity at all the stages at which it is to be processed, before it is released at all into the system. Hence, once an item is released, subsequent queueing in between downstream stages is minimised, as it does not have to wait for authorisation cards. As a consequence, the system inventory level is reduced and replaced with card inventories instead. Another benefit of the generic control of authorisations cards is that it makes the control mechanisms applicable to systems with flexible routing, since each product model can dynamically select the cards for the workstations that belong in its route.

However, the global control of cards, can lead to blocking in high-mix systems in which products have different routing possibilities. Because items obtain all the cards for the workstations along their routes before being released into the system, it could become a problem for other products. If for any reason, an item becomes stuck at an upstream workstation that it does not share with other items, it will continue to hold on to downstream authorisation cards that could be directly used by other items that are processed through different upstream workstations. This could lead to starvation of the downstream workstations, if there is no card available to authorise the release of those other items. Methods, such as continuous monitoring and direct release of items to starving workstations – even if it violates their workload limits [14] – and the differentiation of indirect from direct load [15], have been proposed to avoid this problem. The problem has been described as premature idleness of the downstream stations, in other studies on divergent systems [13]. Another study suggests setting a proper load limit at critical points in order to avoid the problem [12].

4 Nested Implementation of Multiple Control Mechanisms

Based on the above, it is clear that control mechanisms, such as Generic Kanban, GPOLCA and COBACABANA, that operate generic control of cards cannot be applied in the type of highly variable routing system of this work. However, it is possible to apply elements of the Generic Kanban, in a way that takes advantage of its workload-regulating ability, to balance the workload among the operator teams at S8. It has been previously demonstrated that COBACABANA, which has a similar logic to the Generic Kanban, is effective at balancing workload across intermediate stages of a manufacturing system [12]. The Generic Kanban will be applied here to achieve a balanced workload distribution among parallel workstations, i.e. the operator teams at S8.

In a nested configuration of two control mechanisms, the POLCA will be applied across the system, while a Generic Kanban will be used to synchronise the release of items into the system to match the work rate of the operator teams. The steps involved in setting up this nested configuration are as described in the following sub-sections.

4.1 Implementation of POLCA

POLCA has been reported to be suitable for high-mix manufacturing environments in which the traditional Kanban control mechanism would result in the proliferation of inventory. This is because the traditional Kanban control mechanism would need to keep stage level product specific base stock for each of the products produced in the system [16]. POLCA uses its cards to signal the availability of capacity downstream and release parts for processing, unlike the traditional Kanban control mechanism which uses its cards to signal the need for the transfer of a specific part type downstream to fulfil a demand or to replenish stock. POLCA keeps inventory of cards instead of physical parts and, as a result, is able to avoid the need to keep inventory for each specific product type. The above contrasts between the two have only been made to enable the reader understand POLCA within the context of the more widely known traditional Kanban control, and to describe some of the reasons why the traditional Kanban is not being considered in this work.

The first step taken in the implementation of POLCA in the case study system is to identify the possible paired cells formation for the eight different processing routes, as shown in Table 1. As shown in the table, there are between 3 to 5 paired cells that can be formed along each of the routes.

Next, the possible paired cells across the routes are listed along with the routes to which they apply and the total number of such routes, as shown in Table 2. The aim of this information is to ensure that the paired cells are set up with adequate cards to correspond to the number of routes they serve, and the expected production volume of the products processed along the routes. This is because, as earlier discussed in Sect. 3,

Table 1. Paired cells for routes

Paired cells	Routes served	Number of routes served
S2-S3	All	8
S3-S4	R2	1
S3-S5	All, except R2	7
S4-S5	R2	1
S5-S6	R2	1
S5-S7	R3, R5, R8	3
S5-S8	R1, R4, R6, R7	4
S6-S8	R2	1
S7-S8	R3, R5, R8	3
S8-S9	R4, R5, R6	3
S8-S10	R7, R8	2
S9-S10	R6	1

Table 2. Paired cells and routes served

Routes	Steps	Number of paired cells
R1	S2-S3-S5-S8	3
R2	S2-S3-S4-S5-S6-S8	5
R3	S2-S3-S5-S7-S8	4
R4	S2-S3-S5-S8-S9	4
R5	S2-S3-S5-S7-S8-S9	5
R6	S2-S3-S5-S8-S9-S10	5
R7	S2-S3-S5-S8-S10	4
R8	S2-S3-S5-S7-S8-S10	5

setting appropriate card limits at such critical points in the system is important to prevent the possibility of the system becoming blocked.

The card allowance for each paired cells can be determined using the same formula as in [17], but with the incorporation of the average lead time across the different product models that share the paired cells, as well as the expected production volume for all the product models during the planning horizon, as expressed in Eq. (1).

For instance, the number of cards assigned to paired cells S2-S3 will be:

$$Number\ of\ cards\ for\ paired\ cell\ S2 - S3 = (LT_{S2} + LT_{S3}) \times \left(\frac{NUM_{S2,S3}}{D}\right) \quad (1)$$

where LT_{S2} and LT_{S3} are the estimated average lead times for the two cells (workstations) over the planning period of length, D, and $NUM_{S2,S3}$ is the total number of items that go from workstation $S2$ to $S3$ during the same period. Here, this will be the total number across the product models that use the paired cells.

4.2 Implementation of Generic Kanban Control

At this point, the unbalanced workload among the operator teams at S8 has not been directly addressed, even if POLCA's balancing of workload across the system's workstations would have had indirect impact in regulating the flow of items into S8. Therefore, a Generic Kanban control mechanism is implemented to balance the workload among the operator teams. The Generic Kanban operates a global assignment of cards, which are connected to the level of WIP allowed in each team and monitored globally through centralised display boards to determine when new items can be released into the system, and the type of product model to release.

As shown in Table 3, a Generic Kanban board showing the number of free Kanbans available for each of the operator teams is displayed to support the decision on the type of product model to release from the intermediate buffer into the sewing section. This ensures that the planner releases product model types upstream in synchronisation with the work rate of the teams at S8. Therefore, the factors that have to be considered when a new item is to be released into first workstation of the sewing section (i.e. S2) are the availability of a S2-S3 POLCA card and a free Kanban for one of the operator teams that are capable of processing the item. From then on, the progress of an item downstream through its required workstations is controlled locally by the availability of POLCA authorisation cards for the paired cells involved, until the item reaches S8.

Table 3. Card settings and generic kanban display for operator teams

Team	Total number of Kanbans	Kanbans in use	Free Kanbans
A	35	30	5
B	26	26	0
C	28	24	4
D	32	30	2

As earlier described, and as shown in Table 3, there are four operator teams responsible for carrying out the processing required at S8 for the different product models. Each team is capable of processing certain product models only, such that each product model would have between 2-4 teams capable of processing it. The release of an item into the paired cells that connect into S8 (i.e. S5-S8, S6-S8 and S7-S8) will be authorised by the generic Kanban connected to the group that will process the item. This should occur instantaneously, because an item must have obtained the generic Kanban before its release into the sewing section. It can be interpreted as there being four virtual loops that connect into S8 (i.e. to 8A, 8B, 8C and 8D) to authorise the release of items to its operator teams. Once an item has completed processing at S8, its generic Kanban is detached and returned to the centralised Kanban board. On the other hand, the paired cells that connect out of S8 (i.e. S8-S9 and S8-S10) will operate with POLCA cards to authorise the release of items downstream.

5 Insights, Conclusions and Future Work

The step by step practical implementation of POLCA in a case study manufacturing system, which has variable routings and high product mix, gives a good insight to industry practitioners on how POLCA can be implemented in systems with complex product routings. It shows how paired cells can be created from the system's workstations, while reducing the complications resulting from the variety of product routings, or from the common use of the same workstations along multiple product routes.

If physical distance between workstations does not make exchange and synchronisation of cards between paired workstations difficult, then POLCA should be practicable in such systems, as presented in this work.

It has been demonstrated how the benefits of different control mechanisms can be combined in one system, through a nested configuration of POLCA and the Generic Kanban control mechanisms. POLCA alone can deliver a balanced workload distribution across workstations, but combining it with the Generic Kanban control mechanism helps to achieve a balanced distribution of workload among the multi-skilled operator teams. This extends existing knowledge from previous works which have mostly focussed on balancing workload across intermediate workstations of a manufacturing system. It should be mentioned that other concepts, such as Workforce training and Staffing and Balanced product-mix release methods, have been used to achieve workload balance at operations involving teams. However, such static methods would only offer limited solutions to the dynamic change in product mix and routing involved in the system considered here.

The future aim of this research is to implement and optimise the nested POLCA-Generic Kanban configuration, and compare its performance against existing alternatives. Simulation modelling will be applied for this purpose, and existing techniques, such as Evolutionary algorithms and metaheuristics algorithms, which have been successfully applied in Kanban related research, will be applied in optimising its required numbers of POLCA cards and Generic Kanbans.

