Michael F. Zaeh
*Editor*

# Enabling Manufacturing Competitiveness and Economic Sustainability

Proceedings of the 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013), Munich, Germany, October 6th–9th, 2013

Springer

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# Preface and Acknowledgements

Ladies and Gentlemen,

Dear readers of these proceedings,

Dear participants of CARV 2013,

The *iwb*, the Institute for Machine Tools and Industrial Management of Munich University of Technology is extending a warm welcome to all of you. We are proud to have you here in Munich and we are delighted to host the 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production, CARV 2013.

What triggers us to again focus on these subjects? The business environment of manufacturing enterprises is more than ever before characterized by increasing turbulence and complexity. Hence, the challenges for manufacturing companies arise from the need to design and realize organizational structures and technical solutions that can quickly and economically react to unpredictable boundary conditions. In addition to the changeability of internal processes, the agile configuration of supply chains and co-operation networks is indispensable to cope with the requirements of future markets. The availability of solutions that go beyond flexibility will thus be decisive for the competitiveness. An efficient interaction between changeable and virtual production is consequently the key for creating sustainable, fast reacting and adaptable business structures in order to face the future market environment.

As the chairman of this conference, I would like to thank a number of people:

- I am very thankful to my esteemed colleagues Prof. Dr. Hoda A. ElMaraghy, Prof. Dr. Waguih ElMaraghy and Prof. Dr.-Ing. Gunther Reinhart for being my co-chairs supporting me with valuable advice at any time during the preparations for CARV 2013.
- Many thanks go to my 55 colleagues from four continents, who act as members of the scientific committee. You all did a wonderful job in reviewing papers and giving feedback very precisely and absolutely timely. It was a pleasure to work with all of you.
- Special thanks are to be attributed to our keynote speakers for their invited talks. In my eyes they are a precious enrichment for CARV.
- We are thankful to Holiday Inn Munich City Centre for their efforts to provide a very nice venue for this conference, being located within walking distance from the city centre of Munich, and to Springer for being a reliable partner to print these procedures.
- Most of all I owe thanks to Michael Niehues, Thorsten Klein and Fabian Keller, graduate research assistants and PhD candidates at *iwb* and Fraunhofer RMV, for doing all the organizational and preparatory work which was necessary to make CARV 2013 a success and to make your stay in Munich as comfortable as possible. They did a marvelous job and their patience and endurance must be admired. They really made my life easy.
- Last but not least, I would like to thank all of you for submitting papers and for coming to Munich. CARV can only live with you, not without you. We are glad that you selected CARV for publishing your precious research results and for sharing them first hand with us. Following the advice of our reviewers we could accept 77 of your papers.

By the way: CARV is coming home. We took off in the year 2005 with the 1st CARV and then again hosted the 3rd CARV 2009 and now the 5th CARV 2013. In between it went across the Atlantic Ocean and took place in Toronto (2nd CARV 2007) and in Montréal (4th CARV 2011), both hosted by Prof. Dr. Hoda A. ElMaraghy and Prof. Dr. Waguih H. ElMaraghy.

Some words about Munich and the venue: The city of Munich is located near the Bavarian Alps, in the heart of Europe. Founded in the year 1158, we are looking back at more than 850 years of history. With more than 1.4 million residents, Munich is Germany´s third largest city and one of the most popular travel destinations in Germany. Munich is an important industrial, cultural and transportation centre and attracts many tourists with its elegant shops, fashionable clubs and bars and tasteful restaurants and breweries. The most famous event in the calendar is the Oktoberfest, which will take place from September 21st to October 6th, 2013.

The Institute for Machine Tools and Industrial Management (*iwb*) of the Munich University of Technology (German: Technische Universität München (TUM)) was founded in 1875 and is comprised of the Chair of Industrial Management and Assembly Technology (Gunther Reinhart) and the Chair of Machine Tools and Manufacturing Technology (Michael F. Zaeh). The *iwb* is one of the largest production technology institutes in Germany. The fields of research at the *iwb* include production management, automation, machine tools, assembly technology and robotics, manufacturing process, joining and cutting technology. At the *iwb*, research, teaching and industrial transfer activities are traditionally focused on these topics.

Thanks to all of you again. Let us have good conversations during the four days of CARV 2013.

Yours sincerely,

Michael F. Zaeh

*Chairman of CARV 2013 Conference*

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# Table of Contents

## Vision and Future Perspectives



## Manufacturing Systems



## Product and Production Co-Development

## Enablers of Change and Manufacturing Success

## Global Competitiveness and Sustainability



## Enterprise and Knowledge Management

## Application and Trends

# Variety, Complexity and Value Creation

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**Abstract**

Products variety and complexity and value generation for individual customers as well as the whole society are discussed. Dynamic changes in the world economy and their impact on sustainable manufacturing competitiveness are analysed. An overview of products variety, its sources and drivers and its effect on products design, planning of manufacturing is presented. The effect of variety on complexity of products and systems is highlighted as well as strategies for managing and profiting from it. Variety to enhancing customers' value and the relation between product space and economic complexity are discussed. A multi-facetted strategy for sustainable competitive manufacturing is presented.

**Keywords:**

Variety; Complexity; Value

## 1 INTRODUCTION

Manufacturing is a corner stone of the world economy. The "Manufacturing share of global GDP is 16%, it created 62 million jobs in 2000 and 45 million in 2010, 30-50% of service jobs are in manufacturing, the advanced economies' trade deficit in labour intensive goods is $342 Billion and $ 726 Billion is their trade surplus in innovative goods" according to 2012 McKinsey Global Institute study [1].

Economist and industrialists agree that the economy will grow faster in the next 20 years than it did in the last 20 years and that emerging economies will be primarily responsible for this accelerate pace as they are now building new and large middle class consumers [2]. For example, China has been the second largest "supplier of the market". However, the Chinese market alone is potentially about 250 million consumers. Now as incomes and GDP increase in China it has become "the market" with increasing demand for high quality innovative products, hence, creating important opportunities for advanced economies to exploit. High cost (wages & standard of living) manufacturing economies such as Canada, USA and many European countries cannot just compete on wages and productivity. The cost of manufacturing per minute is about $0.8 in Scandinavian countries and $0.5 in Germany, USA and Canada compared to $0.1- $0.2 in many emerging economies in Europe, the Far East and South America. Globalization trends saw many manufacturing jobs outsourced and off-shored to low labour cost manufacturing countries and the "Hollowing of Corporations" in many developed economies.

Manufacturing is entering a dynamic new phase. As the demand for manufactured goods increases significantly and innovations spark additional demand, global manufacturers will have substantial new opportunities which require different management scenarios and business models. The global competition from both developing and developed countries requires multi-facetted strategies not only for survival but also for excelling and competing in selected industrial sectors.

Key transformative enablers and strategies for productivity in manufacturing, which can create significant competitive advantage for manufacturing enterprises of any size, include: flexile, reconfigurable and changeable manufacturing paradigms, intelligent manufacturing systems, customization, differentiation and personalization of products, intelligent and imbedded sensors and the internet of things, and personalized manufacturing. New transformative business models include: dynamism, global alliances and collaborative manufacturing resources utilization, cloud manufacturing, and selling integrated products and services.

The increasing global competition makes it necessary to generate wealth by being more competitive and offering goods and services that are differentiated by design and innovation. It is important to design and manufacture products smartly to regain competitiveness. Innovation in products, in processes and manufacturing systems, in satisfying customers' needs and creating value to both customers and the economy and finding and growing new markets is essential. *It is no longer sufficient to make things better, we must make better things*.

Sustainable manufacturing - economically, environmentally and socially – is becoming a must. Global competition in advanced manufacturing is growing more intense as products and technologies lifecycles decreases and windows of opportunity shrink. In addition to achieving economies of scale through mass production, today's dynamic markets require achieving economies of scope by rapidly and economically producing alternative variants of products to satisfy diverse global customers and market segments and managing increased product variety, mass customization and personalization. Globalization saw the movement of goods and jobs around the world in pursuit of competitive cost advantages and lead to major economic and social shifts in developing and developed economies alike. The increase in cost of fuel and concern about carbon foot print and environmental sustainability is introducing "*Glocalization*" as the new norm where multi-national companies secure markets in growing economies worldwide while maintaining competitive sustainable local production close to consumers to satisfy the needs of regional market segments. This will create more jobs and wealth locally and bring back manufacturing to developed countries through innovative high value products and new production paradigms to support high variety differentiated products adapted to the needs of local market segments and enhance value generation.

The generated value has several perspectives and foci: the value generated for the customer, the enterprise and/or even to a country as a whole, as discussed in this paper.

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## 2 VARIETY AND CUSTOMERS' VALUE

The market volatility and demand fluctuations as well as increased products variety and complexity require agility, adaptability, responsiveness and effective use of innovative enablers of change. New manufacturing challenges include globalization and shifted and fragmented demands, economic, environmental and social sustainability, customer centred-products, mass customization and personalization, fast developing advanced technologies, and increasing complexity of products and their manufacturing systems and growing regulatory constraints.

A new era of manufacturing is upon us where new business models such as global and dynamic collaborations between companies and distributed and mobile manufacturing. As a new global consuming class emerges in developing nations, and innovations spark additional demand, global manufacturers will have substantial new opportunities which require different management scenarios. Neither business leaders nor policy makers can rely any longer on old responses in the new manufacturing era. The market volatility and demand fluctuations as well increased products variety and complexity requires agility, adaptability and effective use of innovative enablers of change and variety management.

Customer-centred strategies are increasingly important. It has been shown that corporations which focused on the consumers' value have been considerably outperforming those that focused on the shareholders' value [3].

Making value integrates innovation, design and manufacture. It requires understanding of how people receive and perceive value from products and services. According to the USA National Engineering Academy [4], satisfying customer's needs (utility) and wants (emotions) and using technology to ensure compelling customer experience during the design, customization, ordering and use of products proved to be winning strategies. For example, Nokia makes low cost mobile phones; compared to Apple which created products that appeal to customers' emotions in addition to function. As a result, Apple's market capitalization has reached almost $600 Billion and Nokia's has dropped to $15B and declining. Customer's value has many dimensions including quality (e.g. AM radios by Sony gave way to FM, and B&W TV lost to colour, HD and 3-D televisions) and convenience (e.g. Sony's Portable Radios, Discman and Walkman were overtaken by multimedia personal electronic devices, then by Apple's IPods and iPads with Apps adding even more value).

Products customization and personalization are on the rise. People modify and alter products they buy to create more value for themselves or for re-sale. Owners of high-end sports equipment, bicycles and motorcycles are known to customize them after market by adding parts and decorative designs. The ability of individuals to design and produce is becoming increasingly easier. For example, with the emergence of new low-cost technologies such as 3D printing, people can easily be involved in innovating, designing and making personalised products. Producers are continuously re-imaging brands and products and enhancing their customized features to stay ahead. All these trends and the proliferation of products variety and associated complexity call for effective management strategies and tools.

## 3 VARIETY MANAGEMENT

A comprehensive review of state-of-the-art product variety management methods has been developed by ElMaraghy et al. [5].

The number of product variants has increased dramatically in recent times. Variety can be seen in the simplest of products to large and complicated products such as appliances, automobiles, and airplanes. Products are designed and manufactured to fulfil perceived needs, which can vary because of differences among users and intended application. In order to address these differences, variety of products is created to meet diversified requirements. For example, a BMW series 7 car can have as many as 1017 possible variants [6]. The concept of variety applies to products and services alike; the provider seeks to achieve more economic benefit and enhance consumers' value by offering a wider spectrum of choice, more differentiating features and functions, and opportunities for customization and even personalization.

Variety is not always good - more product variants may not serve customers well. In reality, offering more product variants incurs expenses from product design to production, inventory, selling and service. Thus, defining the right range of variants with the product features combination that precisely targets the needs and resonates with customers' demands becomes an important issue in variety management.

Product variety can offer the potential to expand markets, increase sales volume and revenues. However, this positive outcome is not always guaranteed unless variety is well-managed in all stages of design, planning, manufacturing and distribution, usage, dismantling and recycling to reap its full benefit.

But the variety challenge is larger than just variety of products. Variety occurs across the entire product life cycle, and is also related to logistics and pre- and after-sales services. Product variants can be derived by innovating new, or adapting existing products to new requirements, scaling current products or changing their modules and components. It is necessary to use variety-oriented methods to manage variety throughout the product life cycle. Variety induces more difficulties to assess and control the factors that influence economical, environmental and social sustainability as a whole. In order to satisfy the user needs but also allow companies to be profitable and sustainable, models, methods and tools are needed to help companies manage product variety in such context.

As outlined earlier, product variety creates both challenges and opportunities for firms. Customers prefer broad product lines and, therefore, marketing managers are rewarded with greater revenue when they increase product variety. However, this may also increase costs and reduce profits.

## 4 ENABLERS OF VARIETY

Variety management strategies, techniques tools and enablers are classified according to three main activities related to products and their variants; namely design, planning and manufacturing (Figure 1). Their granularity ranges from parts to products and extends to the enterprise and market. Each cell contains strategies applicable to the region defined by the intersection of two factors.

### 4.1 Commonality

The notion of grouping and classification to capitalize on similarity and commonality within a class of products is a pre-requisite of success in managing variety. The principle of not "re-inventing the wheel" at any level every time a new variant is introduced is the foundation of any variety management approach. Product families, therefore, are important when dealing with variants which represent individual instances in a class of similar products. As products and their variants evolve and change over time the boundaries of such product families dynamically change as well – a concept that helps manage the co-development of product variants and their manufacturing systems [7].

Variant management considers the product, process and market views. It includes all measures by which the range of product variants offered by an enterprise is controlled and the resulting effects throughout their life cycle are managed. One of the important objectives is the reduction and management of variety-induced complexity and its associated cost.

AlGeddawy and ElMaraghy [8] presented a product family redesign model capable of identifying the product family platform and its potential modules which satisfy the constraints expressed in assembly liaison graphs. It uses Cladistics analysis, a hierarchical classification tool, to cluster components into modules and sub-assemblies up to the core platform. It also defines the optimal point(s) of product assembly differentiation.

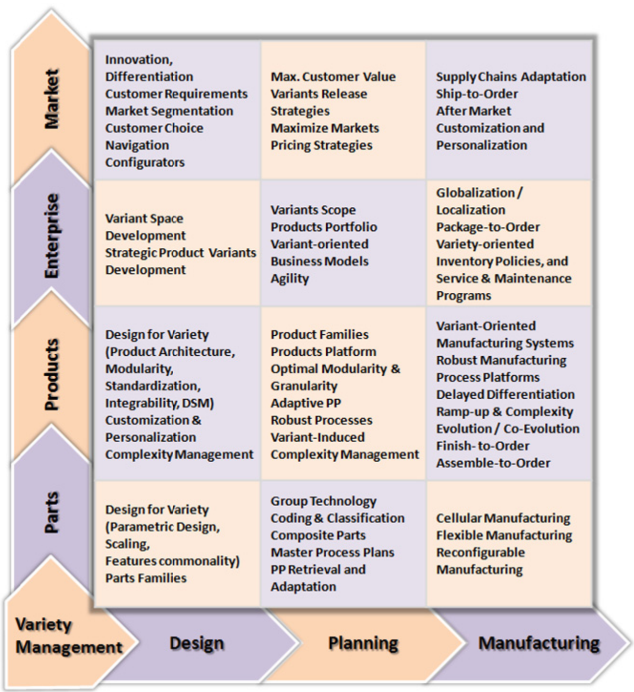


Figure 1: Variety management strategies map [5].

### 4.2 Mass Customization and Personalization

Mass customization (MC) means producing goods and services to meet individual customer's needs with near mass production efficiency and without compromising cost, quality or delivery. It aims at achieving economy of scope at a cost approaching that of economy of scale by delaying products differentiation and capitalizing on commonality and similarity between variants within a product family [9]. The MC concept permeates through the whole value chain from product design to end of life. The variants' portfolio should be planned such that each customer could find exactly what s/he needs.

Product platforms and product modules, incorporated into product family architectures, are established to facilitate planning for product variants. A Product Family Architecture represents the whole structure of the functional elements and their mapping into the different modules, and specifies their interfaces.

Personalization means that products are made-to-measure or to-customers' personal specifications. However, to achieve some measures of economy, only few product components are allowed to be manufactured to fit a specific customer body part or specifications.

The nature and degree of customer involvement differentiate between mass customization, extreme customization and true personalization. Customization is an exercise of configuring a product by selecting pre-designed modules and features within pre-determined scope of offered variety. Customers' value is enhanced by configuring the product that fits their preferences. However, the resulting product is not unique. Personalization entails more active and closer involvement by customers in defining some or all of product features and, hence, often results in unique products.

### 4.3 Design for Variety (DFV)

Design for variety (DFV) is a design strategy and methodology to help designers satisfy individual customer needs, gain market shares and remain competitive in spite of increased product variety. Customers' requirements and their interdependence and integrating them with families of technological solutions are important when designing for variety. Quality Function Deployment (QFD) is a well-known tool for identifying customer requirements and their relationships to product specifications. Integrated use of design methodologies, such as Design Structure Matrix (DSM), Module Interference Matrix, Pugh Matrix and TRIZ supports Design for Variety is recommended. ElMaraghy and AlGeddawy [10] combined an analytical classification model with multi-dimensional DSMs to select the best product variants for each market segment while maximizing component commonality and modules sharing. A summary of Design for Variety methods is shown in Figure 2.

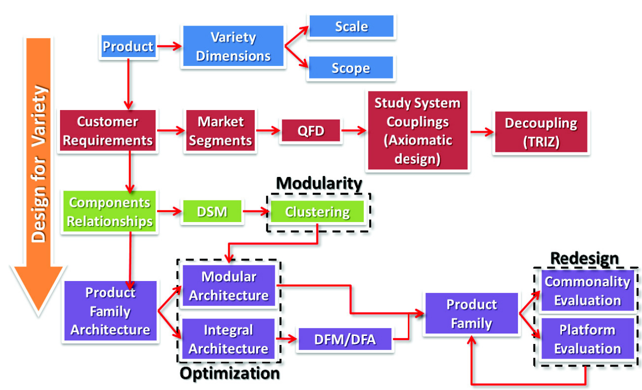


Figure 2: Design methods used in DFV literature [5].