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Balancing a Mixed-Model Assembly System in the Footwear Industry

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Abstract. Portuguese footwear industry has improved dramatically to become one of the main world players. This work is part of a project in cooperation with a large footwear company, operating a new automated assembly equipment, integrating various lines. Balancing such lines implies going from an almost manual preparation executed by experienced operators, to a planning supported by optimisation systems. These complex mixed-model lines have distinctive characteristics, which make balancing a unique problem. The paper proposes the ASBsm – Assembly System Balancing Solution Method, a new method that integrates a constructive heuristic and an improvement heuristic, which takes inspiration from Tabu Search. The solutions obtained, based on real instances, are quite encouraging when compared with other effected factory solutions. Consequently, the balances obtained by ASBsm are now being implemented and articulated with sequencing methods.

Keywords: Footwear industry · Mixed-model assembly line balancing · Optimisation · Heuristics

1 Introduction

Portugal is one of the major world players in the footwear industry. This is the case because the country has chosen to invest in technology innovation, research, manpower qualification, innovative design and internationalisation. Much has changed, from low-cost mass production to serving clients consisting of small retail chains, where orders are small and models are varied. Consequently, work plans vary frequently and traditional flow lines are steadily being replaced by more flexible and sophisticated systems. The case presented in this paper applies to this context of progress and intends to contribute to solving complex balancing problems arising from the new mixed-model flexible assembly system of an important footwear factory.

Footwear manufacturing typically involves cutting, stitching and assembly processes. This work focuses on stitching lines, which are frequently a bottleneck in this industrial sector. Shoe components are placed inside boxes, usually

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not more than 10 pairs, which move along the lines, between any appropriate workstation. The conveyors also transport them from and to the warehouses.

Each model inside a box requires a set of different tasks, with processing times and specific sequences, represented in graphs – the routings. A workstation (operator and machine) should be assigned to each task. In rapidly changing production plans, managing the lines, is a critical issue. Unsuitable plans will create bottlenecks and starvations; appropriate plans will contribute to better sequences, to a better use of the resources and to competitive advantages.

These problems are known in the literature as Assembly Line Balancing Problems (ALBP). As mentioned in Scholl (1999), these are crucial optimisation problems because they are highly complex and important in real world industries. Saif et al. (2014) divide ALBP into different categories. The problem dealt with here is a Mixed-model ALBP (MALBP), with extra complexities. Scholl and Becker (2006), Tasan and Tunali (2008), Chen et al. (2012) refer to this type of problems and illustrate various objectives such as, minimising the number of workstations, reducing the cycle time, maximising the line efficiency and finding a feasible solution.

The paper is organised as follows: Sect. 2 briefly describes the assembly system and the type of balancing problem. Section 3 proposes a solution method -ASBsm, which incorporates a constructive heuristic and an improvement heuristic inspired in Tabu Search (TS). Section 4 includes the computational results based on real data. Finally, some conclusions are provided in Sect. 5, regarding the feasibility of the method to improve current solutions.

2 The Assembly System Balancing Problem

The Balancing Problem described here is being addressed in ongoing research projects in a large footwear company. The assembly system is a new automated production and transportation system especially designed to deal with the current small amounts of very diverse models and types of demand. It is composed of two separate parts located in distinct places. One of them has four stitching lines, with a set of workstations, and conveyors transporting boxes with the components. The other is a U-shape line without an automated warehouse. Although there are differences between the two types of lines, what is important to emphasize is that the boxes can directly move from a workstation to another, according to the planned sequence of tasks, and, in case of the larger system, between the warehouses and any workstation. Figure 1 illustrates these lines. The main purpose of this work is to devise and implement a new balancing method.

Workstations are composed of machines and operators, whose skills must be taken into consideration. There are special operators who are the only ones with the ability to perform some tasks, which should be preassigned to such operators. Machines are classified according to their types and capability to execute certain tasks. There are different types of machines. Each machine has only one operator, but an operator can work with various machines. Shoe components

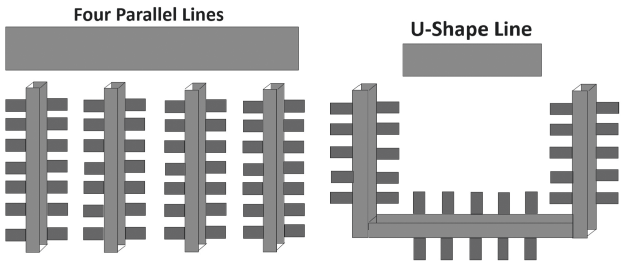

Fig. 1. Different system of stitching lines.

are inside boxes, which are moved by the conveyors. Each box has an associated routing, represented by a graph, defining the operations to be completed in the components and the precedence relations between them. According to the company, balancing involves two main purposes:

Each box has an associated routing, which defines the operations that must be completed in the components and the precedence relations between them. Routings are represented by graphs. In this paper, and according to the company, balancing involves two main purposes:

1. reducing the number of workstations required to complete a known production plan;
2. smoothing operators' workloads.

In the objective function, the weight of each part is analysed taking into consideration their relative importance. This MALBP is unique due to the automated transportation system and the industrial sector.

3 Solution Method: ASBsm

ASBsm integrates two heuristics: a constructive heuristic to generate an initial solution and an improvement heuristic, which is a neighbourhood search procedure inspired by TS. The venture into this method is a consequence of various types of considerations: a new assembly system composed of various stitching lines; reaching a good equilibrium between practical solutions and real modelling limitations; the intrinsic combinatorial complexity of the MALBP; the large dimension of the instances and their unclear data. ASBsm details are presented in the following sections.

3.1 ASBsm: Constructive Heuristic

Production orders of various footwear models are known in advance. The first phase implies the creation of boxes with the shoe parts, usually containing a maximum of 10 sets. The following example with two models A and B, with order quantities of 25 and 20 pairs, respectively, will be used to illustrate the heuristic.

Table 1. Creating boxes and quantities.

Model (j)	Box_{ij}		
	Box (i = 1)	Box (i = 2)	Box (i = 3)
A (j = 1)	10	10	5
B (j = 2)	10	10	-

Table 2. Routings.

Model	Task	Sequence
A	10	2
A	20	1
A	30	3
B	10	1
B	30	2
B	40	3

Table 3. TasModBox matrix.

Box	Model	Task
1	A	20
1	A	10
1	A	30
1	B	10
1	B	30
1	B	40
2	A	20
2	A	10
2	A	30
2	B	10
2	B	30
2	B	40
3	A	20
3	A	10
3	A	30

A possible set of corresponding boxes is in Table 1. Inside each box there are items of the same model, size and colour. Each box has two identifications: The box counter (i) and the model type (j).

The next phase assigns tasks of each box to suitable operators and machines. The heuristic will sort all tasks of all boxes. For that, at the beginning, boxes of all models are ordered. Afterwards, the prior model of the first box is collected (in the example model A of box 1, with the quantity of 10). Then the boxes undergo different tasks according to their sequence and model type. Table 2 shows the sequences. After, next model of the first box is selected (box 1 of B with the quantity 10, in the example) and, when all tasks of all first boxes are listed, then the procedure is repeated for the next boxes until all tasks are sorted in a matrix called $TasModBox$. Table 3 shows the corresponding matrix. For some tasks, there is only one resource available, which leads to a pre-assignment. There are two types of pre-assignment, the first taking into account the operators and the second the machines, as explained below:

1. If only one operator has the ability to perform a specific task, such task must be assigned to him, the workload being updated taking into consideration the processing time of the task multiplied by the amount of boxes. Other tasks can be assigned to that operator if there is enough free time.
2. If a task requires a specific type of machine and only one of those machines exist, it must be selected for that task. Afterwards, if that machine still has enough free time, it may be assigned to other adequate tasks.

After allocating special tasks to the operators and/or machines capable of executing them, the heuristic allocates the remaining tasks. It starts by assigning tasks of $TasModBox$ matrix according to their order and respecting the constraints below:

1. Each task of a model of a box should be assigned to a required operator;
2. Each task of a model of a box should be assigned to exactly one operator;
3. Each task of a model of a box should be assigned to a required machine type;
4. Each task of a model of a box should be assigned to exactly one machine of the required type;
5. Each operator should not work more than an available period of time or defined percentage of the available time;
6. Each machine can only be allocated to one operator;
7. N.er of machines used is less than or equal to a maximum n.er of machines.

After picking a task, the heuristic finds the first operator with the required skill and available time to work on the components in the box; otherwise, it searches for another operator. Next step, it searches for a required type of machine, not yet allocated, repeating the procedure until all tasks are routed. When a task is assigned to an operator and a machine, then a corresponding workstation is created. Quite often Work In Process (WIP) has to be taken into consideration, as there are boxes in the lines, with some tasks already executed. Consequent adaptations of the input data are performed such as updating routings.

3.2 ASBsm: Improvement Heuristic

ASBsm integrates an Improvement Heuristic, which evolves by using different problem adequate neighbourhoods and local search. It takes some inspiration from TS, which has also been applied to solve ALBP (Özcan and Toklui 2009), but not specifically in the footwear industry. The heuristic improves the solutions, not only by local search, but also by promoting diversification. The concept of tabu list shows up when these neighbourhoods are introduced along the procedure.

In order to create appropriate solutions, a careful attempt is made to devise effective neighbourhood structures (Ni), by transferring and swapping a task, or by performing some tasks at once between workstations. All neighbours of a current solution are evaluated and the best one, regarding the objective function, is chosen. The dimension of each neighbourhood structure is related to the instances used. The essentials are explained below.