There are several enabling technologies and design approaches which support design for Variety including: classification and grouping to form products/parts families, platforms and portfolios in order to capitalize on commonality in design features or manufacturing processes, variant-oriented Design and PLM support tools, Design for maintenance and service of product variants, Design for assembly, disassembly, remanufacturing and recycling of product variants, changeable and re-configurable process plans and production planning for variety methods considering logistics, inventory, maintenance, and variant-sensitive capability and capacity planning.

### 4.4 Variety-Oriented Manufacturing

Several manufacturing paradigms have emerged over the years in response to changes in product variety and production volume as illustrated in Figure 3. The emphasis shifted from maximizing production volume and profits through standardization and limiting variety to maximizing the products variety range and achieving economy of scope using adaptability, flexibility, re-configuration and changeability manufacturing systems attributes. Recently, producers are more focussed on maximizing customers' value through differentiation, mass customization and personalization and using technology to ensure a compelling customer experience during products design, specification, configuration and use.

The observed co-evolution of products and manufacturing systems offers insight into the ability of manufacturing systems to adapt to product variety and change as illustrated by ElMaraghy and AlGeddawy [11]. Companies make important strategic decisions to manage such co-evolution considering: 1) determining system configuration that best fits production requirements over time and for many product variants and generations, and 2) accommodating production changes by utilizing reconfigurable machines and adjusting production schedules.

Many manufacturing strategies have emerged to manage product variety such as postponement and delayed product differentiation, using policies such as making, finishing, assembling, labelling and packaging-to-order and introducing the concept of process platforms.

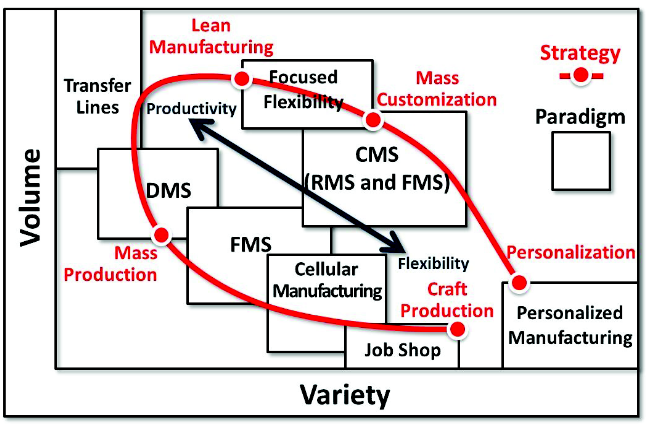


Figure 3: Evolution of manufacturing systems paradigms [5].

### 4.5 Variety-Induced Complexity

Modern complex products or equipment may have many thousands of parts and take hundreds of manufacturing and assembly steps to be produced. The complexity increases with the number of variants, as well as the presence of "multi-disciplinary complexity" as most products and equipment now incorporate not only mechanical and electrical components but also software, control modules, and human– machine interfaces [12].

Variety-induced complexity arises due to the increased number of variants and their features, more multi-disciplinary complex components and modules, lack of processes streamlining and insufficient use of adaptable CAD models and planning tools to capitalize on similarity and commonality. The effect of increasing product variants on cost and profit has been clearly observed due to variety-induced complexity. While it is desirable to satisfy the need for variety, it cannot be achieved at any cost. Modular product and process designs can reduce both complexity and cost.

Higher complexity can be very valuable, if it offers a compelling value proposition to customers. Furthermore, delivering customized solutions does not necessarily add to complexity, it really depends on the product design. For example, Dell succeeded in managing very large combinations of computers, peripherals and software by managing the complexity with "combinatorial assembly" - a mixing and matching of existing modular options, such as screen size, disk size, and memory, to meet customer preferences. Hence, combinatorial assembly is among the proven techniques in complexity management, as is "versioning," or re-packaging existing products for different contexts [13]. The guiding principle is *"As few variants as possible and as many as necessary"*.

Frequent and significant changes in product variants affect manufacturing ramp-up problems regarding parts supplies and inventories, tools, fixtures and machines qualification for yield and quality, manufacturing cycle time and line balancing, systems control and integration as well as training. Industry has primarily dealt with ramp-up issues by trial-and-error, which takes long time for large and complicated systems. This is exacerbated by the extent and frequency of changes due to the proliferation of products variants and should be managed by classification and recognizing similarity patterns.

## 5 PROFITING FROM VARIETY

Companies can benefit from variety as an enabler of innovative business models. There are three strategic capabilities that can maximize profit from variety which can be captured in economic models of variety-driven value creation to determine the best variety extent and parameters which optimize the benefit from offering variety and minimize its cost [5, 14]. These include: 1) *Robust Process Design* to allow manufacturer to reuse or recombine existing resources to efficiently deliver a stream of differentiated solutions, resulting in lower manufacturing cost and, hence, lower variety acquisition costs, 2) *Solution space development* which is the capability of the manufacturer to identify customers' idiosyncratic needs that are not addressed by competitors and target them with appropriate variety offerings, thus increasing product utility, and 3) *Choice navigation capability* of the manufacturer to support customers in finding the most suitable variant, e.g. by offering well-designed and easy to use on-line products specification and configuration systems to minimizing choice complexity and reduce the cost and effort of customizing products.

### 5.1 Value of Delayed Product Differentiation

Delaying the point of product differentiation (i.e. the stage after which the products assume their unique identities) is an effective means of addressing the challenge of expanding product variety. Some companies have developed a strategy of grouping and/or standardizing the product modules or sub-assemblies (e.g. auto body type, engine, and transmission type) into the "first-level", and then grouping the remaining products features as the "second-level" and/or higher levels which proliferate the products variety. This is called "delayed product differentiation". The cost and benefit of this strategy has been discussed by several authors [15]. Their models demonstrated that product differentiation can be delayed through product/process re-design, which will incur additional processing and investment cost. However, this redesign will lower the buffer inventories and increase its flexibility and reduce the complexity of the manufacturing process. Currently industry is increasingly using standardization and modularity in product design (and components) to reap greater benefits from delayed product differentiation.

## 6 THE PRODUCT SPACE AND ECONOMIC COMPLEXITY

Hidalgo et al. [16] proposed the Product Space, which is a network that formalizes the idea of relatedness between products traded in the global economy. The Product Space network has considerable implications for economic policy, as its structure helps elucidate why some countries undergo steady economic growth while others become stagnant and are unable to develop. The hypothesis is that economic development depends on a country's set of (production) capabilities. Products/sectors are more or less closely depending on their underlying common capabilities, which define a "product space". This is illustrated in Figure 4.

The concept has been further developed and extended by the introduction of the Economic Complexity Index and through visualizations of the product tree maps and networks, which have been condensed in the Atlas of Economic Complexity [17].

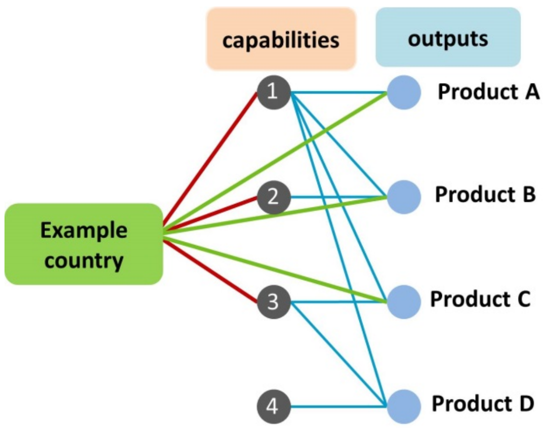


Figure 4: Product space of a country with underlying capabilities [16].

The fundamental proposition of the Atlas of economic complexity is that the wealth of nations is driven by productive knowledge. Individuals are limited in the things they can effectively know and use in production because of the complexity and diversity of the knowledge. Therefore the only way a society can hold more knowledge is by distributing different chunks of knowledge to different people. To use the knowledge, these chunks need to be re-aggregated by connecting people through organizations and markets.

It is worthwhile to define product complexity index, and the Country complexity index. The Product Complexity Index (PCI) is a product characteristic. It is a measure of how complex a product is. It is calculated as the mathematical limit of a measure based on how many countries export the product and how diversified those exporters are. The Economic Complexity Index (ECI) is a country characteristic. It is a measure of how diversified and complex a country's export basket is. It is calculated as the mathematical limit – or eigenvector–of a measure based on how many products a country exports and how many other exporters each product has. Diversity is a country characteristic. It is the number of products that a country exports with comparative advantage. Distance is a characteristic of a country-product pair and it measures how "far" a product is from a country's current productive capabilities. It is calculated by adding the products in which the country does not have comparative advantage, weighted by their proximity to the product in question. The Observatory of Economic Complexity is an open source project that allows users to quickly compose a visual narrative about countries and the products they exchange [16].

In an earlier publication Hidalgo and Hausmann [18] created indirect measures of the capabilities available in a country by thinking of each one of these capabilities as a building block or Lego piece, based on the concept of the division of labour. In this analogy, a product is equivalent to a Lego model, and a country is equivalent to a bucket of Legos. Countries will be able to make products for which they have all the necessary capabilities, just like a person is able to produce a Lego model if the bucket contains all the necessary Lego pieces. From there they develop a view of economic growth and development that gives a central role to the complexity of a country's economy by interpreting trade data as a bipartite network in which countries are connected to the products they export, and show that it is possible to quantify the complexity of a country's economy by characterizing the structure of this network. They were also able to show that the derived measures of complexity are correlated with a country's level of income, and that deviations from this relationship are predictive of future growth and prosperity. It is claimed that this prediction of future growth for the following decade beats measures of competitiveness such as the World Economic Forum's Global Competitiveness Index by a factor of 10.

Japan and Germany rank at the top worldwide in economic complexity. Figure 5 illustrates the economic complexity space map for Germany [17]. Germany exports a variety of complex products, including machinery, automobiles, and medical imaging machines, etc.

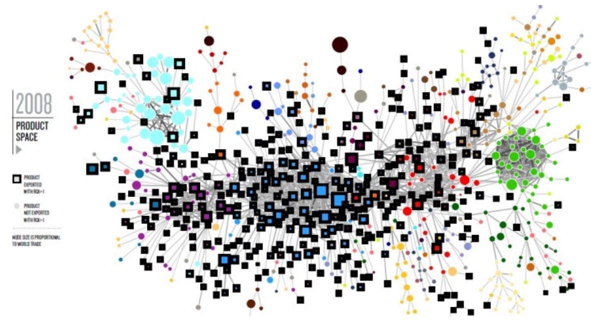


Figure 5: Macroeconomic sectorial product space map for Germany.

## 7 SUSTAINABLE MANUFACTURING COMPETITIVENESS STRATEGY

It is important to remain profitable and competitive in the presence of products variety. Sustainable manufacturing productivity and competitiveness can be thought of as a platform supported by three equally important and complimentary pillars as illustrated in Figure 6.

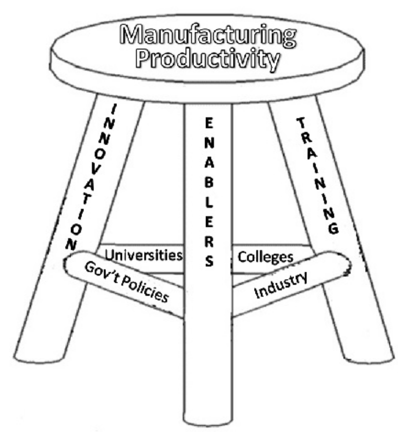


Figure 6: The 3 pillars of Productivity and Competitiveness.

1. *Creativity and Innovation*: Productivity and competitiveness is not just making things better but it is increasingly about making better things and creating value. This will come about by creating an environment conducive to creativity and innovation and providing the tools and support mechanisms for companies to design and produce their own products and/or product variants. Those companies that own the product and manufacturing systems design knowledge and know-how rule the market as evidenced by many companies that have their own innovated and deigned products.

Manufacturing competitiveness is all about differentiation which is a direct result of innovation and brilliant designs. Innovations should be fostered and encouraged at all levels of education as well as in the work place. Companies should encourage and reward innovative ideas about new or modified products and manufacturing processes and systems. There are many pre-requisites for innovation to succeed including: higher research and development (R&D) capacity in all sectors of industry, government, universities, and colleges; greater support for R&D by venture capital and private sector, more well-educated and highly competent people with the appropriate skills and education.

2. *Education, Skills and Training*: Competent, educated and skilled workers and manufacturing systems designers, builders and users are essential. Continuous education and training-through-life is needed in this age of rapidly changing technological advances in order to supply trained workers in the areas needed by industry, educate engineers and technologist to bridge the gap between innovation and successful application of manufacturing technologies and implement competitiveness and productivity enablers.

3. *Technological Productivity and Competitiveness Enablers*: Productivity is not just about working harder, it is also about working smarter and applying enabling technologies and methods to increase quality, reduce cost, manage variety and complexity, and meet fluctuating market supply and demand and delivery challenges. Examples include: a) New manufacturing paradigms of flexible, changeable, reconfigurable and intelligent manufacturing systems, b) Mass customization of products and managing product variety, c) New advanced sensors technology utilized throughout the production and supply chain, d) Advanced intelligent machines and systems, e) Computer-aided design and manufacture, f) Design for ease of assembly and manufacture, g) Additive manufacturing techniques, and h) New business models such as integrating products and service systems, collaborative global companies, etc. A sound manufacturing productivity and competitiveness strategy needs all three pillars to be strong and to work together in order to succeed; just as a three-legged stool which would not be stable if any leg is missing or is short. These three pillars can be further strengthened by three important elements that can hold them together for added stability: 1) Government fiscal, training and tax incentives policies, 2) Educational programs in Colleges and Universities which need to get closer to industry and be themselves adaptable and changeable to ensure that they offer relevant educational programs, and be customer-centric and provide experiential learning and internships/co-op opportunities and foster entrepreneurial skills, and 3) Industry Leadership as manufacturing companies have the responsibility to identify and evaluate new and advanced technologies that can benefit their business and invest in new technology, advanced equipment, and infrastructure as well as its employees training and education.

### 7.1 Sustainability and Evolution of Engineering Systems

The growing global population, demographic shifts, climate change and increasing pressure on natural resources have all brought sustainability to the top of the political, social and business agenda. Sustainability is the capacity to endure. Limited attention has been accorded to the social dimension of sustainability as envisioned by the United Nations Division for sustainable development [19] articulated objectives: ‘‘Recognizing that countries will develop their own priorities in accordance with their needs and national plans, policies and programmes. The challenge is to achieve significant progress in the years ahead in meeting three fundamental objectives: a) to incorporate environmental costs in the decisions of producers and consumers; b) to move more fully towards integration of social and environmental costs into economic activities; and c) to include, wherever appropriate, the use of market principles in the framing of economic instruments and policies to pursue sustainable development’’. Sustainability, similar to the topic of complexity, presents both major challenges and tremendous opportunities for businesses. Many companies have realised that by investing in energy-efficiency measures, responding to changing consumer buying patterns and ensuring sustainable business practices in their supply chains, they can operate more efficiently and create value in new ways. In this process the performance objectives for engineering have changed from a triangle: Quality/Cost/Time to a sustainable design solution that includes also the environmental and social impacts as well as energy considerations as illustrated in figure 7.

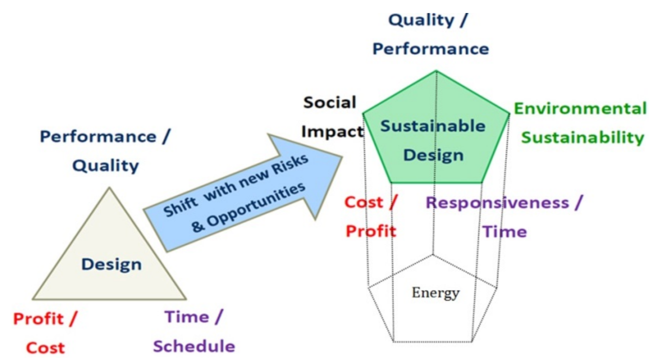


Figure 7: Shift in engineering objectives for sustainability.

## 8 DISCUSSION AND CONCLUSIONS

The most important issues related to product variety and its management were discussed. Competitiveness of companies is mostly driven by customer satisfaction that most often induces variety and complexity throughout the product life-cycle. Increased demand for customized and personalized products caused a large growth in the number of companies filling these demands and hence leading to more competition amongst them and better value to consumers. Therefore, it is strategic for companies to adapt their organization and practices in order to effectively manage variety throughout the product development processes even if many internal and external factors are impacted by variety. Families, platforms, architectures are essential concepts in designing, planning and producing for variety as product variants evolve over time. While increasing commonality and integration is proven to decrease design and manufacturing cost, differentiation and modularity have to be considered for enhancing customer satisfaction. The balance between these competing criteria provides the ideal product choices and optimum product architecture designed for ease of variety generation. Variety induces additional complexities in products and systems which must be carefully measured and managed to keep cost of offering variety down.

Variety management has to consider the product range, the product architectures as well as the manufacturing system and the supply chain in a holistic and integrated manner. Variety management has to be considered in three dimensions: 1) Scope, to cover different market segments, 2) Scale, to produce in response to fluctuating demand ranging from a one variant unit as easily as a high demand of that variant, and 3) Time, so companies can sustain the evolution of their line of products and its variants.

Understanding customers’ value in the face of wide range of products attributes and possibilities is a challenging issue for manufacturing industry. Defining the optimum variety level remains a challenge for many enterprises. Models and tools are needed to ensure that they identify the optimal set of products variants and adopt the right variant-oriented business models which maximize consumer's value as well as their own shareholders value.