N1: transfer all tasks of a machine and operator to another machine and the assigned operator;

N2: transfer one task of a machine and operator to another machine and the assigned operator;

N3: transfer tasks of a machine and operator to other machines and the assigned operators one by one (could be more than one machine and operator);

N4: if the first operator works on more than one machine, swap all tasks of a machine and operator with another machine and the assigned operator.

The search progression for all neighbours has similarities and dissimilarities. Two situations may occur for all neighbourhood spaces: in one situation, an occupied machine is selected and if it happens, it is of one type only. The heuristic then looks for another occupied machine of the same type; following this, the goal is to find operators who are assigned to each of the machines. In a second situation, an occupied machine is taken again but it has different types. Then, another occupied machine is chosen, regardless of its types. After that, the operators assigned to both machines are established.

About $N1$, and considering the first situation, if the operator of the second machine has the ability to perform every task in the first machine and has sufficient free time, it is possible to transfer tasks. In the second situation, all assigned tasks of the first machine and operator, one by one, are considered and if the second machine and operator have the ability to perform them and they also have enough free time, tasks can be transferred as well.

In $N2$, the difference to $N1$ is that only one task transferred at each step.

Regarding $N3$, tasks are transferred one by one and if the selected operator and machine do not have enough time, another machine and operator will be chosen to perform the remaining tasks. Therefore, tasks assigned to a machine and operator may be transferred to different machines and operators.

$N4$ essentially follows the previous processes. However, in this case all tasks of both machines will be controlled to see if each machine and operator have the ability and enough free time for new tasks. At the beginning the heuristic looks for operators who have worked on more than one machine.

The computational experiments showed that the neighbourhood structures can have different impacts on both objectives. Table 4 illustrates the best impact for each objective.

Tabu list and Diversification: ASBsm includes a diversification phase to drive the search into new regions by changing the neighbourhood types. After exploring a neighbourhood and the best solution is found, such neighbourhood enters a tabu list, being forbidden for a number of iterations. In the next step, a new neighbourhood is searched. It is expected that other neighbourhoods, with diverse effects, may have the chance to improve the current solution. As there are 4 neighbourhood structures, the length of the tabu list is 2 iterations.

Table 4. Neighbourhoods and objectives.

Reducing N.er worksations	Smoothing workload
N1	–
N2	N2
N3	–
–	N4

Aspiration criterion: If a neighbourhood structure (non-tabu) does not improve the current solution, then an aspiration criterion is employed, overriding a tabu state by resorting to the older element of the list. If again an improvement is not met, then another tabu neighbourhood (first, not recently becoming tabu, then recently being tabu) is applied and examined.

Termination condition: The termination condition is 30 iterations or no improvement occurs during these iterations; then the algorithm ends sooner.

4 Computational Results

This section includes the computational results obtained with ASBsm. The program was implemented in C++ and compiled with Microsoft Visual Studio 2008 and the tests were run on an Intel (R) Core (TM) i5-5200U CPU, with 8 Gb of random access memory. Nine data instances were selected for the tests, taken from the real data available regarding some days. Medium-size (MS) and large-size instances (LS) are respectively related to the U-line and to the system of parallel lines.

Gaps between initial solutions and final solutions were calculated, in order to get an idea of the improvements achieved. Moreover, and as optimal solutions are not known, rough Lower Bounds (LB) on the number of workstations were also obtained. For this, the processing time of each task is calculated, given the requested quantity and, as each task needs a unique machine type, the time required for each type of machine is measured. Without going into detail, since there are machines of different types all possible combinations of machine types are considered. Finally, the LB for the number of workstations is derived by summing the number of workstations required for all machine types.

The extensive company data per day, (an average 230 excel lines for the medium-size up to 1800 for the large size problems) required an algorithm for reading the data and adapting it to the format required by ASBsm. It was also necessary to adapt WIP, which is usually included in the data. The maximum size of the boxes created is 10 (pairs of components). Table 5 summarises the results. The available time depends on the line, varying from 8 h for instances $MS-1$, $MS-1$ and $MS-3$ to 9 h the others.

From Table 5, it is possible to conclude that ASBsm could improve its initial solutions by 22% on average, with a minimum improvement of 9% and a

Table 5. Computational results of MS and LS instances.

Instance	N.er Model	N.er Box	N.er Task	N.er Operator	N.er Machine	Initial Solution				Improved Solution					Lower Bound		
						N.er Operator	N.er Machine	Objective.	Time(s)	N.er Operator	N.er Machine	Objective	Time(s)	Improvement	N.er Workstation	Objective	Gap
MS-1	15	127	15	28	41	14	14	16.14	0.15	9	9	11.14	0.58	31%	8	10.13	9%
MS-2	11	171	10	26	40	9	9	11.06	0.15	8	8	10.04	1.04	9%	7	9.04	10%
MS-3	16	159	15	28	41	12	12	13.96	0.17	9	9	10.89	2.50	22%	8	9.90	9%
MS-4	41	209	30	27	48	15	17	19.33	0.31	10	11	13.29	0.76	31%	9	11.23	16%
LS-1	303	334	70	86	146	59	61	62.81	5.10	46	48	49.80	104.49	21%	42	43.79	12%
LS-2	320	356	62	86	152	58	58	59.81	5.21	48	48	49.79	127.78	17%	42	43.78	12%
LS-3	298	335	68	86	148	64	64	65.77	4.91	45	45	46.76	131.71	29%	43	44.76	4%
LS-4	326	377	73	86	143	64	64	65.67	6.5	52	52	53.64	186.46	18%	45	46.62	13%
LS-5	344	399	69	86	148	63	63	64.81	6.8	48	48	49.80	152.97	23%	43	44.80	10%

maximum of 31%. Concerning LB, the average gap is 11%, with a minimum of 4% and a maximum gap of 16%. ASBsm is fast and can be used for real cases, whenever necessary; the running times are shown in Table 5.

It should be mentioned that some of the results were also tested by simulation to guarantee a successful implementation. However, what is more relevant from the results is the confidence acquired in the new optimisation method ASBsm to deal with the balancing problems accompanying the novel assembly systems of the company.

5 Conclusions

The Portuguese footwear industry combines tradition with cutting-edge technologies, innovative design and an extraordinary export growth. However, much more can be done to optimise some procedures of the main production phases. That is the case addressed in this paper – one of the major companies benefiting from flexible assembly systems but still managing large stitching lines, certainly supported by some automatisms and experienced operators, although without optimisation methods.

This paper specifically addresses the balancing of stitching lines and proposed a solution method – ASBsm, which integrates two heuristics: a constructive heuristic to generate an initial solution and an improvement heuristic, which is a neighbourhood search procedure that takes some inspiration from Tabu Search. The method improves the solutions, not only by local search, but also by promoting diversification by performing alterations on neighbourhoods. Some lower bounds were also considered to help evaluate the solutions. In conclusion, the balancing method has succeeded in computational tests and its results are under implementation and evaluation at the factory to avoid most manual planning.

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Analyzing the Impact of Different Order Policies on the Supply Chain Performance

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Abstract. Influenced by the high dynamic of the markets and the steadily increasing demand for short delivery times the importance of supply chain optimization is growing. In particular, the order process plays a central role in achieving short delivery times and constantly needs to evaluate the trade-off between high inventory and the risk of stock-outs. However, analyzing different order strategies and the influence of various production parameters is difficult to achieve in industrial practice. Therefore, simulations of supply chains are used in order to improve processes in the whole value chain. The objective of this research is to evaluate two different order strategies (t, q, t, S) in a four-stage supply chain. In order to measure the performance of the supply chain the quantity of the backlog will be considered. A Design of Experiments approach is supposed to enhance the significance of the simulation results.

Keywords: Order · Supply chain · System Dynamics · Inventory management · Design of Experiments

1 Introduction

Today, manufacturing companies are confronted with the influences of a dynamic environment and the continuously increasing planning complexity [1]. Reduced time to markets, rising product diversity as well as complex multi-tier and world-spanning supply chains are faced with growing inter-connectivity of production machinery, enterprise resource planning systems and manufacturing execution systems. Due to globalization, the number of market participants rises resulting in a growing competition amongst the individual companies [2].

In order to remain profitable as a business, the industrial enterprises in high-wage countries must identify cost carrier of the production process in order to reduce unnecessary costs. This is why companies focus on the production steps with a high share of added value and reduce the depth of production [3]. A strong trend towards reduced inventory is sensed so that components are delivered "just-in-time" (JIT) for the production. Accordingly, the process of ordering must be designed in a way which ensures a smooth production. As part of inter-company value chains the individual view of ordering is not adequate anymore. Rather, the analysis and optimization of the whole supply chain continues to gain importance [4].

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Considering these problems, companies lack on an efficient design of their order processes. In order to create a better understanding of complex interdependencies in the supply chain a simulation model of a four-stage supply chain was designed (sub-supplier, supplier, manufacturer and customer).

In this research t, q and t, S order policies are going to be implemented in a supply chain model. In order to further investigate the interactions of the parameters in the supply chain, a Design of Experiments approach was used. Hereby, the interactions of the parameters are investigated and principles how to design an efficient supply chain are derived. The emphasis is put on the interplant relation instead of the internal production itself.

The remainder of this paper is organized as follows: First, we give a short introduction about the today's challenges for manufacturing companies and further discuss related work in Sect. 2. Next, we introduce the methodology of System Dynamics in Sect. 3. Section 4 focuses on the description of the simulation model and in Sect. 5 we present the results of predefined simulation scenarios. Finally, we conclude in Sect. 6 and highlight future work.

2 State of the Art

Due to the close link between ordering, inventory management and production a separate analysis of these sections is not sufficient. Thus, the emphasis is put on the optimization of all companies involved in the value-added process (supply chain). To investigate the cooperation and acting of a supply chain various research approaches already exist. In the following, these approaches are outlined.

Moizer et al. (2014) examine the advantages of a close cooperation between the manufacturer and its suppliers of a retail supply chain and the influence of efficiency and performance. A simulation was used based on a trial group consisting of 12 retailers in the US. It was shown that collaboration can cut costs, risks and inventory for both the retailer and their suppliers [5].

Langroodi and Amiri (2016) investigate the choice of the most appropriate region for order placements in a five stage multi-product supply chain, consisting of a customer, an incorporate retailer, manufacturer, material distributor and supplier, in four different regions using a System Dynamics model. A scenario analysis with varying costs and demands was conducted. The model aims to minimize the costs of orders between two stages consisting of transport, price for the product and order placement and thus choose the best supplier [6].

Hishamuddin et al. (2015) analyze disruptions of supply and transportation on the system's total recovery costs and other performance measures in a three stage supply chain with multiple suppliers. Thus, different scenarios of disruptions were established to evaluate system costs and stock-outs. It was shown that transportation disruptions have more damaging effects than supply disruptions due to the higher lost sales quantity. In addition, disruptions in the earlier stages have a higher negative impact to the supply chain compared to later disruptions [7].

Li et al. (2016) examine the dynamic risks effects in a chemical supply chain transportation system. Therefore, a System Dynamics model was built and risk scenarios were established regarding the probability and consequence severity in order to compare order fulfillment rate, transportation and inventory level to measure the performance. The major sources of risks transpired among other as breakdown in core operations, inappropriate choice of service provider and lack of inventory management. The researchers used only a questionnaire as the input for various risk scenarios, which could be a source of bias. Thus, it would be necessary to use a more extensive data source [8].

This paper continues a previous research which focused on the simulation of s, q and s, S order policies. The previous paper was called "A simulation based approach to investigate the procurement process and its effect on the performance of supply chains" [9]. Combining the model components and results of both papers, further research will focus on analyzing and comparing all four order policies as a whole.

3 Methodology

System Dynamics is a computer-aided approach for modeling, simulating, analyzing and designing dynamic and complex issues in socio-economic systems. Initially called Industrial Dynamics [10] the field developed from the work of Jay W. Forrester at the Massachusetts Institute of Technology.

Simulation models based on System Dynamics contain four different types of elements [11]:

1. *Levels* represent state variables of the system
2. *Flow variables* symbolize temporal change of the state variables
3. *Auxiliary variables* are used for decision rules describing casual relations
4. *Constants* are parameters to be set for the simulation

Supply chains mainly consist of inventory (information or material) as time based variables and flows as activities (transport of material and information). Decisions steer running activities and thus the state of the system [12]. A superior aspect to other simulation models is the possibility of feedback loops within the model. Thus, it is suitable for analyzing complex problems [13]. A common way to analyze a system's behavior using System Dynamics is a scenario analysis. This was done by using the tool Vensim.

4 Description of the Simulation Model

4.1 Model Structure

The model consists of a sub supplier, a supplier, a manufacturer and a customer (Fig. 1). Between the respective supply chain partners a material flow and an information flow is taking place. The sub supplier serves as an infinite source of order items and the customer is able to create different demand situations. The supplier and the manufacturer are modelled according to a simplified business structure, which is described in the following paragraph.

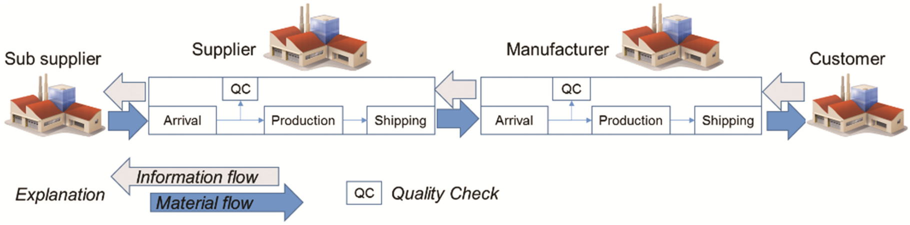

Fig. 1. Model structure

The business structure of both the supplier and the manufacturer are composed of an arrival warehouse for incoming goods, a quality check (QC) for the incoming goods, a production and a shipping warehouse from which the products are delivered to the customer.

The parameters contained in the model are shown in Table 1. Conducting a scenario analysis maximum stock level, periodic time, fixed order quantity and production rate were defined for both the supplier and the manufacturer.

Table 1. Parameters in the simulation model for the supplier and the manufacturer

Code	Declaration	Setting range
HB	Maximum stock level supplier	500–2000 pieces
HB 0	Maximum stock level Manufacturer	500–2000 pieces
L	Periodic time supplier	2–14 days
L0	Periodic time manufacturer	2–14 days
Q	Fixed order quantity supplier	200–1000 pieces
Q0	Fixed order quantity Manufacturer	200–1000 pieces
PL L	Production rate supplier	500–10.000 pieces/day
PL H	Production rate manufacturer	500–10.000 pieces/day

The customer demand is induced by an Excel based data generator. Thus, based on several parameters different demand situations can be applied to the simulation model. An expected demand and a standard variation need to be specified prior to the simulation as well as the initial situation with regard to a so-called trend, season or a constant demand.

4.2 Order Process

In the beginning of the simulation a certain stock is available in the shipping warehouse from which the demand is satisfied. According to a constant time interval a new order is placed at the supplier. The order quantity varies depending on the order policy investigated. This paper puts emphasis on frequent order points (t, S and t, q order policy), because order policies using a variable order point has already been investigated in a previous research paper at APMS 2016. Order policies with frequent order points can have two different modes for determine the order quantity. When using a t, S strategy the order quantity varies due to the stock replenishment up to a maximum stock level. Whereas in the case of a t, q strategy a fix quantity is ordered every time regardless of the maximum stock level [14].

5 Results of the Simulation

Two different order policies with frequent order points (t, s and t, q) has been analyzed based on different scenarios of demand situations (seasonal, trend and stationary). The results were compared by evaluating the quantity of the backlog. However, the results of the backlog did not differentiate much in the scenarios of a seasonal, trend and stationary demand pattern. This is why the results presented in this chapter will only be based on seasonal demand pattern.

Figure 2 illustrates the backlog of manufacturer and supplier for t, S and t, q order strategy based on a seasonal demand pattern. From the figure, it can be inferred that for the considered parameters, when both manufacturer and supplier implement t, q strategy, backlog of manufacture is high (around 21000 pieces) and backlog of supplier is relatively low (around 2000 pieces) at 440th day. Likewise when both implement t, S strategy backlog of supplier is high (around 7000 pieces) and that of manufacturer is relatively low around 15000 pieces at 440th day.

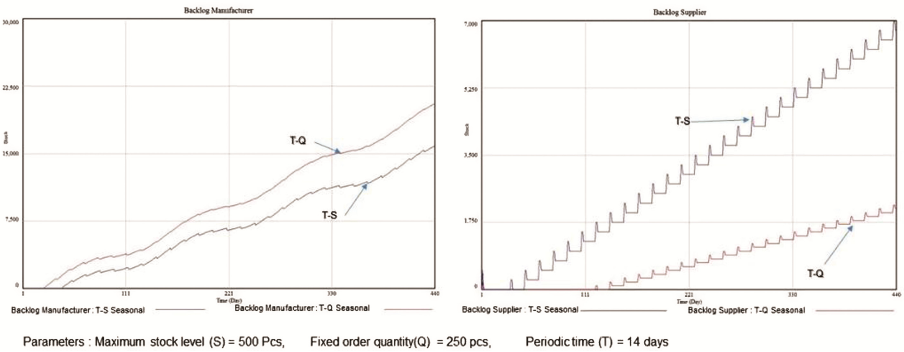

Fig. 2. Results of the Scenario analysis based on seasonal customer demand structure

Further, it can be observed from the graph of backlog manufacturer that the nature of graph is influenced by the customer demand, which is seasonal in this case. Hence a wavy graph is obtained for both t, S and t, q strategy. The backlog difference between the t, q and t, S along the time increases, hence a gap between both graph increases with time, and it is maximum at 440th day. The manufacturer backlog is relatively low with t, S strategy as the manufacturer tend to order after every time interval 't' till he reaches his maximum stock ‘S’, which would lead to more ordered parts at his end to serve the customer demand. In contrary the manufacturer backlog is high with t, q strategy as he would order only fixed order quantity ‘q’ after every time interval ‘t’ which would put manufacturer in high backlog.