Manufacturing systems should be designed to be flexible, changeable and reconfigurable to achieve both economic scope and scale and to enable smooth adaptation to dynamic change, and increase productivity when producing increased product variants. The concept of "manufacturing process platforms" should be better explored with the objective of developing methods to integrate the design of modular products platforms with modular manufacturing processes platforms to ensure robust, integrated and economically sustainable product and manufacturing process design and implementation.

Economical, social and environmental sustainability is a major goal for companies as they face new challenges. The influence of increasing product variety, with its inherent focus on increasing demand and consumption, but also with its abilities to leverage products that are more fit to their purpose, on the possibilities of achieving a sustainable society should be investigated. As an example, product variety introduces many new challenges in recycling and remanufacturing. Models and methods for including product commonality in environmentally sustainable manufacturing analyses and assessments are important to develop.

The manufacturing competitiveness challenge has changed, especially in advanced nations – the high cost manufacturing countries such as Canada, USA and most of Europe. Traditionally, the objectives were to lower cost, shorten production cycle time, and raise quality. Today, lean manufacturing, eliminating waste and continuous improvement are still a pre-requisite. However, in advanced nations, producing standard products using standard methods will not be sufficient to maintain competitive advantage. Many companies in developing countries are able to acquire and deploy the best current technology and advanced machinery. However, maximizing the utilization of these machines and having the knowledge and expertise to integrate them into intelligent, flexible, adaptable and changeable manufacturing system which can respond to changes in products and markets quickly and efficiently are needed to reap maximum benefit from such sophisticated equipment. This is where advanced countries can excel. High cost manufacturing countries cannot compete on wages and productivity alone. Companies must focus on innovative new products, processes and systems in order to compete globally and stay ahead of competitors.

The new manufacturing challenges are multi-facetted and should therefore be met at many fronts; requiring a multi-pronged approach including training for upgrading skills, education to deepen knowledge relevant to productivity and competitiveness, and research and development targeting generating and applying new knowledge and technologies and innovating new products, processes and systems paradigms in support of manufacturing. Harnessing the power of intelligent, agile, flexible and changeable manufacturing helps meet the challenges of proliferation of product variety and production complexity.

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# Cycle Management for Continuous Manufacturing Planning

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**Abstract**
Cycle management as a potential new paradigm in manufacturing planning contributes to the management of the entire innovation processes improving its efficiency and flexibility. Building on existing ideas about single cycles and established manufacturing planning approaches, a generic cycle model and a cycle information sheet as uniform modeling framework for mapping, analyzing and managing cycles are proposed. In addition, ideas for continuous manufacturing planning and the application of cycle management are outlined based on first results from an extensive literature review on manufacturing planning. Going forward, the full literature review will serve as input for the development of a detailed approach for a cycle-oriented continuous manufacturing planning fostering the establishment of cycle management in manufacturing planning.

**Keywords:**
Manufacturing resources; manufacturing structure; changeability; change management; generic cycle model; cycle information sheet; innovation process

## 1 INTRODUCTION

Management of innovation processes is a demanding challenge for industrial enterprises [1]. Numerous, partly interrelated influencing factors such as changing market requirements or emerging technologies create a complex environment for innovation. At the same time, different disciplines and functions within enterprises including e. g. product development, manufacturing planning or service development already are or do now become integral contributors to the overall innovation process [2,3]. Beyond that, shortening innovation processes increase their own repetition rate – in their entirety as well as for their separate parts [4]. Hence, the understanding of the influencing factors, their interdependencies and effects should be described comprehensively and transdisciplinarily. Together with an approach for an improved handling of frequently reoccurring processes the management of innovation processes can become subject of cycle management as a new paradigm for innovation management [5].

## 2 CYCLE MANAGEMENT

### 2.1 What Is Cycle Management?

Cycle management is understood as management of cycles in terms of planning, organizing and monitoring. Taking not only the innovation process – the core element of innovation management [6] – and its context into consideration, but focusing especially on involved influencing factors and the process's character of repetition, cycle management goes far beyond classic (innovation) process management.

Within the various disciplines and functions involved in the innovation process, first approaches for a basic cycle management already exist. The concepts of product life cycles and life cycle management are well established in industry [7,8], technology life cycles are a useful concept for strategic technology planning [9] and life cycle engineering became a common approach in sustainable manufacturing [10,11]. The understanding and modeling of one singular cycle from the respective disciplines' perspective is the commonality. Based on these ideas, cycle management now considers multiple cycles within and in the context of the innovation process simultaneously. In manufacturing and manufacturing planning that means to combine e. g. product life cycle, technology life cycle, manufacturing resource and structure life cycle as well as cycles like technical changes in product development as a basis for cycle oriented planning methods. Such cycle oriented planning methods are understood as cycles or combination of cycles also, hence being subject of a general cycle management.

### 2.2 What Is the Benefit of Cycle Management?

In principle, the introduction of cycle management creates a new perspective in manufacturing planning to cope with the challenges for the innovation process introduced in chapter 1 – by utilization of changeability in manufacturing. Taking advantage of understanding and modeling manufacturing-relevant cycles in the innovation process and its context, adaptations of manufacturing structures and resources will become easier to detect, earlier to assess, better to schedule and faster to execute. That means, different cycles can be controlled, analyzed, compared, combined, influenced and also evaluated with respect to manufacturing planning and the overall innovation process. Beyond that, cyclic processes and planning methods can also be designed and redesigned.

### 2.3 Requirements for Performing Effective Cycle Management

A profound combination of the cycles which are already described in literature (e. g. technology life cycle, product life cycle) with established manufacturing planning methods (see e. g. [14,12,13]) is hardly possible. On the one hand cycles are currently not described in a transdisciplinary intelligible way complicating or even preventing their comparison, evaluation and combination. On the other hand available planning methods are focused mostly on one-time events (e. g. building of a factory, setting up a new assembly line), the application to recurring ones is – if at all – only outlined (cf. [15], [12]).

In consequence, the requirements for an effective cycle management are three-fold:

(1) A generic cycle model.
(2) Continuous manufacturing planning.
(3) Applying cycle management in continuous manufacturing planning.

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A generic cycle model (1) has to be defined, which is transdisciplinarily intelligible, i. e. in application all cycles can be mapped similarily. Also, a continuous planning method for production (2) has to be developed, addressing the handling and implementation of changes in production. Finally, (1) and (2) have to be combined (3) in order to take advantage not only of the modeled cycles and their interdependencies, but also their influences on production over time. By this, a continuously adapting production is enabled in terms of change as standard instead of change as singularity or exception.

## 3 GENERIC CYCLE MODEL

### 3.1 Definition of Cycles

The *Collaborative Research Centre 768 "Managing Cycles in Innovation Processes" (SFB 768)* suggests the following definition of a generic cycle: Cycles are temporally and structurally recurring patterns which can be separated in defined phases. Cycles are determined by their triggers, phases, duration, repetition and effects. Triggers have to be defined to be able to forecast the starting point of a cycle. Once active, a cycle runs through different phases which can be specified depending either on the time passed since the beginning of the cycle or the magnitude of the cycle's dependent variable(s). The duration is the time it takes for a complete iteration whereby the ending is marked by completion of the cycle's last phase. Besides, the period in-between two iterations defines the frequency of repetition. Finally, effects of a cycle are determined by the dynamic behavior (e. g. duration, magnitude) of its dependent variable(s). However, these are strongly linked to the user's intention and perspective.

### 3.2 Modeling Cycles

The generic definition of cycles in paragraph 3.1 provides a first guideline defining which information is needed to model cycles and hence enable their management. Besides these content-related requirements also formal prerequisites have to be met:

- Comparability: modeling enables a comparison of cycles and their properties.
- Compatibility: modeling enables the combination of cycles in order to analyze their interdependencies.
- Clarity: modeling supports quick understanding of given information.

Modeling cycles as two-dimensional function graphs or as abstract process models are by far the most common ways of depicting cycles up to now. Another alternative is displaying the fundamental data of cycles in tables, particularly for the sake of comparing multiple cycles. While abstract process models are suitable to outline basic characteristics of a cyclic phenomenon (e. g. sequence of certain phases), function graphs and diagrams are used to plot the dynamic behavior of dependent variable(s) requiring sound knowledge of the cycle at hand. The interdependencies of cycles can be documented in e. g. Design Structure Matrices (DSM) helping to assess the significance of single cycles.

To provide a comprehensive overview of cycles as a basis for successful cycle management the Cycle Information Sheet (CIS) is proposed, combining abstract process model, function graph, table and DSM (see Figure 1).

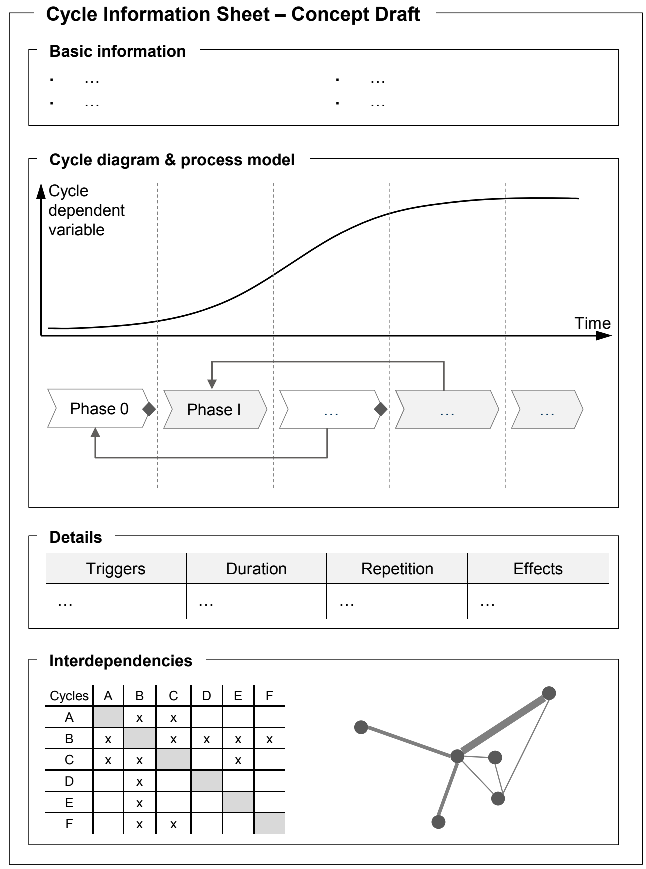


Figure 1: Cycle Information Sheet (CIS) – Concept Draft.

### 3.3 Cycles in Manufacturing

In the context of manufacturing cycles can be used to characterize processes, manufacturing structures, resources and technologies. As a means to document and visualize dynamic behavior, cycles not just provide valuable input for planning and decision making but also help to cope with the complexity arising from the interdependencies of influencing factors. In the following some examples of important cycles affecting manufacturing planning are listed:

- Product life cycle
- Technology life cycle
- Factory life cycle
- Manufacturing resource life cycle
- Process life cycle
- Employee cycle
- Knowledge life cycle

So far, these cycles have been modeled in their specific context not considering the need to compare or combine different cycles with regard to cycle management. As proposed in paragraph 3.2 the CIS can be used as a uniform modeling framework for cycles. To allow for comparability and compatibility the conversion of relevant cycles for manufacturing planning applying the CIS is currently in progress within *SFB 768*. First attempts of modeling and simulating interdependencies of cycles within manufacturing structures have also been made as a further step towards successful cycle management [16].

## 4 CONTINUOUS MANUFACTURING PLANNING

### 4.1 What Is Meant by Continuous Manufacturing Planning and Why Is It Needed?

Manufacturing planning sets the ground for efficient and effective manufacturing in industrial enterprises in the context of the innovation process, specifically as part of the solution creation. To date, mainly planning of one-time events with focus on establishing new manufacturing setups is subject of manufacturing planning (cf. e. g. [15,12]). For example, the installation of a new assembly line is planned in very detail, while usage and maintaining the suitability and hence the performance of the manufacturing structure and resources are taken care of mostly at an operative level. Occurring changes and adaptations in manufacturing – even foreseeable ones – are generally handled in terms of singularities and disturbances of manufacturing rather than as standard events.

Continuous manufacturing planning aims at the concurrent application of planning approaches during manufacturing execution. That means, required changes and adaptations are no longer handled as singularities but foresightedly planned, continuously evaluated and circumspectly implemented. Doing so, adaptation of production can be accelerated and smoothened enhancing the innovation process regarding duration, reactivity, flexibility and thus efficiency.

### 4.2 How Is It Done Today?

Manufacturing planning differentiates production into specific levels (cf. e. g. [17]). First results from an extensive literature review indicate, that available planning approaches mainly focus on the factory or manufacturing structure level [12]. Only few authors discuss the level of manufacturing resources in more detail (e. g. [19,18]). Most screened methods address either planning of one-time events (e. g. setting up an assembly line or developing a new factory layout) or planning of basic characteristics of production (e. g. the required level of changeability of manufacturing structures or resources or the implementation of single reconfigurations) (cf. [21,20,15]). Continuous planning of occurring changes and adaptations for manufacturing is – if at all – only mentioned as a potential application for manufacturing planning but not elaborated further. However, e. g. Hernández [15], Westkämper & Zahn [22] and Nyhuis et al. [23] consider continuous planning as one main research topic for manufacturing planning in the future.

Full results of a literature review giving insights into available manufacturing planning methods, their objectives, foci and relationships as well as detailing the need for further research regarding continuous manufacturing planning will be available in the near future.

## 5 APPLYING CYCLE MANAGEMENT IN CONTINUOUS MANUFACTURING PLANNING

Integrating cycle management in approaches for continuous manufacturing planning takes advantage of cycle know-how by enriching the input data for continuous planning. That way, the application of planning approaches concurrent with manufacturing execution can be set up not only on discrete, event-based information, but on comprehensive, time-dependent information about cycles.

With the integration of cycles, the continuous planning method itself requires and shows a cyclic character enabling a holistic, well-founded and timely management of change and adaptation in manufacturing. That means, not only cycles as influencing factors, but also the continuous planning method as a cycle-oriented planning approach becomes subject of cycle management.

Within continuous manufacturing planning, cycles and cycle-related information form the basis for a continuous implementation of changes utilizing available changeability in manufacturing. Hence, a comprehensive compilation, analysis and visualization of that data is an essential element of such a planning approach. An efficient handling of these information and management of adaptations is enabled by cyclic processes as part of the continuous planning approach.

First attempts in this direction have already been made at the *Institute for Machine Tools and Industrial Management* of *TUM*. Zäh et al. [24,25] investigated relevant cycles in manufacturing, Karl et al. [26] developed a method for the identification and determination of reconfigurations (adaptations) of manufacturing resources and Reinhart & Pohl [27] elaborated an overview of selected cycles in manufacturing structure planning. All represent sound input for further research regarding cycle management.

Overall, the continuous planning approach with applied cycle management will address two levels of manufacturing planning – manufacturing structure and manufacturing resources. As these two are closely interlinked, planning for both levels should set up on a joint information and methodological basis. From this basis both are then to be differentiated in terms of e. g. the respective manufacturing level in focus, differing relevance and characteristics of cycles or the detailing of processes in the continuous planning approach. Together, planning for both levels in manufacturing provides one comprehensive, cycle-oriented planning approach for manufacturing enterprises.

## 6 SUMMARY AND OUTLOOK

Cycle management as a potential new paradigm in manufacturing planning builds up on established ideas of single cycles such as the product life cycle and established methods for manufacturing planning. Driven by the need for a continuous manufacturing planning and a comprehensive management of cycles, the transdisciplinary unification of cycles, a manufacturing specific application and the development of a continuous planning method are discussed in this paper.

Going forward, further research will be conducted regarding the conversion of manufacturing-relevant cycles applying the generic cycle model and the CIS. Also, a strong focus will be on the elaboration of a continuous planning method with applied cycle management based on the already ongoing literature review on planning concepts and change management as well as the compilation of CIS.

The research is and further will be conducted within the *Collaborative Research Center 768* at *TUM* by subprojects B4 (“Manufacturing Structures”) and B5 (“Manufacturing Resources”).

## 7 ACKNOWLEDGMENTS

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# Morgenstadt – Urban Production in the City of the Future

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**Abstract**

Already today cities are the biggest entities of industrial and economic activity and the growth of urban populations is steadily increasing. By 2030 the number of people living in cities will rise to five billion, facing great challenges to infrastructure, economic development and life-quality induced by scarce resources, climate change and the mere number of people. Addressing the city of tomorrow and its markets therefore requires a new way of thinking for almost every industry sector. Conventional single-consumer-related products have to be replaced by integrated approaches forming whole urban systems: A new relationship of information, resources, products and users will lie at the heart of the innovation loop that cities will have to master within the next decades. Within the convergence of urban systems representing the Morgenstadt, also the production sector plays an important role and will be a crucial factor to reach a sustainable living and working environment in urban systems. This paper discusses the main challenges for our cities in the next decades and introduces five hypotheses for urban production in the Morgenstadt.

**Keywords:**

Three most representative keywords; Urban Systems; Urban Production; City of the Future

## 1 INTRODUCTION – CITIES AS LIVING LABS FOR INNOVATION AND FUTURE MARKETS

The enormous challenges of an increasingly urbanized global society drive companies, city administrations and research institutes around the world to develop strategies and solutions that address problems like climate change, resource depletion, population growth, increasing consumption, individual mobility etc. Since 2007 more than half of the world's population lives in cities - and its share is increasing. Only investments in urban infrastructures will amount to US$350 trillion within the next 30 years [1]. It is therefore undisputed that cities represent the omnipresent markets of tomorrow. But with their complex network-structures conventional paradigms of consumer-related production- and distribution strategies have to be replaced to create a lasting effect on a global scale.