Whereas in the case of supplier backlog, it can be noted that there is an initial backlog as early as day 1 for t, S strategy and then in the course of time it is zero for some time. Then the backlog is observed as the day progresses. It can be seen that, there is a sudden increase and drop of backlog, which is a result of the supplier being able to deliver the order in time for a short duration and then he will be in backlog after some time. This process repeats periodically as seen in Fig. 2. The same process repeats for t, q strategy, too, but the difference is that the backlog is zero for more than 100 days and then the backlog increases in the course of time with abrupt increase and decrease in between.

Based on the simulation results a Design of Experiments analysis was conducted to visualize and identify the factors that influence the backlog of delivered parts most. The main effects charts in Fig. 3 illustrate the examined factors (also see Table 1) and indicates if it has a positive or negative impact on the backlog when changing from a predefined minimum to a maximum value.

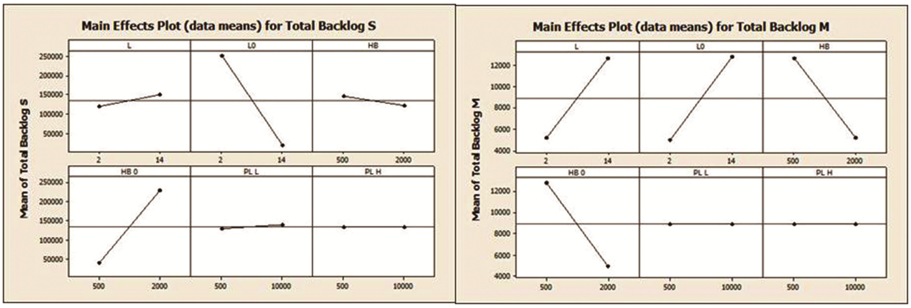

Fig. 3. Main effects chart for t, S order strategy with seasonal demand

A horizontal line in Fig. 3 implies that there is no effect on the backlog, the steeper the line the greater the influence on the backlog. Hence, there would be almost no effect of production rate of supplier (PL L) and manufacturer (PL H) on supplier and manufacture backlog. It is also observed that the greatest influence on the backlog of the manufacturer and supplier are the periodic time (L, L0) and the maximum stock level (HB, HB 0).

An interaction plot shows the interdependencies between factors when changing specific factor settings. Because an interaction can magnify or diminish main effects, evaluating interactions is extremely important.

The lines in Fig. 4 are indicating the strength of the interaction between the parameters. If the lines are parallel to each other, no interaction occurs. The more nonparallel the lines are, the greater the strength of interaction is.

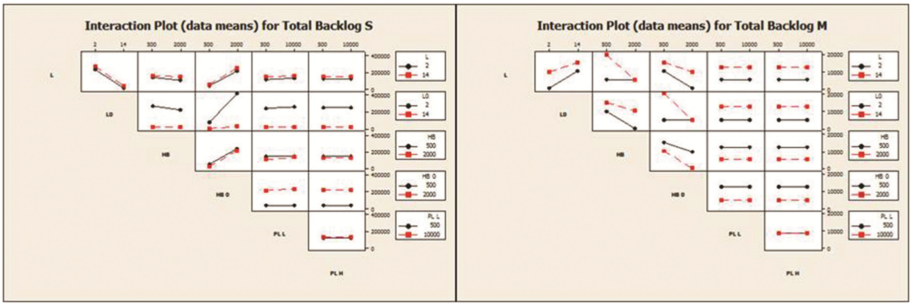

Fig. 4. Interaction plot for t, S order strategy with seasonal demand

Evaluating the **Supplier's backlog**, almost no interaction between the maximum stock of the manufacturer (HB 0) and the supplier (HB) can be detected. But it can be seen that there is an interaction between manufacturer's periodic time (L0) and maximum stock level of manufacturer (HB 0). Other parameters like production rate of supplier (PL L) and production rate of manufacturer (PL H) do not have much impact on backlog of supplier, as from figure it can be seen that, those parameters are plotted as parallel lines.

Evaluating the **manufacturer's backlog**, it stands out that there is a great influence between the maximum stock of the manufacturer (HB 0) and the periodic time manufacturer (L0). Other parameters like production rate of supplier (PL L) and production rate of manufacturer (PL H) do not have much impact on the backlog of the supplier.

Due to this fact, it would be advisable that the supplier and the manufacturer plan on their maximum stock for a decreasing backlog.

The main effects charts for t, q order strategy with seasonal customer demand are illustrated in Fig. 5.

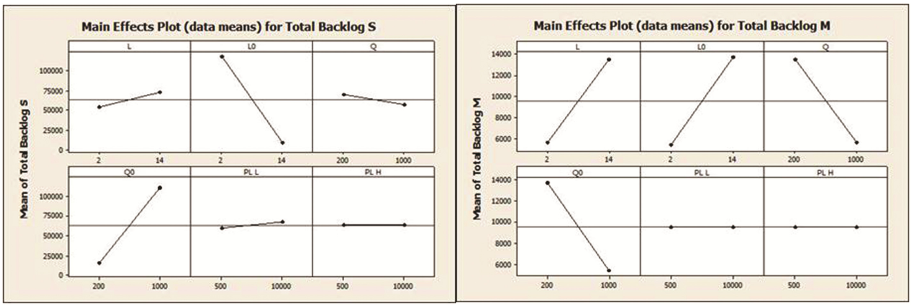

Fig. 5. Main effects chart for t, q order strategy with seasonal demand

Similar to Fig. 3 there is almost no effect of production rate of supplier (PL L) and manufacturer (PL H) on supplier and manufacture backlog. It is also observed that the greatest influence on the backlog of the manufacturer and supplier are the periodic time (L, L0) and the fixed order quantity (Q, Q0).

In the below Fig. 6 an interaction plot for t, q order strategy is illustrated.

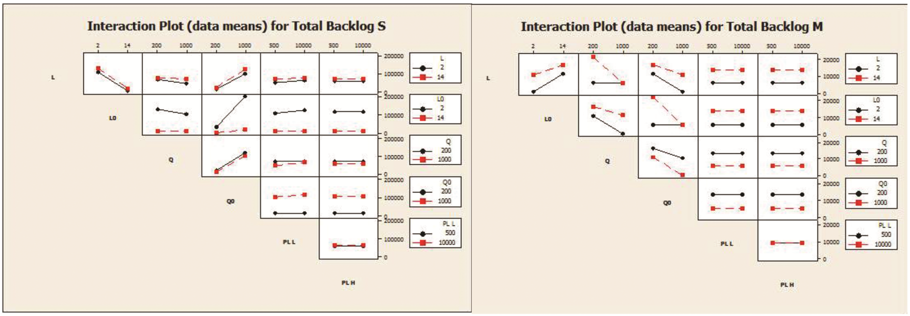

Fig. 6. Interaction plot for t, q order strategy with seasonal demand

Similar to Fig. 4 the lines in Fig. 6 are indicating the strength of the interaction between the parameters. Evaluating the **supplier's backlog,** no interaction between the fixed order quantity supplier (Q) and manufacturer (Q0) can be detected. But it can be seen that there is an interaction between manufacturer periodic time (L0) and the fixed order quantity manufacturer (Q0). Other parameters like production rate of supplier (PL L) and production rate of manufacturer (PL H) do not have much impact on backlog of supplier, as those parameters are plotted as parallel lines. Evaluating the **manufacturer's backlog**, it stands out that there is a great influence between fixed order quantity manufacturer (Q0) and the periodic time manufacturer (L0). Other parameters like production rate of supplier (PL L) and production rate of manufacturer (PL H) do not have much impact on backlog of supplier, as those parameters are plotted as parallel lines.

6 Outlook and Further Research

In this paper, a simulation of a four-stage supply chain was presented and two order policies were compared. After introducing the basics of ordering and inventory as well as System Dynamics, the model structure was explained and t,S and t,q order policies were chosen for a comparison.

It was shown that the periodic time and maximum stock level are main causes for the supply chain's performance. Due to the dependency of the backlog of the supplier by actions of the manufacturer, a close cooperation between all companies involved is advisable. The vendor managed inventory where the supplier manages the inventory and orders of the manufacturer is a method trying to decrease the backlog. In further investigations this method could be considered and implemented in the simulation model. Additionally, other parameter could be added to the model, which might influence the supply chain's performance e.g. costs for inventory and ordering or late delivery charges (liquidation damage) in order to further specify decision rules. Moreover, instead of using the backlog as a main measuring unit for the supply chain performance further objectives such as costs or average inventory level could be considered.

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Passenger Transport Drawbacks: An Analysis of Its "Disutilities" Applying the AHP Approach in a Case Study in Tokyo, Japan

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Abstract. Passenger transport is a key player in urban mobility. However, it imposes some disadvantages, such as: time wasting, cost of fares and other costs, insecurity, discomfort and damage to the environment. These disadvantages herein called disutilities affect passenger choices and therefore it is necessary to consider them encompassing all modes of transportation. In this study, an analysis of these disutilities was conducted with the purpose of measuring its drawbacks. To this end, a case study in the Greater Tokyo Area (Japan) was carried out and assessed using the Analytic Hierarchy Process. The results showed that from 0,000 to 1,000 automobiles produce the highest level of disutility (0.182) compared with seven other modes of transportation.