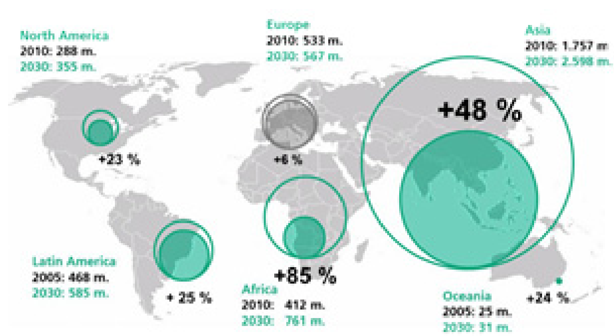


Figure 1: Growth of urban population until 2030 (UN World Urbanization Prospects, 2010).

Ecological sustainability and the pursuit of economic prosperity are the two key issues for cities in the future. Both goals can be achieved by recognizing cities as future markets for sustainable concepts of mobility, housing, communication, energy generation, production and consumption. But these concepts will inevitably link different technology sectors and products with each other in a much stronger way than today. Solutions will increasingly have to overleap sectorial boundaries and combine multiple technologies and value creation processes.

A new relationship of information, resources, products and people therefore lies at the heart of the innovation loop that cities will undergo within the next decades.

In many urban contexts – especially in Europe – solutions have been developed that boost energy efficiency, reduce carbon emissions, strengthen participatory governance and care for high quality of life. Products like zero energy houses, renewable photovoltaic energy, electric cars and participatory budgets mark a first step within the transition to sustainable and smart cities. They act as catalysts for green cities and as promoters of sustainable transition within other cities around the world. However, they fail to represent a real quantum leap in terms of urban systems innovation. This will occur when actors from different business sectors, research institutes and governance officials join together for inventing urban systems.

## 2 CHALLENGES FOR NEW VALUE CREATION

A sustainable future city system combines economic and ecologic efficiency and provides the basis for a high-quality working and living environment. Making smart use of information and communication technologies within all areas of urban life and connecting buildings, devices and people with each other is the essential starting point for systems of urban innovation. It will allow for the development of closed loops of production, consumption and recycling for resources, materials and energy within all relevant areas of urban

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material flows and at the same time provide for transparent and participatory governance.

Cities as future markets thus open up a great variety of new product segments and business strategies, but also pose a big challenge for companies and business-related ventures. Not only do they have to develop innovative products and concepts, they also have to invent new ways of sales and distribution and they have to succeed within complex networks of governance and stakeholder-management. The traditional way of looking upon individual users and consumers increasingly fails to provide the necessary solutions for complex problems of emerging megacities. The new point of departure for product development has to be the needs of a city as systemic entity that comprises several networked individual systems (energy, mobility, security etc.). In this system the product itself does not represent the most important component anymore. It is the way of organizing processes and structures with respect to the users and urban structures that makes the difference.

The big challenge is to develop unique game changers as enabler for future markets. Innovative solutions for public participation, cloud intelligence and open innovation concepts will thereby shape the pathways of transition:

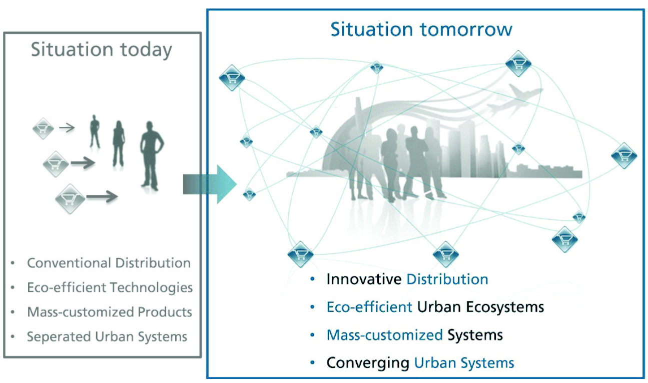


Figure 2: Developing the urban market of the future: from singular to interconnected solutions.

Creating value in the city of tomorrow will have to increasingly rely on the lasting cooperation of economic, political and social players, for risks of investments and high upfront costs need governmental support and sound governance structures. Market failures like price distortions and perverse incentives have to be tackled between companies and city administrations – or even higher governmental bodies – for ensuring the cost-effectiveness of sustainable innovations. At the same time institutional failures like short-term oriented policies and backward oriented administrations have to be addressed with fresh and innovative collaborative approaches for the invigoration of sustainable urban innovation systems.

## 3 INTRODUCING THE MORGENSTADT

On behalf of the former German federal research minister Annette Schavan and the former Fraunhofer-President Hans-Jörg Bullinger, from 2010 on a group of experts has initiated the future-oriented project entitled “Morgenstadt – an answer to climate change”, describing the vision of a typical built city of the future in Europe [2]. As stated in the initial vision its inhabitants use energy in environmentally friendly ways, transforming our cities into $CO_2$-free place (reduction of carbon emissions by at least ninety percent compared with today).

Morgenstadt, the zero emission, energy efficient and climate adaptive city, is one of the high priority forward-looking projects of the high-tech strategy 2020 for the federal government of Germany being under development. Forward-looking projects will pursue specific objectives related to scientific, technological and social development over a period of ten to fifteen years. Innovation strategies for the realization of these objectives will be formulated and will form the basis of road maps for achieving interim milestones.

To contribute to the project the Fraunhofer-Gesellschaft, Europe’s largest applied research organization, has developed a concept for a systems research Morgenstadt highlighting the demand for a systemic and holistic approach for joint research on urban production/logistics, mobility/ transportation, planning/building, information/communication, security and safety, decentralized production and distribution of energy and long-term technology management between these technology sectors.

Fraunhofer is already today developing concepts, products and solutions for all of these areas and will consequently play a key role in bringing about future cities that are sustainable and deliver high quality of life. In the Innovation Network “Morgenstadt: City Insights” which joins almost forty stakeholders from industry, cities and research several institutes from Fraunhofer engage as missing link in combining future needs and required actions in selected cities all over the world.

### 3.1 Fields of Research – Urban Systems

*Mobility*

How can the masses of people in tomorrow’s cities be moved most effectively by at the same time assuring quality of life and zero impact on the environment? Highly efficient mass transit systems like in Hong Kong or emission free mobility-on-demand solutions represent some of the groundbreaking solutions to be analyzed and developed further.

*Energy*

The future city will not depend on fossil energy. Renewable energies, energy efficient technologies and communicating energy grids will become the drive-train of tomorrow’s cities. But where will the energy be produced? Already today energy-plus-houses produce more green energy than they need. Integrated community energy solutions that link houses, wind- and solar parks, biomass sites and electric vehicles can be a starting point for an integrated urban energy system of the future.

*Communications*

Already today technologies exist that enable communication between devices, buildings, vehicles and people. Geographic information processing, wireless internet and smart-phone technology possess almost infinite potential for the development of smart solutions for urban systems. Some cities like Qatar or Mannheim already try to make use of this potential and thereby provide the framework for innovative business- logistic- and transportation processes.

*Buildings*

There are several groundbreaking technologies that allow buildings to communicate with their environment, to produce more energy than they consume and to work with light, biomass and air from the local environment. In a future city these technologies will be integrated into systems that allow groups of buildings to create closed cycles of energy- and material flows and to shape the micro climate of a city.

*Resources*

The big challenge of future urban systems is the smart and sustainable use of resources. Full integration of advanced recycling techniques into urban material flows and the holistic use of cradle-to-cradle systems for production and consumption will be imperative for the sustainable megacity of tomorrow. This also implies innovations in product design with a highest possible share of biodegradable materials or recyclable product concepts. Learning from inspiring cities will provide for the basis of future urban resource cycles.

*Governance*

A new urban paradigm needs efficient governance concepts that enable participation and acknowledge the complexity of systems innovation. Frontrunners like Zurich, Copenhagen, Amsterdam or Sydney are already working with systems that integrate citizens into decision structures and create smart collaborations between city administrations, innovative companies and research institutes.

*Security*

The resilient city of the future will already integrate security concepts and systems at the design stage of urban planning and policy implementation, therefore ensuring the capability to identify and dominate emerging risks as well as to effectively manage catastrophic situations and quickly return to normal status. New smart and multi-functional protection technologies and materials complemented by sophisticated planning tools will ensure the security of the future urban system whilst not affecting the civil liberties of its citizens.

*Production*

In the future city transportation and handling of goods will happen fluently within intelligent structures of production and distribution - presenting the backbone of sustainable trade, services and urban production. At the same time essentials have to be provided at any time to all citizens. The city of tomorrow will be involved more deeply in the provision of production and logistic services by providing, planning and monitoring specific urban infrastructure and services for production and logistics.

## 4 URBAN PRODUCTION IN THE CITY OF THE FUTURE

Manufacturing and logistics of the Morgenstadt ensure smooth process procedures such as transportation and handling of goods, commerce, services and production, as well as the provision of sustenance for residents. Future economical, ecological and social circumstances, however, will lead to a realignment of the design and the way of running of urban production sites with their logistic networks.

In the Morgenstadt, production sites will be organized in a city-friendly manner. For urban production, value-adding processes, production technologies and processes are designed and specifically selected, in order to ensure that pollution and noise emissions are minimized. Contrary to popular belief, production and city can work in close symbiosis: Waste heat, excess energy and recycled materials can be exchanged between production sites and urban supply or disposal systems. Residents of the Morgenstadt will be perfectly able to unite their individual way of life with their jobs, as production sites would be located close to residential areas and, therefore, within walking or cycling distance. Despite the decentralized allocation of single production sites within the city, the supply of production sites with (raw) materials and energy is no problem at all. This is due to the fact that companies and urban councils would work closely together. Through the common use of urban resources (e.g. trade areas and distribution channels), it is possible to highly increase production efficiency as well as relieve demand from already well-working infrastructures. Transportation of goods within the city would only take place underground (e.g. cargocaps) or in autonomous electric vehicles.

Altogether, technical and business processes for the transportation of materials and goods will change significantly with the transition to Morgenstadt. Some of the main elements of the highly innovative logistic strategy of Morgenstadt include new solutions for the possibility of good transportation, altering organisation forms for transportation in concentrated traffic areas and the efficient use of existent infrastructure through collaborative focusing on value streams. Private households will be well provided for with all vital goods through new supply channels. In addition to shopping in retail and groceries stores, residents will be able to use new options for the transition of goods: distribution transports, automated goods delivery, express goods delivery services and other “last-mile solutions”, which are specifically designed towards the needs of certain residential areas and will be provided for public use. “Last-mile solutions” combine many services of commerce and manufacturers, which help to implement the very personal wishes of people.

The Morgenstadt as a city, will be more strongly involved in the delivery of production and logistic services - through provision, planning and surveillance of certain urban infrastructures and other parts of production and logistic tasks - than today’s cities. For that reason, the Morgenstadt uses certain planning departments, necessary IT instruments as well as important business concepts to retain important services provided together with commerce and manufacturers.

Energy and resource efficiency are important aspects of urban production and have been discussed on many occasions. In the following five additional hypotheses for urban production beyond sustainability are introduced.

### 4.1 Five Hypotheses for Urban Production

*1. Urban Production – integration of market and customer*

A local vicinity to the market permits new forms of customer integrated product development in urban production. For a vast number of products, new individual solutions can be developed through an emerging vicinity to the potential clients. New solutions require a continuous adjustment of production processes in a versatile factory that reacts even with small range of units to conditions of increasing volatile market behavior. Depending on the product, the market vicinity allows for new business models that are beyond the scope of ongoing product and service integration. Telling examples therefore are so called Physical Apps – customer specific individualized components for off-the-shelf products - which can be produced in small numbers so fast that the product experience of the customer even begins with the production process.

*2. Urban Production – 24-hour run for new ideas*

A local vicinity to internal and external production network leads to a formation of numerous decentralized cross-linked Micro Fabs, Rapid Prototyping workshops that have the ability to manufacture individual products in the short run. Through the use of agile methods, the interdisciplinary processes of integrated product and process formation can be significantly accelerated. The broadening of the productive time, in terms of product creation, towards a 24/7 principle (product creation around the clock) requires a faster transformation of product concepts into their production (Xtreme Process Engineering). The linking of production and development networks will be continuously affected by means of simulation-aided planning. Therefore aspects of city visualization including the participative planning of logistical and transportation processes can be deployed through the use of Virtual Reality.

*3. Urban Production: flexible working time – stable future*

A local availability of qualified labor allows for a highly flexible reaction to permanently changing environmental conditions. Intertwined capacity deployment in several production units diminishes idle time and significantly increases the value-added capacity deployment, and therefore, the productivity. Multi-Jobs will permit employees to work for many companies. A need for standardized and intuitive operational work processes, workplace and working environment beyond company borders is therefore existent. Flexible labor deployment is not regarded as a negative point anymore, but is seen as an opportunity for higher employment security, increasing time sovereignty and better social participation.

*4. Urban Production – I work, where I live*

A close vicinity to the living environment of employees makes Patchwork-Relationships, which allow employees to be on duty in several companies, possible. Therefore, the possibility to dissolve boundaries of rigid working time and fixed working places arises. In the production, accruing idle time can be used more effectively by the employees. Technologies and methods for higher employee involvement allow everyone to decide, to the extent necessary, when and where the employee will work in the urban production. Decentralized alignment processes via context-sensitive mobile devices return additional pieces of lost time sovereignty to the employee that could be used for other objectives, such as volunteer work, childcare or leisure. On one hand this development needs a change in thinking from the perspective of all participants (company, employee, unions and municipality) and on the other hand, the willingness for continuous training and qualification required for the needs of new technologies, innovative planning and control processes. Cooperative networking during the work planning, for instance, makes a productive and fulfilling form of work and life integration in the urban environment possible.

*5. Urban Production – age-appropriate working in the city of tomorrow*

The vicinity to all production and living environment facilities allows for age-appropriate working. Shorter distances between residence and work places permit short working time, part-time and infrequent work. Changes in lifestyle expectations enhance rest periods of employees and ensure their know-how for the employer. Older employees can freely arrange their working time and cover specific hours that hamper young families. These circumstances allow older employees to contribute their capacity and expertise in case of urgent need.

## 5 CONCLUSION

In this paper the main challenges for our future cities deriving from global megatrends were discussed. In the coming years it will be our obligation to fully understand these social and technological developments in the context of an interconnected urban system and to utilize them for the benefit of the society. Focusing on the production sector in the city of the future five hypothesis for urban production were presented

In the long run, in order to develop integrated future urban planning processes with regards to specifications of urban environments, methods for participation and planning are required. A useful tool would be the development of a Virtual Urban Engineering method kit. Therefore, Virtual Engineering method modules should be combined with public participation. Usage of method elements from social media area, citizen experience research and the Open and Bid data approaches are especially applicable.

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# Tools and Methods for SMEs to Introduce Mutability in Special Purpose Machines

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**Abstract**

In the paper tools and methods for customer oriented development of mutable production systems are presented. An easy to use benchmark, taking into account the complete life cycle, enables system manufacturers to assess their approach regarding own expenses as well as from a customer's perspective, making one able to legitimate specific measures and according costs during the acquisition phase. Furthermore, a tool using the commonly known structure of the House of Quality enables the customer to evaluate various technical options provided by the manufacturer. By means of prioritizing requirements for the mutable system as well as including interdependencies between eligible options, a best suiting configuration of variants can be determined. The paper therewith especially focuses on methods and tools to help manufacturers of complex production systems to introduce mutability in a reasonable extent.

**Keywords:**

Reconfiguration; Evaluation; Development

## 1 INTRODUCTION

In consideration of current and future conditions of the global economy, where dynamic markets lead to an economic environment characterized by uncertainty and short term changes, enabling mutability in production systems is an important task. This is even more essential for special purpose machines, which are built for high volume production of very specific products and thus rarely provide any flexibility. However, to ensure the possibility to adapt to new requirements without compromising system performance and productivity, measures for enabling reconfiguration on demand have to be implemented. Despite functional aspects, the reuse of investment and resource intensive components is another important driving factor for mutability in special purpose machines.

A joint research project approaches the task on a conceptual, methodical as well as on the technical level by directly transferring results to industrial trial. In order to introduce mutability tailored to suit the demands, a holistic method for comparing technical options based on customer requirements was developed. The method was implemented in different tools to help manufacturers to handle such complex tasks. The methods and according tools to apply them were kept as plain as possible to specifically meet the needs of small and medium-sized enterprises (SMEs).

## 2 BASIC APPROACH

Research regarding a holistic methodological approach towards mutability is mainly conducted on the level of factory planning [1], [2]. In the context of production system development however, shortcomings regarding the level of knowledge can be stated. Although concepts for the systematic identification of drivers for change and the deviation of scenarios [3] as well as methods for layout planning of mutable factories [4] exist, there is still a need for easily manageable methods on system level, which include technical, organizational and also economic aspects.

Within the joint research project "WPS – Wandlungsfähige Produktionssysteme" a methodology for customer oriented development of mutable production systems is being developed together with industry partners. The methodology can be easily adapted to each participating SME by adjusting formal utilities to the according needs.

In this context different tools were developed which can be combined to a user specific procedure. These tools include a *status questionnaire* as a first simple step to comprehend the current state regarding mutability in each company as well as the influences affecting the own products. System manufacturers are asked to assess current solutions in their portfolio regarding exposure to change, the quantity of occurrence, measures taken to react as well as optimal measures presuming a mutable production system. From this, key aspects of activity in terms of domain and hierarchy level are derived and the focus of work for different types of production systems can be specified.

The second tool is used for an *economic evaluation* of the company's products over their life cycle. Therewith, necessary measures derived from the questionnaire can be evaluated regarding their economic impact, identifying the costs that accrue during the different phases. This tool can either be applied for overall measures regarding a group of products and the whole product portfolio or for single products, making it a universal aid for estimating the financial efficiency of mutability.

To support the development process and ensure the inclusion of economic constraints during its course, a third tool was introduced, which is based on the idea of the *House of Quality*, known from quality management. It is used to combine customer requirements with existing and/or possible technical solutions provided by the according manufacturer. It enables to allocate certain measures regarding mutability on the engineering level to according requirements, giving the advantage to build and assess different product variants at a very early stage of development.

Figure 1 represents a possible work-flow using the introduced tools. While the questionnaire is intended to be an entry point towards considering mutability in the development process, the evaluation

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table and the House of Quality can be seen as consistent aids assisting product development in an iterative manner. These two will also be presented in more detail within this paper.