Keywords: Urban mobility · Transportation disadvantages · Decision-making

1 Introduction

People usually move from one place to another to meet their needs, as human activities occur in different areas of the city [1, 2]. Therefore, Passenger Transport (PT) is the main provider of access to work, leisure, education, etc. [3]. PT can be divided twofold: (i) private, such as automobiles and motorcycles; and (ii) public, where passengers pay a fare to ride, like on buses and trains. Even with PT being important for the economy, it imposes some disadvantages to the passengers and the society, given that it wastes time, costs money, is unsafe, uncomfortable and harms the environment, consuming non-renewable energy and urban space [4, 5]. These disadvantages, called disutilities, influence customer choices and transportation takes the character of a service of negative consumption, in other words, something that everyone needs, but nobody wants [6, 7]. Thus, there is not PT mode that does not present some issues. All modes of transport may present drawbacks; hence, it is important to minimize their levels of disutility [8].

The purpose of this study is to evaluate the levels of disutility in PT modes and classify them. To this end, a case study was conducted in the Greater Tokyo Area, Japan. This area was chosen due to the data access, high concentration of population and availability of all transportation modes. The evaluation was made applying the Analytic Hierarchy Process (AHP) approach.

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2 Methodology

The levels of disutilities can be measured or evaluated by specialists. The weights of each disutility are submitted to the AHP to calculate the "Total the Disutility" of each mode of transportation.

2.1 Analytic Hierarchy Process (AHP)

AHP is a structured technique for organizing and analyzing complex decisions based on mathematics and psychology, developed by Thomas L. Saaty in the 1970's. It is a multi-criterial decision-making approach that measures and establishes priority scales based on specialists' judgments about a given subject via the means of peer comparisons [9]. AHP is a methodology to calibrate the numeric scale for the measurement of quantitative as well as qualitative performances [10], and it has been used to solve several logistical, strategic and transport engineering problems.

AHP applications consist of breaking the problem into steps [11]: (i) define it; (ii) structure the decision hierarchy; (iii) construct a set of pairwise comparison matrices; and (iv) use the priorities obtained to weigh them.

In the present case, AHP is a means to determine the level of disutility of the PT modes, considering a displacement between two points. The criteria considered for the decision-making is related to "Passengers" and "Society" and the sub-criteria related to the disutilities is outlined in Sect. 3. To set the weights adopted, bibliographical references were selected, as can be seen in Table 1.

Table 1. Bibliographical references for weights adopted in pairwise comparisons

References	Criteria		Sub-criteria				
	Passenger	Society	Total time of displacement	Cost	Insecurity	Discomfort	Negative impacts on communities
Raymundo and Reis [12]	X	X	X	X	X	X	X
Vasconcellos [13]			X	X	X	X	X
ANTP [14]					X	X	X
Gibson et al. [15]							X

2.2 AHP Framework

The AHP method utilizes peer comparison between each one of the criteria, sub-criteria and alternatives, considering levels from a nominal scale [16], shown in Table 2, and, in this case, considering the bibliographical references previously cited in Table 1.

Table 2. Peer comparison nominal scale (Source: Adapt [11])

Scale	Meaning
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6 and 8	Intermediate values

These comparisons are established to determine the levels of importance of each criterion, comparing, for example, criterion "i" with criterion "j" [13] (Eq. 1).

$$A = \begin{pmatrix} 1 & a12 & \ldots & a1n \\ a21 & 1 & \ldots & a2n \\ \ldots & \ldots & \ldots & \ldots \\ an1 & an2 & \ldots & 1 \end{pmatrix} \tag{1}$$

Thus, AHP correlates several criteria and performs by peer comparison, identifying inconsistencies in the analyses. If the specialist specifies that b > a and a > c, therefore it is expected that b > c, otherwise an inconsistency is pointed out by the software. Thus, AHP displays an inconsistency index ("II") [17, 18], mathematically expressed by (Eq. 2). The maximum inconsistency allowed to guarantee the reliability of the chosen decision is II < 0.10. In the case of "II" being greater or equal to 0.10, it is necessary to adjust the comparisons before proceeding to the criteria analysis (Eq. 2):

$$II = \frac{\lambda max^n}{n^1} \tag{2}$$

where: "λmax" = auto maximum value; and "n" = matrix dimension or order of the matrix.

Then, the "consistency ratio" ("CR") can be obtained by (Eq. 3) [19, 20]:

$$CR = \frac{II}{RI} \tag{3}$$

where "CR" corresponds to the "consistency ratio", related to the answers given by specialists; "II" represents the inconsistency index and "RI" is the "random index", calculated to square matrices of "n" order by the "Oak Ridge National Laboratory" – ORNL, being 1 = 0.00; 2 = 0.00; 3 = 0.58; 4 = 0.90; 5 = 1.12; 6 = 1.24; and 7 = 1.32.

To determine the weights of each criterion, sub-criterion and alternatives, changes between the options should be compared, considering the preferred scenario and the less recommended one. Whenever possible, averages should override the judgments of specialists to avoid errors by the subjectivity of responses. To reduce the inconsistencies in the model, we opted to work with quantitative comparisons between the weights, using collected data from the case study and specialists' opinions [21].

2.3 Decision Tree

A decision tree was adopted to solve the proposed problem [22], considering two criteria and five sub-criteria. A second layer of 11 sub-criteria was considered from the five sub-criteria. Peer comparisons were performed considering Table 1.

The decision tree (Fig. 1) identifies the objective, criteria and respective sub-criteria (in two layers), indicating the alternatives considered. Once the decision model variables were determined, the data was inputted in the Expert Choice® version 11 (2014), generating the results shown in Sect. 4.

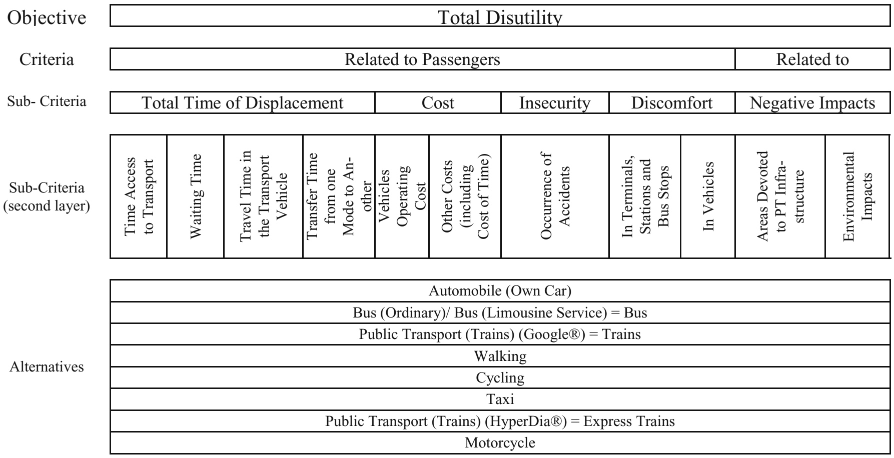

Fig. 1. Decision tree case study

2.4 Case Study

The case study refers to an experiment from Narita Airport to Tokyo Central Station, for the following PT modes: Automobile (own car); Taxi; Bus (Ordinary); Bus (Limousine Service); two Train options (Narita Skyaccess/Oedo Line and Narita Express), the first of them is a train with several stops and a compulsory transfer from one line to another, and the other is an express train, with few stops and no transfers; Cycling, Walking and Motorcycle, totalizing nine modes. Due to the AHP software limitation to eight alternatives, it was necessary to blend Bus (Ordinary) and Bus (Limousine Service) into a single alternative, simply called "Bus". However, this was a minor change that did not invalidate the analysis.

To perform the peer comparisons of the AHP method, the weight values of the disutilies per each mode of transportation were defined according to the bibliographical references shown in Table 1 and in transport specialist opinions. The purpose was created an overview of method application. Future studies intents to compare the judgments of specialist with the system users. Some restrictions of the AHP method, such as limited judgment scales and the consideration of which criteria are independent of each other, did not invalidate the results obtained.

3 Results and Discussion

The main objective of the study to measure the “Total Disutility”. The results showed that an Automobile produces the highest level of disutility (0.182), followed by Bus, Taxi, Motorcycle, Trains, Walking, Cycling and Express Trains (0.083), as can be seen in Table 3. Apart from Bus, our result is close to that found in other studies, like Vasconcellos [13]. EMPLASA [7] could explain the second position occupied by Bus.

Table 3. General result

Objective and criteria	Alternative weights (bold highest disutility - italic lowest disutility)							
	Automobile	Bus	Trains	Walking	Cycling	Taxi	Exp. trains	Motorcycle
Total disutility	**0.182**	0.148	0.119	0.107	0.098	0.140	*0.083*	0.125
Passenger	**0.169**	0.097	0.130	0.138	0.122	0.123	*0.092*	0.129
Society	0.216	**0.277**	0.093	*0.026*	0.029	0.185	0.060	0.114

Additionally, the criterion “Passenger” has a higher weight (0.667), compared with the criterion “Society” (0.333). In the case of the criterion “Passenger”, Automobile (0.169) produces the highest disutility and the lowest is related to Express Trains (0.092). Concerning “Society”, the highest disutility is represented by Bus (0.277) and the lowest by “Walking” (0.026).