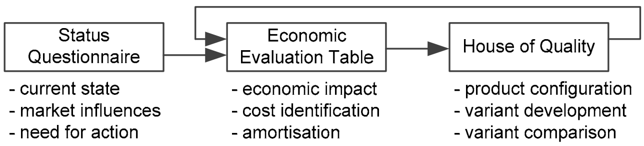


Figure 1: Developed tools and their outcomes during the work-flow.

## 3 TOOLS FOR NEED BASED MUTABILITY

### 3.1 Assessment of Cost Impact

Analysis and assessment of economic efficiency for mutable production systems is a topic hardly explored. Especially for system manufacturers, approaches using target costing come to mind, but have to be examined deeper in this context. The consideration of mutability adds further aspects to take in mind - such as effects of changing cooperation relations, changing or unknown risks as well as the ability to deliver certain services. Existing research focuses on typical risks in the delivery of products and services of conventional nature [5].

Various scientific approaches, especially in the context of investment appraisal including uncertainties, were analysed in terms of applicability for mutable production systems. This includes preliminary work regarding scenario techniques [6] as well as risk analysis for dynamic cooperation networks [7].

It was assessed that especially for SMEs complex scientific methods to predict the demand for reconfiguration and the quantification of risks is not reasonable due to the enormous time and effort needed in comparison to the small increase of predication accuracy. Considering the projects focus on special purpose machinery manufacture the inclusion of customers' point of views regarding the predicted development of according markets is not conducive. In fact, an empirical approach based on the experience in conducted projects was identified as most reasonable. Here, existing systems and methods of project documentation can be utilized by each system manufacturer for a project specific prediction of the need for mutability especially in the context of price formation.

For this purpose a form was developed as an excel tool which can be used to estimate the economic effects of introducing mutability over the life cycle for a specific product portfolio or single product. The main focuses of this table are to quantify cost differentials caused by introducing mutability, allocate them to certain phases of the systems life cycle and provide a basis of decision-making in the context of risk evaluation taking into account possible quantities of events leading to reconfiguration.

To allow cost allocation to the according phases of the system life cycle, sections were divided as shown in Table 1. Costs $K_i$ being accumulated from development until primary operation of the conventional system, representing the sum of cost $K_i$ for phase 1, are used as cost base ($K_{ent}$*=100%*).

$$K_{ent} = \sum_{i=1}^{n} K_i = 100\% \tag{1}$$

For each cost object $K_i$ belonging to phase I the value $K_i$ for each single matter of expense (e.g. mechanical design, purchase part), representing the non-mutable system, is specified by its percentage of cost base $K_{ent}$*=100%*. The costs for introducing mutability can be expressed through $W_i$ which describes the percentaged change of each value $K_i$ in this context. The value of cost change $P_i$ referred to the overall costs of each life cycle phase can be obtained by

$$P_i[\%] = \frac{K_i[\%] \cdot W_i[\%]}{100\%} \tag{2}$$

with the percentaged change of costs for phase I being

$$P_{ent} = \sum_{i=1}^{n} P_i \tag{3}$$

Costs for the reconfiguration process $K_j$ and disposal $K_k$ are also specified by their percentaged value towards $K_{ent}$. Since $K_j$ are cost objects occurring during "reconfiguration" of a non-mutable system, they can either refer to different kind of modifications or the purchase of a new system. The values for *W* and *P* are calculated accordingly. With this approach, costs in the reconfiguration and disposal phases can be depicted as percentage of $K_{ent}$ enabling the system manufacturer to assess expenses for enabling mutability in relation to the costs for the conventional system. For a mutable system, higher estimated costs in phase I can thereby be contrasted and evaluated to savings during phase II and III.

In conclusion the tool helps to achieve information regarding

- relative cost difference between conventional and mutable system
- Possibility of assessment from either manufacturer or customer point of view
- Calculation of investment costs as part of target costing processes or price negotiations
- Assessment of follow-up costs during operation, reconfiguration und disposal
- Systematization and inclusion of cost factors from the entire life cycle
- Traceability of cost impacts back to single cost objects and identification of main cost changes owed to enabling mutability
- Calculation of cost amortization regarding different quantities of reconfiguration processes

| **I. Development / Operation** | | | | **II. Reconfiguration** | | **III. Disposal** |
|---|---|---|---|---|---|---|
| *Acquisition/ Distribution* | *Planning / Design* | *Manufacturing* | *Initial Operation* | *Planning* | *Reconfiguration* | |
| cost positions ⁝↓ | cost positions ⁝↓ | cost positions ⁝↓ | cost positions ⁝↓ | cost positions ⁝↓ | cost positions ⁝↓ | cost positions ⁝↓ |

Table 1: System life cycle phases for cost allocation.

### 3.2 House of Quality

*Introduction to the Method*

The House of Quality is a method used in the Quality Function Deployment relating to Yoji Akao [8]. The Quality Function Deployment itself is an established method regarding tasks of quality control and has been considered for various fields of application, like e.g. production processes [9] or software development [10]. Goal of the Quality Function Deployment is the planning and development of products to be optimally adapted to the customer's requirements, which is reflected in the method of the House of Quality. In the following, after giving a basic introduction to the original method, a basic approach will be proposed, how this method is applicable to support a customer oriented planning and development of mutable special purpose machines. For further introductory information to the method please refer to the relevant and extensive literature on the topic, like e.g. [8] or [11].

The method House of Quality can be used to derive design requirements, which are optimal with respect to the customer's requirements. Therefore the customer's requirements and the design requirements for the circumstances of the case need to be collected and compiled in a list. They represent the dimensions of the current case's examination and can be mutually brought into relationship by arranging customer's requirements as columns and design requirements as rows of a matrix (see Figure 2).

Each cell of the resulting matrix now represents the relationship of a defined customer's requirement with a defined design requirement and will be rated by the manufacturer according to a predetermined scale.

Another essential element of the House of Quality are the correlations of the design requirements, which are stacked in a triangle above the list of design requirements and lead by their roof-like appearance to the name of the method (see point 4 in Figure 2). For each pair of design requirements exactly one cell in this triangle of correlations exists, in which this pair gets rated. Normally, the dimension for that evaluation consists of the range positive, negative and no influence, whereas other range values are feasible. This triangle of correlations formally describes the fact that a combination of two design requirements affects the resulting design in the evaluated way.

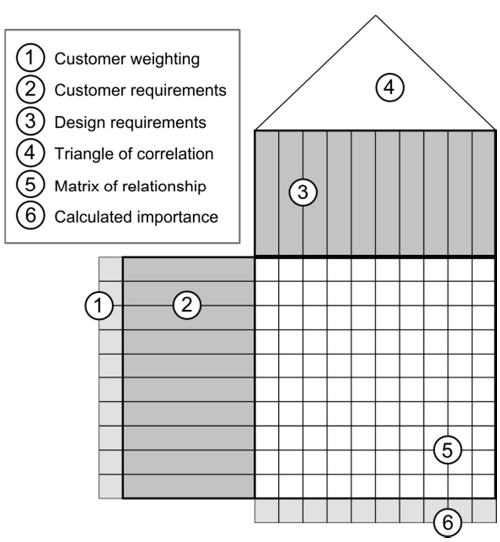


Figure 2: Schematic overview of the method House of Quality.

After a House of Quality is created, it can be submitted to the customer describing his request formally by weighting the customer's requirements. Based on the completed matrix of relationship from the manufacturer's side and the customer's weighting, an importance can be derived for each design requirement by multiplying the evaluation of each customer's requirement with its associated weighting and by summing the resulting values.

The derived importance now indicates which design requirements are particularly essential to fulfil the customer's preferences and gives a formal basis upon which further steps of the product planning can be facilitated.

Besides the above stated basic modelling structures of the House of Quality, other structures are feasible, such as the comparison of the own product to potential competing products, or the assessment of technical difficulties of design requirements. Ultimately, the actual application is crucial, which modelling structures are useful or necessary and may be supplemented therefore.

*Using the House of Quality for Planning and Development of Mutable Special Purpose Machines*

In the research project WPS the House of Quality was considered to provide a partially formal approach to the planning and development of mutable special purpose machines. With respect to the original approach of the House of Quality, the objective is to support the planning and development of mutable equipment that is to be designated as optimal for the customer's preferences, as well as for his assessment of potential change drivers.

Using this approach the goal is to assist the planning process through a two-step procedure using derivations of the House of Quality. Thereby the first step describes the comparison of variants and the second step represents an evaluation step.

*Comparison of Variants*

For the first step of the two-staged approach, the goal is to select out of a set of possible technologies or strategies within the treatment area of the manufacturer, those that are optimal for the customer's requirements, and derive a mutable product variant out of them. In this approach, technologies and strategies are treated similar to the design requirements in the original approach, which differ in the provision of various enablers of mutability and thus affect specific customer requirements differently. For example, the manufacturer could provide different types of connectors for the media supply of technology stations. Should changes of technology stations be considered as a common scenario by the customer, the choice of a uniform connector would be conceivable, whereas a low-cost special connector can be provided if this scenario is considered unlikely. As technologies several alternatives of real components or modules that can be supported by the manufacturer are appreciated, while strategies are rather different approaches that the manufacturer can employ within product planning and development. Often this relationship cannot clearly be separated, because various strategies may affect the use of various components and vice versa. The technologies and strategies which are taken into account to derive a product variant are specific to the manufacturer and may also vary by the given product class.

Within the project the customer requirements were defined regarding commercial and technical aspects of the special purpose machines on one side and requirements for mutability on the other. As shown in Table 2, mutability aspects can be subdivided into the time required for preparing and realizing the reconfiguration in case of mutability as well as into the probability of the occurrence of special drivers of mutability. Herein we subdivide into geometry, lot size and technology, wherein others are possible. So the customer for example can express that changes of lot sizes within the lifetime of the machine are very likely whereas technology changes are rather uncommon. It can be assumed that the definition of the customer's requirements is deemed to be generic and may therefore be substantially transmitted to other application areas.

| | | |
|---|---|---|
| Mutability | Drivers | Geometry |
| | | Lot size |
| | | Technology |
| | Time | Preparation |
| | | Realisation |
| Technical aspects | | Productivity / lot time |
| | | Rebuilding / variants |
| | | Requirements of precision |
| | | Service kindness |
| | | Energy efficiency |
| Economic aspects | | Acquisition costs |
| | | Costs of mutability |
| | | Delivery Time |
| | | Design |

Table 2: Identified customer requirements.

With respect to the original approach of the House of Quality, an importance for each technology or strategy of the manufacturer can be derived from the weighting of the customer’s requirements and the completed matrix of relationships. This defines a proper base for the derivation of the optimal product configuration in compliance with the correlations between the considered technologies or strategies.

The derivation of the optimal product configuration is a very complex task, because e.g. even a set of twenty technologies or strategies result in about one million possible product configurations to be considered. So an algorithm was developed, which formally evaluates all possible configurations, and serves a sorted list of them according to the determined evaluation result.

The evaluation result by the algorithm consists of the evaluation of the selected technologies of a product configuration, and the evaluation of the correlations between them.

$$C_{conf} = C_{technology} + C_{correlation} \tag{4}$$

In the technology evaluation, all importance values of the selected technologies or strategies, derived by the original method, are summed up. A configuration thus benefits from well-rated selected technologies.

$$C_{technology} = \sum_{t \in T} I_t\,; \quad T \ldots selected\ Technologies \tag{5}$$

Furthermore, relations between two selected technologies are assessed so that for each pair of technologies the sum of their importances is multiplied by the factor $w$, which is determined by the type of the correlation. Thus, a configuration benefits from positive correlations between selected technologies or strategies.

$$C_{correlation} = \sum_{\substack{t_1,t_2 \in T \\ t_1 \neq t_2}} w_{t_1,t_2} * (I_{t_1} + I_{t_2}) \tag{6}$$

The factor $w$, determined by the type of correlation, can be adjusted and should be chosen either positive or negative according to the relationship, whereat its absolute value indicates the impact of correlations on the overall result and can be adjusted accordingly. It is also possible to provide different levels of positive or negative relationships in the House of Quality and to consider these by different absolute values of the factor $w$ in the evaluation.

In addition, a special correlation for the triangle of correlations was introduced, which specifies technologies or strategies to be considered as mutually exclusive. Product configurations having this correlation are therefore invalid and will not be evaluated further by the algorithm. This technique may reduce the complexity of the evaluation significantly under certain circumstances.

The specially developed evaluation algorithm can be used as an assistant to make the vast amount of possible product configurations accessible to the user. Thus, in addition to a sorted list of all valid product configurations the best rated product configurations can be visualized graphically with respect to the customer requirements. It can be assumed that using this basis, the user can compare configurations with each other much better, in order to derive optimal product configurations acting as a framework for the development of concepts for customer oriented mutable special purpose machine.

*Evaluation Step*

The optimal product configuration determined by the comparison of variants can serve as a basis for an initial concept of the desired special purpose machine. After the creation of that concept, included technologies or strategies can be evaluated much clearer regarding their affection to the customer’s requirements or their correlation to each other. Therefore it can be useful to re-evaluate the concept in a second review step with respect to the customer's requirements and compare it with possible alternative approaches. In contrast to the comparison of variants, the evaluation step is closer to the original idea of the House of Quality, resulting in relatively few adjustments from our side. However, for the evaluation step the matrix of relationships has to be determined separately for each considered concept, which can be a relatively expensive part for the manufacturer, especially if multiple alternate concepts are taken into consideration. However, the result of the evaluation step can be considered to be much more precise than in the comparison of variants and may therefore expose further aspects to be considered in the planning phase what may result in a more detailed assessment of the concept for the desired mutable special purpose machine.

## 4 APPLICATION OF TOOLS AND METHODS

The proposed formal tools can be integrated into a vendor-specific overall strategy, for supporting customer-oriented development of mutable special purpose machines on the one hand, and the progressive development of the manufacturer`s product portfolio towards the support of reconfiguration aspects on the other hand.

*Supporting Planning and Development of Customer-Oriented Mutable Special Purpose Machines*

To design and develop customer-oriented special purpose machines, the presented House of Quality for the comparison of variants can serve as a basis for the derivation of an optimal product configuration from the proprietary product portfolio. This production configuration can be extended to a first concept for the mutable system. Since the evaluation of the comparison of variants is rather rough due to its generics, a more precise verification regarding few alternative approaches, which may also be derived from well-rated alternative product configurations of the comparison of variants, can be performed using the House of Quality evaluation step. Besides, the proposed rating table can be taken into account to test and optimize derived concepts in terms of their cost-effectiveness.

*Inspection and Improvement of the Product Portfolio*

In order to develop customer-oriented mutable special purpose machines, it is furthermore essential that customer requirements are optimally served on the one hand and a positive cost-benefit ratio of the mutable system can be facilitated both for the manufacturer, as well as for the customer on the other hand. For this a perfectly aligned product portfolio is essential, which can be verified with the proposed evaluation tables. In addition, the House of Quality for the comparison of variants can be used to optimize the applicability of the current portfolio regarding requested customer requirements.

## 5 CONCLUSIONS

In this paper different methods and tools for customer oriented planning of mutable special purpose machines were presented and it was shown how a possible workflow can be facilitated by their use.

It was shown how the planning and development of mutable special purpose machines can be improved by a partially formal approach both in the short term as well as in the long term, for the purpose to make these machines more cost-effective and better adapted to the customer's situation. In the short term, the planning and development can be improved by using the House of Quality and thus increasing the transparency regarding which specific requirements of the customer lead to what technical realizations and what are the reasons for taking certain enabler of mutability into consideration while discarding others.

In addition, the formal approach allows a comparison of multiple alternatives supporting the identification of customer's requirements more early and comprehensively in the planning process. Furthermore, the results of the House of Quality can be used in long term to identify whether components within the portfolio of the manufacturer need to be added, improved or discarded. The proposed cost-benefit calculations can furthermore identify potentials for cost reduction in certain life cycle phases of the special purpose machines.

## 6 ACKNOWLEDGEMENTS

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# A Three Level Model for the Design, Planning and Operation of Changeable Production Systems in Distributed Manufacturing

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**Abstract**

This paper reviews the state of the art in reconfiguration of distributed production systems and develops an integrated model for the design, planning and operation of changeable production systems in distributed manufacturing. For the model development, a heuristic research method was applied involving a selected group of experienced experts. To test the practical relevance of the model, it was successfully applied for the design of a geographically distributed manufacturing network based on scalable and modular manufacturing units.

**Keywords:**

Production Systems; Changeability; Distributed Manufacturing

## 1 INTRODUCTION

The globalisation of the markets and the worldwide competition forces the enterprises to implement new technologies and organise themselves using new concepts in order to maintain their competitivity [1]. The global competitive pressure and the dynamics of the market continue to grow and require a high degree of flexibility of producing enterprises: hardly predictable volumes and shorter innovation cycles require production systems that not only produce high quality products at low costs, but also allow a quick reaction to changes in market and customer needs. In this context, market responsiveness can be considered the rate at which a production system is able to adapt to changing market and business objectives in terms of volumes, product mix and innovation [2]. However, an increase in market responsiveness is often associated with higher resource utilization and major cost disadvantages [3]. To meet all these challenges, the manufacturing industry is increasingly requiring concepts related to distributed modular and scalable production systems as a solution for enhancing market responsiveness at a manageable level of fixed costs and of the related risks.

Distributed Manufacturing was originally focused on manufacturing architecture and control within single plants; later it was extended to the virtual manufacture of products and the networked organization and includes all issues surrounding industrial networks [4]. A production system should not only produce high quality products at the lowest possible price; it should be also quickly adaptable to market changes reacting to consumer behaviour and trends. Geographically distributed production facilities composed by reconfigurable production systems allow these quick adjustments of production capacity and functionality with respect to local customer needs [5]. In this context, production system design becomes an increasingly complex and dynamic task, focusing not only on the efficient and systematic organization of the production resources within a single production system but also extending the boundary of design to a corporate value chain of various individual production systems interacting in collaborative production networks [6].