3.1 Sub-criterion (Two Layers) and Alternatives

The results corresponding to each sub-criterion and the alternatives weights are represented in Tables 4 and 5 and discussed in the sub-items 3.2.1 to 3.2.5. The results are in general compatible with what is (currently) observed in the Greater Tokyo Area, concerning the level of supply of transportation modes (quality and quantity), the demand requirements and the equilibrium between these elements [12].

Table 4. Sub-criteria (first layer) and alternatives weights

Sub-criteria (first layer)	Alternative weights (bold highest disutility - italic lowest disutility)							
	Automobile	Bus	Trains	Walking	Cycling	Taxi	Exp. trains	Motorcycle
Time of displacement	0.077	0.136	0.156	**0.196**	0.147	0.081	0.141	*0.066*
Cost	**0.184**	*0.076*	0.121	0.152	0.121	0.129	0.119	0.091
Insecurity	0.224	0.067	0.050	0.135	0.102	0.143	*0.044*	**0,229**
Discomfort	0.116	0.172	**0.255**	0.059	0.117	0.106	*0.046*	0.129
Negative impacts on communities	0.216	**0.277**	0.099	*0.026*	0.029	0.185	0.060	0.114

Table 5. Sub-criteria (second layer) and alternatives weights

Sub-criteria (first layer)	Sub-criteria (second layer)	Alternative weights (bold highest disutility - italic lowest disutility)							
		Automobile	Bus	Trains	Walking	Cycling	Taxi	Exp. trains	Motorcycle
Time of displacement	Access	**0.207**	0.142	0.086	*0.015*	0.179	0.122	0.062	0.187
	Waiting	*0.022*	0.286	**0.309**	*0.022*	*0.022*	0.139	0.177	*0.022*
	Travel	0.027	0.053	0.077	**0.461**	0.238	*0.022*	0.095	0.027
	Transfer	0.177	*0.066*	**0.487**	*0.066*	*0.066*	*0.066*	*0.066*	*0.066*
Cost	Vehicles	0.262	0.086	0.092	*0.020*	*0.020*	**0.301**	0.074	0.145
	Other	0.158	*0,073*	0.130	**0.195**	0.162	0.074	0.134	0.074
Insecurity	Accidents	0.224	0.067	0.050	0.135	0.102	0.143	*0.044*	**0.236**
Discomfort	Infrastructure	0.094	0.068	**0.232**	0.204	0.133	0.094	**0.037**	0.137
	Vehicles	0.124	0.211	**0.263**	*0.031*	0.084	0.110	0.050	0.126
Negative impacts on communities	Infrastructure	*0.284*	0.144	0.080	**0.030**	0.040	0.233	0.066	0.123
	Environmental Impacts	0.190	*0.328*	0.098	**0.025**	**0.025**	0.167	0.058	0.110

3.1.1 Total Time of Displacement

Walking is the mode with the highest level of disutility caused by its very long travel time. In second place is Trains (long waiting time, travel time and transfer time). Cycling comes in third place (long travel time), followed by Bus. The lowest levels are represented by Motorcycle, Automobile and Taxi, while Express Trains play an intermediate role. Our result is compatible with what is observed in Tokyo, where Motorcycle, Automobile and Taxi perform almost the same average speed [12].

3.1.2 Cost

Automobile shows the highest level of "Cost" due to its operating cost, followed by Walking (high time cost), Taxi, Trains and Cycling. In an intermediate position, there are the Express Trains and Motorcycle, while the lowest level is represented by Bus. Fares, and consequently their subsidies, influenced the performance of the public modes, determining their competitiveness. Vasconcellos [13] shows Automobile with a very high cost, while public transportation has the lowest values.

3.1.3 Insecurity

Motorcycle represents the highest level of "Insecurity", followed by Automobile, Taxi, Walking, Cycling, Bus, Trains and Express Trains. Even in Japan, non-motorized modes (Walking and Cycling) are subjected to a high risk and are relatively less protected from traffic threats shared between Automobile, Motorcycle, Taxi and Bus, not to mention trucks. The data collected by Raymundo and Reis [12] related to Tokyo confirms our result, where Motorcycle is the most unsafe, followed by Automobile, Walking and Cycling, Trains and Bus.

3.1.4 Discomfort

A trade-off occurs due to Trains showing the highest level of "Discomfort" and Express Trains the lowest. In Trains, compared to Express Trains, passengers in Tokyo face worse conditions concerning infrastructure (terminals and stations) and worse conditions in vehicle comfort. From the higher levels to the lower ones, we have Bus, Motorcycle, Cycling, Automobile and Walking. ANTP [14] reached similar conclusions when analyzing the discomfort of PT modes in São Paulo, Brazil.

3.1.5 Negative Impacts on Communities

The highest position is occupied by Bus, followed by Automobile, Taxi, Motorcycle, Trains and Express Trains, while the lowest level is represented by Walking and Cycling. Bus has the highest position in “Environmental Impacts” because most of them are still diesel powered, polluting much more than the other modes. Gibson et al. [15], studying most of cities in the European Union countries, arrived at a similar result to ours.

4 Conclusions

The measurement of disutilities of the selected PT modes in the Greater Tokyo Area and the establishment of priorities among them allowed us to identify the reasons that influence the performance of these transportation systems.

When it is known that, on a scale from 0,000 to 1,000, where the values are complementary, the Automobile produces the highest level of disutility (0.182), followed by Bus (0.148), Taxi (0,140), Motorcycle (0.125), Trains (0.119), Walking (0.107), Cycling (0.098) and Express Trains (0.083), it is not difficult to suppose that similar situations are happening in most metropolitan areas of the world, requiring the minimization of total disutility produced by PT.

The results show that it is worthwhile for public transportation to invest in better trains, subsidize fares and substitute the bus fleet by vehicles that pollute less. For private transportation, it is worth protecting walking and cycling from the shared traffic threats. Finally, it is important to highlight in a more transparent way the harmful effects of automobiles, taxis and motorcycles. From this, it could be possible to improve them and then to integrate them to the non-motorized individual modes and to the public and collective modes in a more effective manner.

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The Impact of Organizational Culture on Performance Measurement System Design, Implementation and Use: Evidence from Moroccan SMEs

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Abstract. Several earlier studies have viewed organizational culture (OC) as a key factor for performance measurement systems (PMS), yet its role is not well understood and the reviewed literature indicates a gap in articles describing the relationship between various types of OC and PMS. Thus, the following study sets out to explore how OC type impacts PMS design, implementation and use. The investigation is carried out using the case study methodology in two Moroccan manufacturing SMEs. Our findings suggest that there is a relationship between OC type and PMS life cycle.

Keywords: Performance measurement system · Organizational culture · Small and medium enterprises · Semi-structured interviews

1 Introduction

The structure of today's business context is changing promptly, generating an important deal of uncertainty. This environment obliges firms, especially small and medium-sized enterprises (SMEs), to be more innovative and to constantly review their processes and practices in order to survive on the current competitive environment. This means that they must keep a close eye on their performance [1]. Therefore, performance measurement systems (PMSs) are considered as a means to gain competitive advantages and continuously react and adapt to external changes [1].

Although research studies underline the key role of PMS in supporting managerial growth, particularly in SMEs [2], a lot of initiative of its implementation failed and the reasons for failure are varied and of diverse nature [3]. Among those important factors figures organizational culture [4]. According to Bourne (2005), organizational culture is one of the important drivers of successful PMS implementation [3].

Organizational culture has been defined as the attitudes, values, beliefs and behaviours that represent an organisation's working environment, organisational objective, and vision [5]. Kandula (2006) once remarked that due to differences in organizational culture, the same strategies do not yield the same results even if two organizations belong to the same industry and operate in the same geographical context [6]. Although the significant and definite influence of organizational culture on the management of

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organizations is recognized by literature [7], the research stream fit with the impact of this factor on PMS is still lacking and the studies investigating the impact of the main types of organizational culture on PMS are not enough studied [8]. In order to fill this research gap, and taking into account the growing economic relevance of developing countries, this paper investigates the impact of organizational culture on PMS design, implementation and use in the Moroccan SMEs.

The remainder of this paper is organized as follows: in the next section we will discuss the relationship between performance measurement system and organizational culture from the opinion of previous literature. Subsequently, we present the methodology of the study and the findings, followed by a discussion of the results and the conclusion.

2 Performance Measurement System and Organizational Culture

Through a systematic literature review of issues affecting how companies manage through measures Franco-Santos and Bourne [9] have found out that factors influencing performance measurement system (PMS) are divided in two main categories; process factors which are concerned with different phases of PM systems (i.e., design, implementation, use and update) and contextual factors which emphasize the environment in which the PM system operates. Moreover, they split contextual factors into internal factors relating to organizational context and external factors concerning the environment and industry characteristics.

Furthermore, the PM literature underlines the importance of aligning PMS with organizational culture or the users' cultural preference [10]. Franco and Bourne for example, suggest that organizational culture that emphasizes teamwork, ownership of problems, risk-taking, entrepreneurship, continuous improvement and encourages performance discussion and analysis without punishing people's errors are critical to success of PMS. However, literature did not clearly provide how alignment between the organizational culture and the PMS should be developed [9].