Diverse authors promote the concept of agility [7, 8, 9], changeability [10, 11, 12] mostly referring to the same or at least a very similar idea of a manufacturing system that shifts quickly between product models ideally in fast response to customer demand [9].

In many research works about Distributed Manufacturing the main focus has been given often to isolated aspects of layouts, organizational structure, process design or collaboration mechanisms [13]. A comprehensive approach for the design of scalable modular production systems that promote distributed production in collaborative networks in a highly dynamic environment is still missing.

This paper reviews the state of the art in reconfiguration of distributed production systems and develops an integrated model for the design, planning and operation of changeable production systems in distributed manufacturing. For the model development, a heuristic research method was applied involving a selected group of academics and practitioners, all of them experienced experts in the field of production systems and supply chain network design. First, the state of knowledge and future trends in the field of interest were analysed based on literature review and incorporated into a workshop guide. In the next step, a group of experts was asked within a guided workshop about their experiences and perceptions of future developments and trends in the design, planning and operation of changeable production systems in Distributed Manufacturing. The results of the expert workshop were summarized and analysed. On this basis, a three level design framework was developed: at the highest or design level, the elements and rules for the production system and network design are defined. The planning level includes the production system and network planning processes to realize an interaction-enabled production network. At the implementation level the operational processes are described, which drive the "steering" of the orders through the networked distributed production system.

To test the practical relevance of the model, it was successfully applied for the design of a geographically distributed manufacturing network based on scalable and modular manufacturing units.

## 2 LITERATURE REVIEW

Most efforts in Distributed Manufacturing have been directed towards applications of information technology from the mid-1990s onwards [14] like the design of its architecture [15, 16], resource and task allocation [17, 18], and scheduling and control [19, 20, 21, 22]. Later, as more research emerged, additional approaches and philosophies around the topic of Distributed Manufacturing such as Holonic Manufacturing Systems [21, 22], Bionic Manufacturing Systems (BMS) [23, 24], Fractal Factory and multi-agent systems

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[1, 25, 26] and the networked organisation [27] were developed. However, the impact of this expansion has been little discussed because of the traditional focus on information technology [14]. All of the concepts have basic properties in common, including autonomy, distribution, decentralization, flexibility, adaptability, and agility [28]. Research into industrial networks has mostly neglected the dynamic forms of communication and coordination [14]. Collaboration is a hot topic in industrial networks and needs expansion beyond the current concepts to arrive at a more grounded theory [29, 30]. Manufacturing systems should present self-organisation features and re-organisation techniques in order to adapt to the external changes. The way to represent the re-organisation techniques and the responsibilities associated to the trigger of the reorganisation is a complex task, which requires additional research in order to develop a standard model to represent those techniques [1].

Driven by many of the requirements outlined before, a number of research, development and protoyping programmes are currently underway world-wide in order to provide support for modular, distributed manufacturing production units which are readily integrable. The focus of much of this research is essentially the development of system capabilities for so called "*plug and play*" manufacturing, where production units can be rapidly interchanged, reconfigured and yet be capable of determining their own role in production [31]. These type of modular solutions are commonly used both in the design of machines and equipment as well as in the construction of manufacturing systems which allow to build reconfigurable manufacturing systems [32].

In the literature there are a number of discussed approaches about flexibility, modularity and reconfigurability of manufacturing facilities as well as for changeable and agile production systems [2, 7, 8, 9, 10, 11, 12]. The term flexibility is often used in the context of flexible manufacturing systems [33] and describes different abilities of a production system to handle changes in daily or weekly volume of the same product (volume flexibility), to manufacture a variety of products without major modification of existing facilities (product mix flexibility), to process a given set of parts on alternative machines (routing flexibility) or to interchange the ordering of operations (operation flexibility) on a given part [34]. Scalable modular systems satisfy changing capacity requirements efficiently through system reconfiguration, and in the early flexible manufacturing literature, this capability is called expansion flexibility [35]. According to Browne et al. [36], Sethi and Sethi [37] and Abdel-Malek and Wolf [38], expansion flexibility references the capability to expand or contract production capacity of a Flexible Manufacturing System using a modular structure. Scalability is a key characteristic of reconfigurable manufacturing systems, which allows adjusting the system throughput capacity rapidly and cost-effectively to abrupt changes in market demand. Adding or removing machines to match the new throughput requirements and concurrently rebalancing the system for each configuration, accomplishes the system reconfiguration [39]. One of the major challenges at the early design stages is to select a manufacturing system configuration that both satisfies the production functional requirements and is easy to operate and manage [40], especially in terms of its adaptability to changing environmental factors.

The following two research works show two examples of modular and reconfigurable production systems, which are also applicable for Distributed Manufacturing:

Hildebrand et al. [41] developed a so-called PLUG+PRODUCE concept, which could be applied also for distributed manufacturing systems. The research aims were to develop a modular factory concept, which should enable particularly for small and medium enterprises, to expand the production without much effort and move the production facility also to a new location. The research focuses on the design of a standardized "type factory" with the aim to duplicate it without great effort. However, the approach is based on a specific example of the industrial partner in the research project and can therefore be used as a good example but as an only limited guidance for the design of production systems for distributed manufacturing systems.

Zäh and Wagner [42] developed in their research project named "Market-oriented production of customized products" a concept of mini-factory structures. The objective of the project was to develop a modular concept of a mini-factory for the purposes of mass customization. The design of the mini-factory is based on a modular kit which differentiates in necessary basic modules and optional modules. The requirements for the mini-factories are similar to those from the task of this work, but it is strongly focused on the topic of mass customization. The concept therefore has significant weaknesses to be generally applied.

Only few of the shown approaches in literature, to achieve changeability and reconfigurability in manufacturing, provide information on the specific application in decentralized structures and Distributed Manufacturing networks. All the discussed approaches show important and relevant findings for this work, but are not universally applicable concepts. Therefore, in the present paper an approach is demonstrated which can be used for design, planning and implementation of changeable and distributed manufacturing systems.

## 3 HEURISTIC RESEARCH APPROACH FOR THE DEVELOPMENT OF THE DESIGN-MODEL

The development of the model presented in this paper is based on a project, whose goal was to develop a new production system for distributed manufacturing, which fulfils todays but even more future requirements in a medium and long term horizon. The second challenge was to develop not only a new production system, but also to standardize the future procedure for the development of the model. There were various approaches available, including customer surveys (e.g. Delphi method) or the analysis of competitors - even cross-industry - in order to solve this problem. It became quickly clear, that using classical approaches, the focus of the project, namely the development of a forward-looking, long-term replicable model, not or only partially could be achieved The customer on the one hand, can possibly relate only to current needs and competitors on the other hand helps only bringing very short-term limited inputs for the development of the future model. It was therefore necessary to find other methods and procedures for problem solving - "Thinking against the rule through creativity."

### 3.1 Short Description of the Heuristic Research Approach

To obtain the necessary vision, an interdisciplinary team was formed, consisting of process owners and national and international experienced experts who were involved in the specific industry as well as in other related industries. The composition of the team should lead once to the fact that ideas and trends from different sectors could benefit from each other, on the other hand this composition should ensure that the developed model respects the specific restrictions of the specific industry. Figure 1 shows the applied approach of the heuristic research.

In the first step, the industry-specific and general future trends, which were associated in the project, were examined. Among the most important in this case were supra-adaptability, concentration on human capital and collaboration in networks. These were the guidelines for the development of a new design model for distributed manufacturing systems.

In the second step using various creative and product development techniques (brainstorming, Axiomatic Design, etc.) in guided workshops were derived customer value/customer needs and functional requirements from these future trends. On the basis of these functional requirements were derived then suitable design parameters and, if possible, measurable objectives. The method of Axiomatic Design was a very helpful and useful tool to derive based on functional requirements a set of design parameters and guidelines for systems designer. Simultaneously to derive the design parameters Axiomatic Design allows the determination of an optimal path and an ideal sequence of the determined design parameters to reduce the complexity in planning and implementation of the manufacturing system.

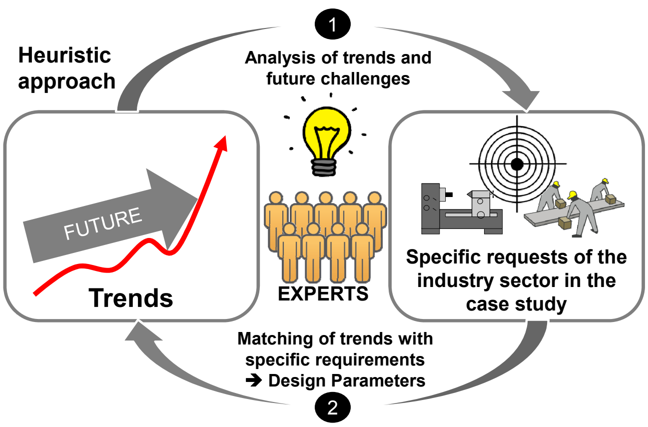


Figure 1: Structure of heuristic research approach.

In the final step, the results were combined and concentrated in clusters and grouped thematically. It has been found out, that the elements could be clustered in an optimum manner differentiating by three different hierarchical levels: (1) an innovation level, (2) a coordination level and (3) a fulfilment level.

### 3.2 Results of the Expert Workshops

The result of the guided expert workshops was a hierarchical structure of the approach to design and implement a changeable manufacturing system using three levels as shown in Figure 2:

1. *Innovation (Design Level)*: This level consists in a strategic definition of the design guidelines of the manufacturing system. To guarantee a certain dynamics, the design model should be reviewed and adapted periodically.
2. *Coordination (Planning Level)*: To enable the fulfilment and implementation of the manufacturing system, it is necessary to ensure that decisions and solutions are scheduled: the activities have to be planned and coordinated.
3. *Fulfilment (Operational Level)*: The manufacturing system should operate correctly and precisely fulfilling the defined functional requirements.

Based on the identified and in Figure 2 showed three levels was developed a design approach and framework for the design and implementation of manufacturing systems.

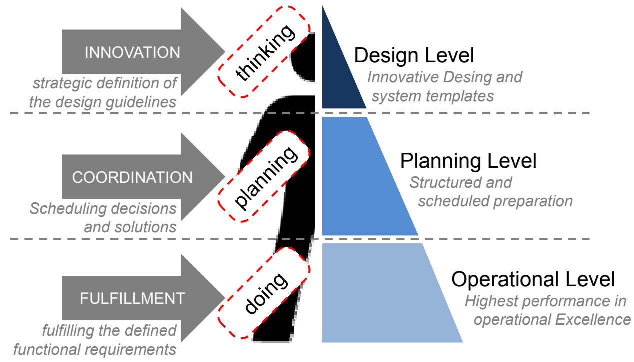


Figure 2: Three identified levels in the approach.

## 4 THREE LEVEL DESIGN FRAMEWORK OF DISTRIBUTED AND CHANGEABLE PRODUCTION SYSTEMS

To give system designers of distributed manufacturing Systems a tool for the design and implementation the following three-level model based on the findings seen in the section before is proposed (see Figure 3). The model illustrated here has both, the three identified levels, as well as a feedback loop for the continuous adaptation of the Manufacturing Systems. The shown approach was developed and applied exemplary in a real case study. The company in the case study is a new Italian franchise brand, which has begun his activities several years ago with the opening of its first own outlets. The specialty of the company in the case study is the combination of coffee shop and self-made products in a shop. For the production of its own products, the company has established in advance an own pilot production unit. After the initial experience with the pilot production and outlets in the pilot market, the company pursued the vision of an international chain of franchise outlets and started at the end of 2010 a project for the development of a concept for global expansion and the related supply of the outlets. Due to the required freshness of the products, the limited shelf life and because of possible local needs of customers in the target countries, the company decided to produce with geographically distributed franchise production units.

### 4.1 Definitions and Terminology

For a better understanding of the elaborated framework two introduced terms have to be defined previously:

*Design Elements (DE):* A Design Element is equivalent to the term design parameter in the common Axiomatic Design language. A Design Element describes a concrete design solution derived from the functional requirements of a production system.

*Design Field (DF):* The so called Design Fields represents a clustering of the identified design parameters or Design Elements into thematically coherent groups.

### 4.2 Normative Design Level

At the normative level or Design Level, the system designer defines the design of the manufacturing system. At this level, Design Fields with Design Elements (Design Parameters) are elaborated and defined. Thus the modelling framework with its design templates is created. The horizon of the Design Level is long term and is thus over a period of five years. Periodically, the Design Fields and Elements, however, should be checked for any necessary

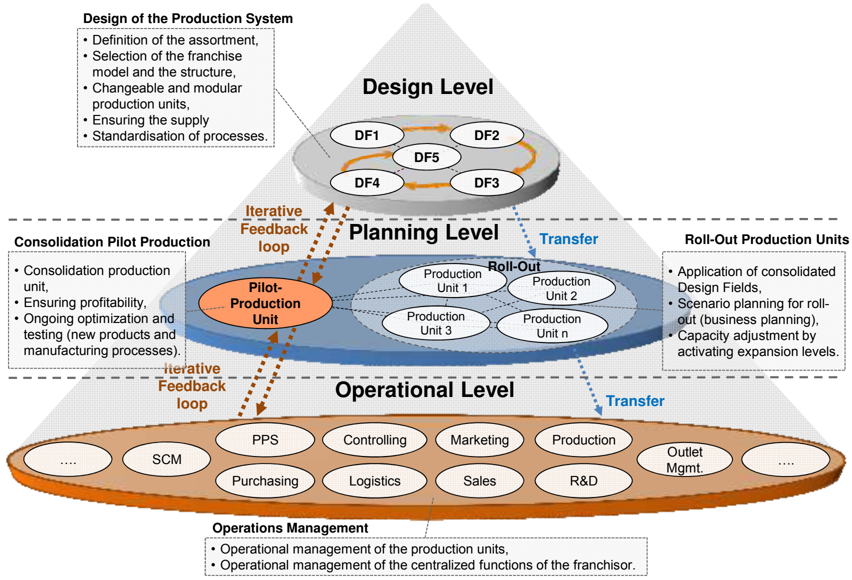


Figure 3: Three-level model for the design, planning and operation of a changeable Franchise production system.

adjustments (trigger point for the re-design of the production system - see also [43]). For a systematic modelling of the manufacturing system, are defined so called Design Fields (DF), which are run successively. At this Design Level, aside from the specific and location depending factors in the manufacturing system, the system designer can create a uniform and standardized template of the manufacturing system. The identified five Design Fields with their set of design parameters form the normative framework for the further expansion, adaption and development of the manufacturing system with geographically distributed production sites.

Figure 4 shows the identified Design Fields (DF1 to DF5) and graphically describes the order in which the various fields should be treated. After determining the product or service assortment (DF1) has to be defined the right business model (DF2). Once the business structure is clearly defined, the design of decentralized, changeable and profitable production units (DF3) needs to be elaborated. In a next step the supply of the production facilities has to be modelled (DF4). Ultimately, it is necessary to standardize and summarize all results acquired in the Design Fields in form of processes and procedures (DF5).

### 4.3 Strategic and Tactical Planning Level

Once on the Design Level the guidelines and templates for modelling the manufacturing system are developed, it is important to test them with a pilot production unit. Therefore, the first step in the strategic and tactical Planning Level is planning and implementation of a pilot plant. The pilot production unit has to test and develop new products and production technologies. Once the pilot production is consolidated by iterative feedbacks to the Design Level and Operational Level and the profitability of the business model has ensured, finally could be started the multiplication of the production units and thus the roll-out of the business model with distributed production facilities. In this, the consolidated Design Fields and the experiences from the pilot production are transferred into the roll-out. Before the start of the roll-out a multi-year scenario plan or business plan is being developed. The time horizon for this level includes the strategic planning in a time frame of three to five years and an annual, detailed tactical planning and budgeting.

### 4.4 Operational Level

The Operational Level comprises the implementation of the production units and headquarters with all responsibilities. Of particular importance is that before the start of the roll-out of the business model, all processes and operational issues are tested and examined in the pilot production. As shown in Figure 3 by iterative feedback loops is ensured that only a functional and viable manufacturing system is transferred. The time horizon for the Operational Level is dominated through the "daily business" and therefore shorter than one year.

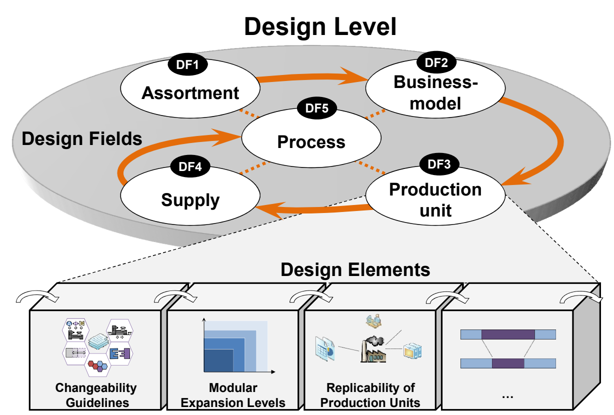


Figure 4: Three-level model for the design, planning and operation of a changeable Franchise production system.

### 4.5 Feedback and Control Loops (Trigger-Points)

As described in Figure 3 between the different levels is an iterative feedback loop, similar to a control loop to transfer the experiences from the pilot production unit to the other levels "adjusting" and

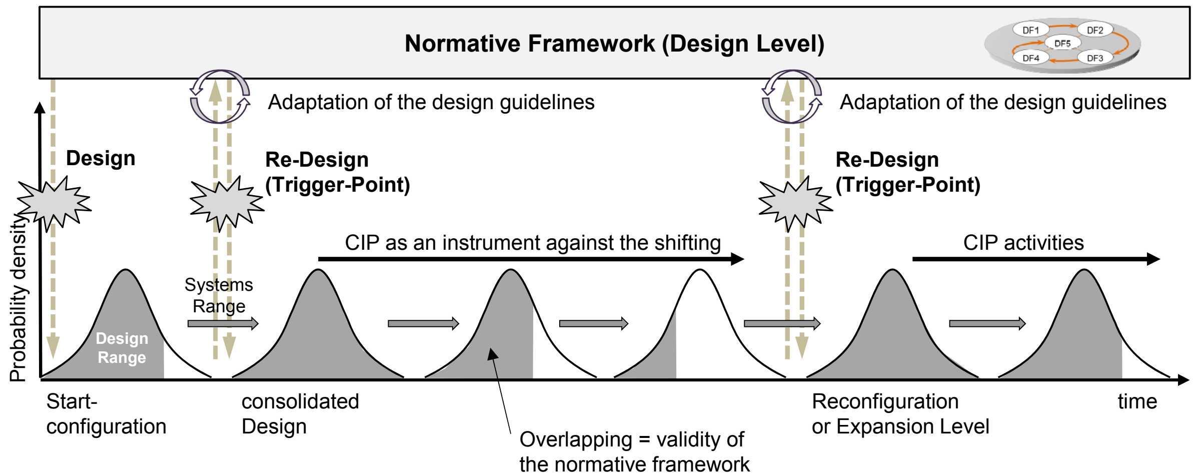


Figure 5: Feedback and control loops for continuous adaption (Trigger Points for Re-Design), in accordance with [43, 45].

consolidating so the manufacturing system. Between the different levels, we can distinguish two types of trigger-points:

- Feedback loop on the design level ("re-design"),
- Feedback loop on the planning level ("re-planning").

The experience gained from the pilot production unit, as well as its reconfigurations are transferred through the iterative feedback loops to new production units (roll-out). The need for these control loops or feedback can be explained using the systems theory. In the normal case can be assumed that the manufacturing system is based on requirements identified at a given time. At the time of initial operation of the manufacturing system the design corresponds (more or less) to the previously defined requirements. The goal of a system design is to make the system range lie inside the design range (maximum probability density) [44]. Complexity arises if the system range (environment and external factors) lies outside the design range (designed manufacturing system).

This is right for static systems or time-independent systems. In Figure 5 we can see the behaviour of a manufacturing system over the time. Companies are now, more than ever, subject of a turbulent environment with the result that the requirements of the production system are constantly changing. Future events are typically unpredictable and might shift the system range away from the defined design range – and thus creates complexity [9]. This ultimately carries the risk that it eventually comes to a collapse of the system, when the overlap between the production system and the requirements does not exist anymore. Once the overlap between the two areas is no longer sufficient, and thus the normative framework of the current design is no longer valid a re-design is necessary (trigger point).

## 5 SUMMARY AND OUTLOOK

By the heuristic approach in this work could be derived with the help of expert groups the shown Three-level-model, which accompanies a production company through the design and planning as well as the implementation. Through the built-in feedback loops, the internally developed knowledge can always be incorporated and transferred to other manufacturing units into the network and a continuous adaptation (changeability) of the manufacturing system is guaranteed. The case study showed very clearly that without the use of a specially, for distributed manufacturing systems, adapted methodology, the implementation of such a Franchise system consistently would take very long and can be blocked by frequent iterative loops in the planning and design phase. Through the approach, not only the design parameters for a changeable and reconfigurable manufacturing system could be defined, but also a simple and systematic approach for its implementation was developed. Further research will be necessary to investigate the right “trigger points” for a periodical re-design of the production system and to analyse how productivity reduces and changes if system range (environment) and design range (production system) shifts asunder.

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# SMART Reconfigurability Approach in Manufacture of Steel and Façade Constructions

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**Abstract**

In recent years the principles of industrialisation and prefabrication of factory-finished elements have gained more and more acceptance in the construction sector. Due to the limited duration of projects in this sector, manufacturing cells and assembly line configurations show a very short life time and they have to be highly flexible and adaptable to changing circumstances. This paper gives an overview about the state of the art in prefabrication and reconfigurability in the building industry. Based on the experiences from an industrial case study the paper shows the first research results of an approach to increase a company's ability for smart reconfiguration of pre-assembly.

**Keywords:**

Reconfiguration; Manufacturing system; Adaptive manufacturing

## 1 INTRODUCTION

Various elements, from which buildings are constructed, like facades, are made-to-order. These made to order products are produced by fabrication shops, which sit squarely at the intersection of manufacturing and construction [1]. In order to secure the competiveness and the enterprise success, enterprises which operate in the construction sector and even more in the high-level façade construction sector have to satisfy the growing customers' requests of higher quality standards, shorter delivery times and individuality. One of the main challenges of the mentioned sectors is the continuous increasing complexity of construction projects [2], its main reason is that primarily all projects are tailor-made solutions and thus, each project is different from each other. Because of the low repeat frequency of similar or equal building elements and the high variance of manufacturing processes the implementation of reconfigurable manufacturing systems is quite challenging.

Switching perspectives demand variability, late receipt of design information, frequent design changes and changes in timing and sequence are arguably the biggest headache for fabricators in this sector [1]. In the last years prefabrication was used as a method to deal with highly complex construction projects [3] reducing waste effectively [4]. Prefabrication is a manufacturing process, generally taking place at a specialised facility where various materials are joined to form a component part of the final installation [5]. Through prefabrication building parts are manufactured in an environment suited for efficient production, where advanced equipment can be used and the working conditions are good [6]. Also in the façade construction sector the industrialization in form of prefabrication of modular elements increased and led to a higher impact of pre-assembly in the manufacturing hall. Industrialization can be seen as a structural means for eliminating, or at least drastically reducing, on-site activities in construction [7].

There are many efforts by companies to increase the degree of industrialisation in the steel construction sector. By modern concepts such as lean production and lean construction, waste and lead times should be reduced [8, 9]. While in the automotive or aerospace industry the application of lean manufacturing methods is common nowadays, the construction industry is lagging behind these developments [9]. Also the concept of reconfigurability has been applied and developed so far mainly in industrial production [10, 11, 12, 13]. While production companies, particularly in the automotive industry, developed relatively early concepts such as Flexible Manufacturing Systems (FMS) or Reconfigurable Manufacturing Systems (RMS) [10, 14] these methods have only been recently used in the building industry.

There are only few experiences in the use of these methods at object manufacturer like steel and façade construction companies. These companies were able to reduce the installation time on site through the introduction of an industrialized prefabrication of modular elements. With an increasing number of variants and a continuous increasing complexity of construction projects [2], the products are becoming more complex and different from each other. This has implications for the production, in particular on the pre-assembly, where always new designs of elements have to be produced and assembled. This makes it difficult for the system designer to design the manufacturing system in an efficient manner. The manufacture and pre-assembly on the production floor are faced in future with the great challenge that they usually have to produce only for a limited duration of the project similar parts or repetitive elements for the same construction site. Therefore, the manufacturing system has to show a particularly high degree of changeability and reconfigurability.

In this paper are described the requirements for a smart reconfiguration of manufacturing system based on the experiences of a real industrial case study in a North Italian façade construction company. The paper shows the principles, which object manufacturer should follow to design their production and assembly. The focus of this research project will be placed on the particular area of the pre-assembly in the manufacturing hall by showing on the case study, how changes and transformations of temporary industrial assembly lines can occur in a rapid way. The research project in collaboration with the company from the case study is still going on; for which reason this paper presents the first preliminary results.

## 2 LITERATURE REVIEW

Manufacturing provides the elements from which buildings, bridges, façade and houses are constructed. These made-to-order products are produced by fabrication shops [1]. Several concepts emerging from the manufacturing industry have in later years been successfully adapted in the construction industry. In Japan the lean production concept is applied to industrialised housing through balancing customisation and standardisation while developing efficient production processes [15, 16]. Other concepts for housing are logistics and supply chain management (SCM) that are

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demonstrated as disciplines with the potential to increase efficiency in the construction process [17, 18]. In this paper will be discussed the industrialisation in the construction industry and the need for reconfigurable manufacturing systems in the steel and facade sector. The construction industry has been slow to adapt to technological change, and remains largely labor intensive and a user of low-technology [16, 19].

### 2.1 Industrialisation in Construction and Prefabrication

Investment in moving forward with industrialised construction leads to productivity improvement, shorter building times and waste reduction which can in turn lead to lower costs for industry, providing the volume of production is important enough to justify investment in plant and equipment. In the construction sector one of the areas of industrialisation that holds potential is the prefabrication of systems and components. This includes building panels and modules that can be undertaken in manufacturing plants under controlled environments and then transported to various sites for quicker assembly. Onsite factories, automation and robotiation of various tasks represent other avenues of development. The vision is to combine advanced manufacturing in factories and on construction sites trough an industrialised construction (see Figure 1) [20].

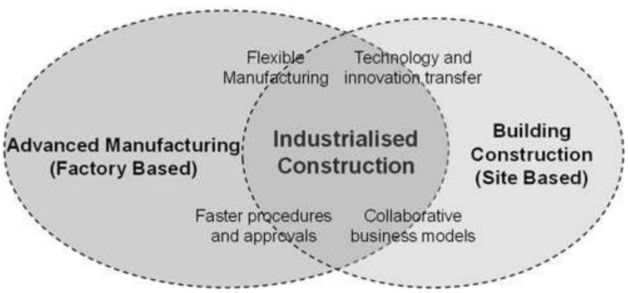


Figure 1: Industrialised Construction as combination of advanced factory based manufacturing and site based construction [20].

An Industrialised Construction would increase the value-adding activities during production and, to a large extent, eliminate the non value-adding activities such as waiting times, transports or controls. The construction industry is also in the process of adopting this approach to industrialisation [21].

Three main principles underpinned the industrialisation of construction: standardisation, prefabrication and systems building. *Standardisation* of building components was a perquisite for their production under factory conditions (*prefabrication*) which – together with dimensional coordination – enabled the growth of *systems building* [16].

Although the construction industry has been associated with delays, waste, poor performance and poor health and safety, the use of prefabrication has been shown to reduce construction delays caused by weather conditions on a project [22]. Glass and Pepper [23] argued, that “the worst place to build a building is on a building site, the best place to build a building is in a factory because it is a more controlled environment”.

Prefabrication, pre-assembly, and modularisation are strategies that have the potential to: (1) significantly reduce project duration, (2) improve productivity, (3) reduce labor needs and costs, and (4) have a positive impact on supply chain problems [5]. At the other side it is generally known, that prefabrication increases the amount of preplanning, engineering and coordination required for the project. The nature of prework tends to increase requirements for design and procurement as well as logistics [24].

The approach of Industrialised Construction requires total synchronisation on construction, manufacturing and design processes. It needs emphasis on rationalisation, standardisation, repetition, collaboration, supply chain partnering and more effective planning and project management [25].

### 2.2 Reconfigurability in Manufacturing

In the eighties the concept of flexible manufacturing systems (FMS) was introduced in response to the need for mass customisation and for greater responsiveness to changes in products, production technology, and markets [26].

The concept of reconfigurable manufacturing systems (RMS) has emerged later in the nineties in an attempt to achieve changeable functionality and scalable capacity [10, 27, 28]. Reconfigurability is focused on the reuse of the original system’s components in a new manufacturing system [29]. Reconfigurability describes the operative ability of a manufacturing or assembly system to switch with minimal effort and delay to a particular family of pieces or subassemblies through the addition or removal of functional elements [30].

Koren [14] proposes to follow six design guidelines for the design of reconfigurable manufacturing systems: (1) Flexibility, (2) Convertibility, (3) Scalability, (4) Modularity, (5) Integrability and (6) Diagnosability. The more these principles are applicable to a given assembly system, the more reconfigurable that system is. Due to these requirements the supplier industry has developed and offered in the last decade modular, scalable and mobile manufacturing and assembly systems for the production industry [26]. In the construction sector these concepts are still missing or are treated only inadequate.

In recent years developed the concept of changeability, as the ability of a factory or a production system to switch from one product family to another, changing the production capacity accordingly. This can be both, interventions in the production and logistics systems, as well as on the building structure and the structure and process organization. Such a change should be possible relatively quickly [31].

Five enablers have been found that the factory planner may use for purposes of attaining changeability in the design phase: (1) Universality, (2) Scalability, (3) Modularity, (4) Mobility, (5) Compatibility [32]. Scalability is a key characteristic of reconfigurable manufacturing systems, which allows system throughput capacity to be rapidly and cost-effectively adjusted to abrupt changes in market demand. Adding or removing machines to match the new throughput requirements and concurrently rebalancing the system for each configuration, accomplishes the system reconfiguration [33].

The disturbances of processes in progress are in the construction industry a basic problem making difficult planning both in relation to time and costs. The conception of introduction of flexibility in construction came into result of observation of problems alongside realisation of runways, the roads of circling, customs terminals, driveway as well as assembly of facade of elevation of high buildings, where the serious factor was the perturbative weather [34]. In the field of prefabrication and preassembly in the construction sector there could be found only few research works in the literature, while flexible and changeable manufacturing systems have been established in the production technology for several years. Thus, in this paper will be explained an approach for rapidly reconfigurable manufacturing system in the preassembly of a facade construction company.

## 3 BRIEF DESCRIPTION OF THE CASE STUDY

The company in the case study is a middle sized North-Italian company with 140 persons employed and operating in the façade construction sector. The enterprise started as a small craft enterprise in 1974. In course of the time the company focused its activity on the production of tailor-made building envelopes by producing different facade typologies and structural elements such as windows and door systems.

### 3.1 Preassembly of Façade Constructions

By working with renowned architects, the company is characterised by the fact that hardly a project is similar to the other. The variability between the single projects results in a very low repetition frequency of similar or equal building elements. As a result, the variance of manufacturing processes and sequences as well as the variance of production times between the single projects increases.

The production of the facades occurs in three departments or fabrication shops:

- Steel construction (supporting structure)
- Sheet metal working (sheet metal cladding)
- Element construction (manufacturing of aluminium profile elements and pre-assembly with sheet metal surface elements, glasses and supporting steel construction).

An analysis of the manufacturing processes in the steel construction department as well as in the sheet metal working department showed that the low quote of repetitive building elements and the mandatory hand crafting production makes it very difficult to industrialise the single processes. More potential has been identified in the third fabrication shop – the element construction department. The production of aluminium profile elements, such as façade elements, doors and windows is easier to standardise and to industrialise. Through the application of flexible and reconfigurable manufacturing systems, the fabrication shop could work more efficient. To facilitate the assembly on the building site the company pre-assembles in the element construction the semi-finished parts to prefabricated modules consisting of:

- Supporting structures from steel construction
- Sheet metal elements from metal working
- Façade elements, doors and windows from element construction
- Glasses, shading systems, etc. from suppliers.

The layout has to be changed for almost any project in pre-assembly, leading to inefficiencies and a high proportion of non-value added time for preparation, changeover and tidy up.

### 3.2 Problem Definition

The company from our case study shows a typical case of an engineer-to-order (ETO) manufacturer with handicraft work. In the course of the trend towards industrialisation and prefabrication the company has already implemented first measures in this direction (see Figure 2). The strong difference in the various projects implies the need of a highly flexible production, particularly in the element construction and in preassembly. So far, the company has succeeded only at the expense of long changeover times (see Figure 3) to ensure this flexibility, which affects the costs of course. Due to the increasing global competition in the façade construction sector and due to rising costs, the company raises the challenge to become more efficient and thus more cost-effective in manufacturing and assembly processes. A step in this direction is to be done through the creation of a more flexible and reconfigurable manufacturing and assembly system.

Figure 2: Industrialized preassembly line of façade modules.

Figure 3: Time-consuming changeover and setting-up of machines.

In the last years was done a lot of research to upgrade the production as quick as possible from a given product to another product. In series or small series production, the product is already known in advance. In the steel and façade sector, every project is different from the other and also during the manufacturing process itself, short-term changes by customers or architects are normal. Engineer-to-order manufacturers such as those of the case study are confronted with special circumstances:

- Parallel assembly of different sized projects
- Each project requires a new layout situation and different machines and staff profiles
- Necessity for reconfiguration of layout and machines within a single project is possible
- Different project durations (from a few days to a few months)
- Short-term changes by customer/contracting entity
- Interruptions (delays at construction site, design changes,…) and therefore changeover to another project
- Commission based material deployment
- Strong reliance on punctual JIT deliveries from suppliers
- Delays in production and assembly result in delays and inefficiencies at the construction site.

## 4 SMART RECONFIGURABILITY APPROACH IN THE PRE-ASSEMBLY OF FAÇADE CONSTRUCTION

To provide engineer-to-order companies, like facade manufacturers, a set of guidelines, that meets the necessities previously outlined for the design of their manufacturing systems, a research project was started to develop an approach for the design of highly flexible and reconfigurable manufacturing systems. In this paper are presented the first results on the investigation of the major requirements of such an approach. The proposed approach should include the principles and concepts already applied in Industrial manufacturing to design flexible and changeable production systems and should extend them fulfilling the requirements of engineer-to-order companies. As we could see in the problem definition, craftsmanship based engineer-to-order companies, like façade manufacturers, have to adapt their manufacturing and assembly system frequently and temporarily without knowing the requirements of the next reconfiguration. A manufacturing or assembly system which is able to fulfil these requirements may be called also a “smart” system.

Together with the project team at the case study company were organized several workshops to investigate what could be the main key objectives to obtain a highly flexible and reconfigurable manufacturing system for an engineer-to-order environment. The results of the workshops could be assigned and summarized to five major requirements. The term “**SMART Reconfigurability**” used in this paper stands for the before mentioned five requirements (see also Figure 4):

- **S**cheduled
- **M**odular
- **A**daptable
- **R**apid and
- **T**emporary.

*Scheduled* stands for planning and scheduling every major reconfiguration of the manufacturing system. In the current situation necessary changes to the processing of orders were not planned in advance. The information-transfer between Engineering and Production about upcoming projects happened very late in the past, so that a suitable planning and scheduling of necessary reconfigurations was very difficult or could not be carried out in time. By introduction of early announcement and regular meetings between production and Engineering, this could be significantly optimized. For this purpose, in the case study, the role of the manufacturing system designer was introduced. This system designer is now responsible to interact as interface between Engineering and Production defining, planning and scheduling all the necessary changes to guarantee a material-flow-oriented layout and the availability of the required tools and devices for an efficient and ergonomic assembly and material supply.