Jwijati and Bittitci (2015), in turn, reviewed the research stream fit with the impact of organizational culture on performance measurement systems, and have noticed that this area of research is still lucking [8]. Moreover, they categorize the research studies into three categories. The first stream discusses the impact of organizational culture on PMS generally. Bittitci et al. (2004, 2006) remark that the relationship between organizational culture and PMS is dyadic [11, 12]. The second stream suggests that a successful implementation of PMS require a particular organizational culture, in this case, we found Bourne et al. (2002) who believed that a "paternalistic culture" is a key success for PMS implementation [13]. Assiri et al. (2006) suggested that a culture stimulating participation and involvement of all employees is considered as one of the main factors enhancing a successful implementation of PMS [14] and lastly De Waal and Counet (2009) showed that a better implementation and use of PMS require a culture focusing on continuous improvement [15]. Finally, a third stream which links particular organizational culture components to PMS as Henri (2006) who demonstrated that there is a relationship between culture types and diversity of measurement and nature of use of PMS [16] and Mendibil and Mac Bryde (2006) who suggested that organizational culture features could be a constraint for the design and implementation of PMS [17]. At last Jwijati and Bititci (2015) have explored the relationship between PMS and the different type of organizational culture as suggested by the competing value framework [8]

As we see from the above, studies investigating the impact of all types of organizational culture on PMS in only one framework are almost inexistent.

3 Methodology

Previous research that has studied the impact of organizational culture on PMS used both qualitative and quantitative research methods. To achieve our purpose, the case study approach has been adopted, this method was chosen for two main reasons. Firstly, the research is explorative, as mentioned above, researches on the topic studied are still lacking. Further, the case studies have proven to be very useful for unveiling possible contingency effects and for finding empirically grounded explanations for them [18]. The criterion for choosing organizational cultures is based on Cameron and Quinn's competing values framework [19] which suggests that organizational culture could be organized and described along two dimensions: structure and focus. The structure dimension depicts the organization's flexibility or control in dealing with emerging conditions. The focus dimension represents the focus of the organization and if this focus is internal or external to the organization. Based on those dimensions, literature discerns between four types of organizational culture: market, adhocracy, clan, and hierarchy. The access to information to identify organization's basic cultural assumptions for selecting significant firms and carrying out our research wasn't easy. Thus, initially two companies representing the dilemma of control versus flexibility were investigated. Both case studies were indigenous SMEs, privately owned and have industrial background.

In preparation for the company visits, a research protocol was designed based on the "performance measurement system phases development" as proposed by Bourne et al., (2000) who suggest that the development of PMS could be divided into four main phases these are: design, implementation, use and review of performance measures [20]. For the design phase, the authors require two steps: identifying the key objectives to be measured and designing the measures themselves. Most of the literature in performance measurement mentioned that the measures should be derived or aligned to the strategy or organizational goals. Regarding the implementation phase, Bourne define it as "the phase in which systems and procedures are put in place to collect and process the data that enable the measurements to be made regularly" [20]. The use of performance measures can be split in two main subdivisions: assessing the implementation of strategy and challenging the strategic assumptions. As to the review phase, Bourne et al., (2000) underline that is required to make certain that the PM system is dynamic enough to reflect the changing business environments [20].

The research protocol was discussed between authors and elaborated upon and then sent by email to managers interviewed. One researcher moved on sites for interviewing general and middle managers each separately, The length of each interview depended on achieving the aim of the research and answering each question, ranging from 45 to 90 min. data were collected through document review, participant observations, and semi-structured interviews. Document review included company site, documents afforded by the organization. Participant observation implied sitting in meetings with top management and their staff. Interviews were used to get input from different actors about aspects of design, implementation, and use of PMS in semi-structured style. The interviews were recorded and transcribed subsequently and local languages (French and Arabic) were the languages employed in each company.

It should be mentioned that in order to identify each organization's culture, we chose the organizational culture assessment instrument (OCAI) supported by the competing value framework. This instrument consisted of six parts, each part consisted of 4 questions or rather four descriptions matched the definitions of the four culture forms as proposed by [19]. Interviewees were asked to distribute 100 points for each part depending on how alike the descriptions were to their organization. Using the OCAI, an organizational culture profile can be examined by establishing the organization's dominant culture type characteristics. This instrument has been tested in more than a thousand organizations and has been found to predict organizational performance.

4 Findings

The organization culture of each case has been analyzed by the researchers qualitatively and the results are synthesized in Fig. 1.

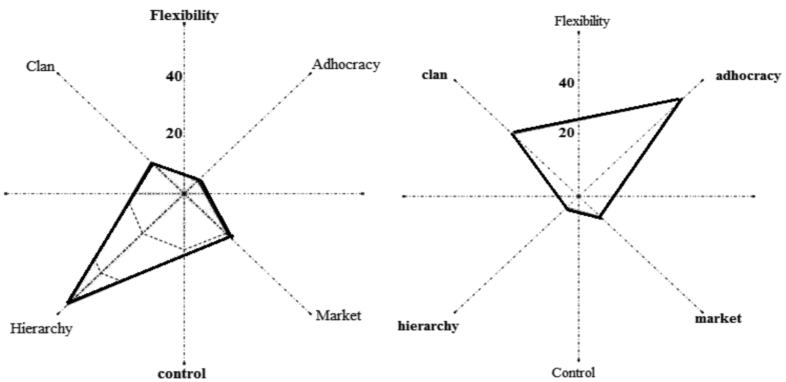

Fig. 1. Organizational culture type of the two companies

According to the results, the firm with a flexible culture tends to use more balanced performance measures, and uses PMS for aims such as learning, improvement and strategy implementation more than the firm which has a controlling culture and which tends to use PMS for aims such as monitoring and legitimization using financial measures. The Table 1 below presents a summary of our empirical evidences.

Table 1. PMS design, implementation, and use across organizational cultures

	Organizational culture type	PMS		
		Design	Implementation	Use
Campany A: is a leader in the field of battery manufacture in the Moroccan market with almost 180 employees and a turnover around 200 MDH	Adhocracy	Measures nature: Financial, production process, customer satisfaction, learning and improvement measures Identifying key objectives: – The performance measures are linked to the company's strategy – The strategy is explicit and communicated to all managers	Data collection: Performance data (such as production process data) are collected using specific software Storage of data: Data are stored in an integrated information system Data distribution: Company distributes data using visual management, regular interdepartmental meetings and online reports	Purpose of measures: – Strategy implementation – Communication – Learning and improvement Reviewing and acting on measures: – Performance measures are reviewed monthly, during a managerial meeting (the meeting include the top and middle managers) – There is an immediate intervention of managers in case of problem – There are not a causal model
Campany B: operates in the tippers and trailers manufacturing with 54 employees and a turnover of 76 MDH	Hierarchical	Measures nature: Financial, customer satisfaction Identifying key objectives: The company's strategy is implicit, and the performance measures are developed by the top management	Data Collection: Data are collected manually and using Excel and ERP Storage of data: Paper format and use of ERP coexistence to store data Data distribution: Company distributes data by means of formal and informal face to face meetings and online reports	Purpose of measures: Control and monitoring Reviewing and acting on measures: The lack of data and traceability obstruct the timely solution of problems

5 Discussion and Conclusion

This study enhances the body of knowledge by providing theoretical insights and empirical findings regarding the impact of organizational culture and PMS design, implementation and use.

In adhocracy culture: we witnessed that performance measures are balanced and derived from strategy. The measures are used for purposes such as strategy implementation, engaging employees by integrating reward systems and regularly updating and reviewing PMS and for continuous improvement which is compatible with adhocracy culture's dynamic and entrepreneurial nature. Moreover, in order to provide necessary data for inter-managerial communication which help middle and top management to take and own decisions, an integrated information system, regular meeting with the use and support of graphs and charts were implemented.

In hierarchical culture: financial and customer measures which have been developed by the top management are used for control and monitoring purposes. The implementation is backed with the authority of the top management, most of data are collected manually which often make the information inaccurate and out of date and create a lack of traceability and consequently, obstruct the review and the update of the PMS. Given the fact that the aim of measurement is controlling, it is the top management who holds the information and takes decisions and communicates it to middle management. This suggests certain compatibility with the focus on formalization and the emphasis the hierarchical culture.

These findings imply that managers need to be aware of the values on which their firm relies before trying to design, implementing and using PMS or adapting organizational processes to foster accurate use. For example, it might be more simple for an organization having flexibility values to use PMS to focus organizational attention than for another having strong control values. Therefrom, before implementing a PMS, organizations are encouraged to define the use they are looking forward to better lead the design of the system toward the appropriate diversity of performance measures.

This study is subject to potential limitations that can be mentioned. It can be asserted that the empirical evidence is based on just two case studies and the results cannot be generalized, it need to be broadened notably by using quantitative methods. a more number of cases may be useful for future research, moreover, researchers could investigate broader aspects of performance measurement and management and other pairs of competing values or other cultures frameworks. For instance, research could tempt to determine the adequate fit between organizational values and performance measurement and management practices to improve organizational performance.

However, in spite of the limitations, we believe that this study is pertinent to academics and practitioners in the field of performance measurement and management. In one hand, the impact of organizational culture on PMS is a prevalent topic which needs to be examined more deeply from different perspectives. In other hand, Morocco, as a developing country, simultaneously experiences the global technological and competitive effects with the other developed countries, so practical importance and necessity of the studies on PMS and organizational culture can be evaluated more clearly.

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