*Modular* means that the single manufacturing and assembly work stations can be decoupled. This leads to an increased flexibility in the use and reuse of process modules, and also to significant reductions in project execution times due to falling setup times. In relation to the growing demand for modular systems the producers of manufacturing and assembly systems or cells reacted in the last ten years developing and offering such systems. On the German market the first pioneers were producers like teamtechnik with his system called TEAMOS, the ZBV-Automation with his system named CORACell as well as Paro offering in 2007 the first modular assembly systems. These systems are currently used mainly in the electronics and consumer goods industries due to the prevailing short product life cycles and the resulting high degree of short-term changes and modifications in these sectors [35]. In the sector of the facade or steel construction there are the same or quite similar requirements to adapt a manufacturing and assembly system as quickly as possible to a new product or project. Nevertheless, the aforementioned and just existing systems of industrial manufacturing and assembly systems are not suitable for this sector. For the future, it is necessary to develop modular assembly systems for flexible use in the assembly of bulky and heavy products, such as in the steel and façade industry.

*Adaptable* is equivalent to changeable and describes the ability of the manufacturing or assembly system to be reconfigured or adapted to produce different products. Looking at the case study of the steel and façade construction manufacturer items are usually very different and it cannot be foreseen in advance which dimension or geometry have the parts and if a future project contains a high or a low number of equal or similar parts. Thus, such an adaptable pre-assembly requires an extremely high degree of changeability and flexibility. Currently, this flexibility is achieved in the case study only due to long setup and preparation times and a costly and time consuming expense to create stencils, gauges or patterns. This not only increases the cost of production, but also the processing times, often resulting in a risk to delivery dates on the construction site. A high degree of adaptability for engineer-to-order companies such as those from the case study includes not only the adaptability of individual machines or assembly work stations, but the ability for a quick and easily reconfiguration of the entire assembly line before beginning a new project. This includes also the design of universal or variably and adjustable stencils or fixing systems.

*Rapid* describes the need of the manufacturing or assembly system to switch as soon as possible in another configuration reducing waste and increasing efficiency in operation. In the presented case study a deeper analysis showed that changes are very often necessary, and thus restricts the available (value-adding) time fundamentally. The frequency of changes is not only due to new projects, but especially to the interruptions of in-progress projects and converting to a different project. Due to various influences such as the weather on the construction site or last-minute changes by the customer such interruptions are unfortunately the norms. Thus, a rapid adaptation of the manufacturing and assembly system has a direct impact to the company's costs. The system designer has to be very consequent in implementing maximum mobility (wheels, roles, crane hooks, integrated apertures for forks, etc.), compatibility (standard connectors) and rapid disassembly and assembly (e.g. use of quick-release fasteners instead of bolts and nuts). It is important to not only optimize the hardware, but also to train the employees in methods of Lean and Quick Changeover (e.g. SMED method), to minimize the downtime.

*Temporary* characterizes the challenge in engineer-to-order companies as in our case study, that a manufacturing system is only valid for a very limited period and has to be reconfigured again and again. While reconfiguration of the production or assembly in many other industries such as the electronics and consumer goods industries often is limited only to a switch to another product variant, in steel and facade construction companies the system has to be changed very often completely. Layouts, staging areas and tools are only temporary in nature and are subject to constant change. Therefore, a system designer should renounce for providing material through rigid systems and transfer points using more likely mobile or flexible shelving and trolleys. The design of the material provision by commission organized areas should be made in a flexible way because the different projects require different space for the provision of the components. As mentioned in point “Scheduled”, an appropriate coordination of the temporary reconfigurations is required.

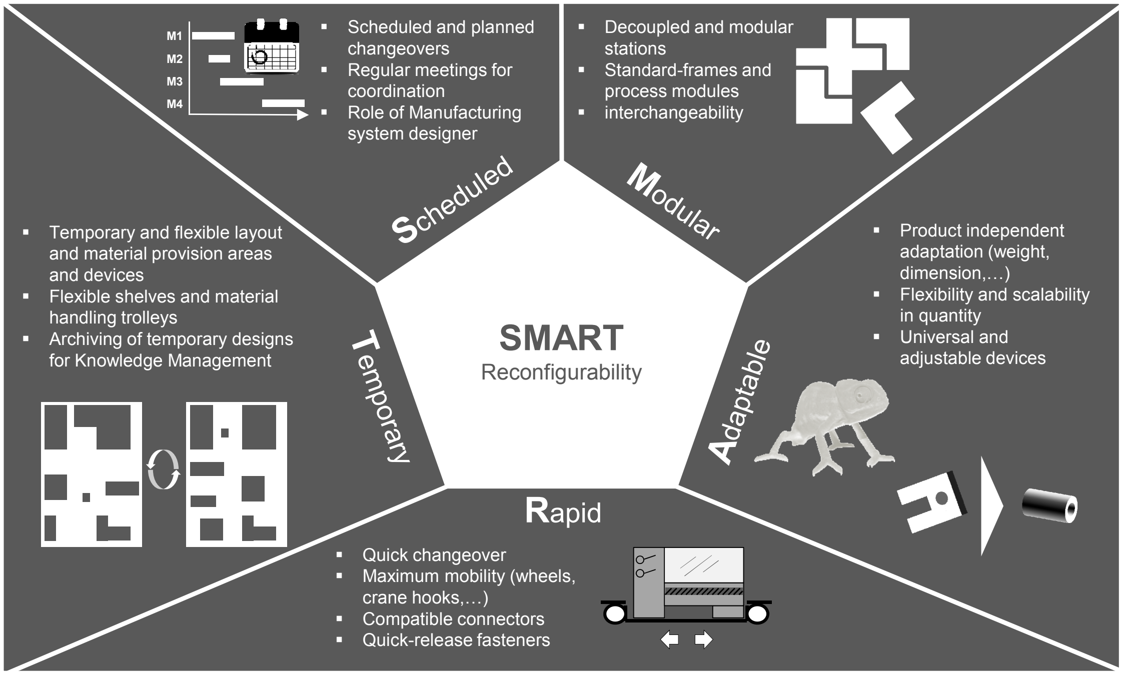


Figure 4: SMART Reconfigurability approach (**S**cheduled, **m**odular, **a**daptable, **r**apid and **t**emporary reconfiguration).

## 5 ACTUAL RESULTS AND NEXT STEPS

In the current state, the preliminary analysis of the requirements for a "smart" reconfiguration of a manufacturing system for engineer-to-order companies in the steel sector and façade construction sector is completed. The results of the preliminary investigation were summarized in the above showed model called "SMART Reconfigurability". The conclusions from the case study are that engineer-to-order companies must be clearly more reactive and adaptable than it is necessary, for example, in mass production or series production due to the constantly changing projects and project requirements. Currently the project team works on the development of concrete design parameters and best practice solutions. An example of the actions that will be implemented in the company is the appointment of a lean-trained industrial engineer for the temporary and project-based layout planning of assembly. In addition, the assembly area will be divided in two different areas: one area for an efficient and industrialized assembly of large and longer lasting projects with repetitive manufacturing steps and a differentiated area for smaller and more handicraft projects with specialized staff for complicated processing and machining. A third action that will be implemented is the construction of mobile and highly flexible material handling trolleys which can be at the same time used as assembly tables reducing so the time for handling.

In a further step this design guidelines should be implemented in the case study to test their practical applicability and their benefit monitoring KPIs such as productivity, average changeover time or lead-time before and after the changes. Further research will not be limited to purely technical design of machines or workplaces, but will put into the focus the following three areas of interest:

- *Technology*: Design of machines and workplaces as well as support and material handling devices.
- *Organisation*: Efficient and highly flexible as well as structured processes for reconfiguration and material supply.
- *People:* A highly flexible Technology and Organisation brings no benefit if the people who work in it, are not qualified.

The development of system design parameters for a smart reconfiguration of manufacturing systems is expected to be completed in 2013 and implemented in parallel and in 2014 in the case study. The project is accompanied in this phase by change management actions to ensure the acceptability among shop workers through an effective involvement and communication.

## 6 SUMMARY AND OUTLOOK

The paper shows the first results of a preliminary study on flexible and adaptable manufacturing systems in the construction sector. The results are based on a research project with a façade manufacturer to guarantee the practical applicability of the research. In the first project phase could be identified the main requirements for a so-called “smart reconfigurability”. Thus, reconfigurations in a manufacturing system in the engineer-to-order construction sector should be (1) scheduled, (2) modular, (3) adaptable, (4) rapidly converted and (5) temporary valid. The next steps in this research project are the development of suitable and concrete design parameters and approaches for the design of the Technical Hardware (Technology), the scheme of necessary processes (Organisation) as well as instruments for the change of mind of the individuals (People).

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# A First Step towards Cross-Platform Integration in Modular Micro-assembly Systems – Concept for a Process Module Construction Kit

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**Abstract**

The potential of modular micro-assembly systems can often not be fully exploited by small companies, as commercial availability of process modules is limited and the development and maintenance of a pool of process modules is too elaborate. To overcome this problem, an open process module interface specification is proposed, which allows integration of process modules into different systems (cross-platform integration). Based on the specification, a process module construction kit is presented, which shall reduce the development effort of process modules. Both concepts are a prerequisite for an independent platform for modular process equipment. A net present value analysis and a SWOT-analysis are performed to evaluate the concept system against special purpose machinery. The results show that a modular system reduces investment risks whilst improving the ability to follow the market dynamics.

**Keywords:**

Micro-assembly; adaptability; Manufacturing system design

## 1 INTRODUCTION

Companies producing sensors, electrical motors or pneumatic equipment are characterised by an extremely wide range of products on offer. Such companies are often forced to produce a significant part of their products manually to cope with the high number of different products. With miniaturisation ongoing, automation of at least the processes determining the product quality becomes increasingly important.

The requirements onto the production equipment then include possibility of reconfiguration and ideally instant change-over. Modular production systems often meet the requirements and are commercially available, but the range of process modules offered is very limited. Special process modules would have to be developed first, which consumes additional time and resources.

The authors of this paper believe that an open interface which allows the integration of process equipment of different providers into machinery of different providers would significantly improve the applied continuous adaption of assembly machines. Particularly companies with wide product ranges could potentially strongly benefit.

Within this paper concepts for a complex process module interface and a process module construction kit are presented. Based on these concepts a platform for process modules is presented and evaluated against special purpose machine solutions.

## 2 BOUNDARY CONDITIONS

Micro assembly systems and micro-assembly tasks are distinguished by some typical boundary conditions compared to conventional macro assembly. To determine these boundary conditions, a survey targeting microsystem manufacturers in Germany has been performed [1].

The most obvious difference between micro and macro is the size of micro-technical products. 87% of microtechnical devices fit into a volume of 100 x 100 x 100 mm³, while 30% are even smaller than 10 x 10 x 10 mm³ [1]. Small structures and functional elements demand positioning accuracies between 5 - 25 microns or even higher during assembly [1]. This imposes high requirements on the overall assembly system, like stiffness and precision, and the positioning technique itself. Furthermore increased demands on cleanliness and defined, constant temperatures have to be regarded. Another characteristic is the high number of product variants. 75% of microtechnical products have up to ten or more variants [1]. This affects the lot size, which is often in a low to medium range with less than 1.000.000 units per year down to single pieces. Micro assembly often requires automation or at least semi-automation and hence suitable micro-assembly systems. Reasons for this are on one hand the limited feasibility of manual handling in the low micron range and on the other hand high requirements on the reliability of assembly processes to ensure consistent product quality [2]. Existing modular systems, particularly for micro-assembly, such as Bosch DTF [3] or Rohwedder MicRohCell modular [4], are designed for certain lot sizes, mostly for mass production. A stepwise adaption to market demand is currently not possible.

### 2.1 Potential of Modular Micro-assembly Equipment

Assembly systems can be regarded from both micro-system manufacturer and supplier perspectives. These different perspectives often do not match in terms of flexibility, adaptability and cost. Here modular micro-assembly systems can support to close that gap and provide opportunities for both parties.

In the field of micro-assembly manufacturers demand flexible production systems by reason of, amongst others, low or unsteady lot sizes and necessity of automation. From a technical point of view a standardised micro-assembly system, consisting of a platform and process modules, allows the stepwise and flexible introduction of (semi-)automated manufacturing. Based on one platform the processes as well as their level of automation can be varied with exchangeable process modules.

From suppliers perspective this would provide the opportunity of customer retention on platform level from the early introduction phase to product maturity. In order to react to low or unsteady lot sizes the adaptability of the assembly system to different products or variants is required by the manufacturers. This can be achieved by the possibility of quick exchange of process modules within a

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modular micro-assembly system. Based on the platform-based processes, which represent a unique feature of the manufacturer, additional processes can be developed and integrated into the micro-assembly system in-house due to extensive reference solutions for process modules. These reference solutions already contain positioning, control and supply infrastructure. Other processes could be bought from other suppliers as a process module or be commissioned according to the interface standards. For assembly system suppliers these off-the-shelf modules could be a new business segment beside custom-built items.

Automated micro-assembly is dominated by special purpose machines. Suppliers have to invest much time and effort for development and build-up of a special purpose machine. At the same time suppliers are dependent on efficient project handling to be competitive.

With a standardised modular micro-assembly system "repetition effects" can be realized during development, build-up, start-up and subsequent maintenance. For instance only one platform design, which is just to be adapted in number of slots for process modules, is required and thus can be easily build-up several times.

The effort for the development and integration of new process modules can be significantly reduced by above-mentioned reference solutions. Furthermore the reuse of already developed process modules with no or minor adaption is possible. Beside the internal use of modular micro-assembly systems for efficient project handling new business segments can be exploited. Instead of complete systems platform and modules can be separately offered off-the-shelf.

## 3 A CONCEPT FOR CROSS-PLATFORM INTEGRATION

### 3.1 Complex Interface

Modular systems can be characterized by a superordinate framework which features interfaces for subordinate modules [5]. Process modules for a modular micro-assembly system require therefore defined interfaces.

The integration of process equipment into a machine concerns three domains: Mechanical integration, supply of the process equipment and control integration. A modular platform, which shall be easily reconfigurable, must provide thoroughly defined interfaces for all of these domains [6].

A number of existing modular micro-assembly systems, as well as different types of process equipment for micro-assembly have been analyzed. The analysis comprised mechanical parameters and physical properties, supply with media, energy and information, as well as control systems. A set of interface requirements was derived from this analysis.

Within the scope of this paper, the authors propose the concept of a complex interface. Figure 1 gives an overview of the elements of the interface concept. The 'mechanical interface' comprises the definition of a generic, blank module. Spaces for process, feeding and control equipment as well as working spaces are defined. Within the 'supply interface' a supply connector is defined, which includes supply of compressed air and electricity as well as connection to Ethernet and field bus. The 'control interface' defines the interface and function blocks for control integration. The overall complex interface definition is a prerequisite for cross-platform integration. It allows machine constructors to provide a compliant interface to a common process module specification. Furthermore it allows third parties to develop and to build process modules for different machines providing the complex interface.

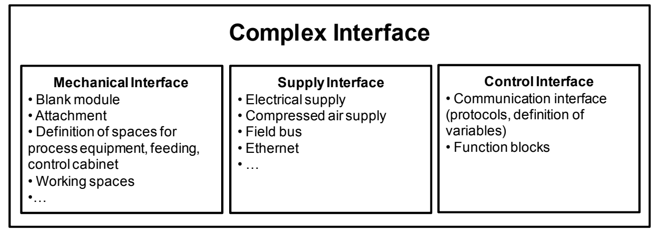


Figure 1: Complex Interface.

### 3.2 Process Module Construction Kit

In order to be competitive, the effort for design and development of process modules featuring the complex interface should be minimal. Reference solutions for the development of process modules do significantly reduce this effort [5].

The authors propose an approach based on a process module construction kit. The basic idea is presented in Figure 2. A set of reference solutions is provided, which is classified according to kinematics (e.g.: z, zy, xyz, xyz + rotation), precision and dynamic parameters. Table 1 shows how such a classification could potentially look like.

Based on the process requirements a reference solution is selected. The reference solution includes a mechanical design according to the complex interface and an implementation of the control system. If a reference solution design is not available among the specified solutions, the module can be either custom developed (according to the complex interface) or a new reference solution can be developed. Latter is to be aspired at, if a comparable module is suspected to be required in the future.

A mechatronic tool interface is provided, which allows instant integration of process equipment, like e.g. a gripper, a dispenser or a camera system. While the complex interface provides interfacing between process module and machine, the mechatronic tool interface, provides a standard interface between equipment on the process module itself. The interface is also comprehensive and provides mechanical, supply and control interface. However, the specifications necessary for a tool interface are different than for a module interface. The applied interface could be based for example on an ISO 29262 tool exchange interface [7]. An adaption to feed-through field bus and media if necessary would be most likely required.

From control point-of-view it would be ideal, if the tool would already feature the required intelligence to just be integrated as field bus device. However, this is currently practically not realistic. Many tools, such as dispensers, still bring their own control boxes, which have to be integrated and interfaced inside the control cabinet. On the other hand, an increasing number of "intelligent" tools become available, e.g. intelligent grippers or intelligent cameras. To cover both intelligent and non-intelligent tools, a number of simple electrical feed-throughs and a feed-through for Ethernet-based field-busses should be integrated.

The tool integration into the process module control is performed on basis of the reference solution control program, which is adapted to the tools. The program structure allows an exchange of the tool function blocks.

| Variables | Solutions | | | | |
|---|---|---|---|---|---|
| Kinematics | none | z | zy | xyz | xyz+φ |
| Precision | 1µm | 5µm | 10µm | 25µm | |
| Dynamics | Low | High | | | |

Table 1: Classification of reference solutions.

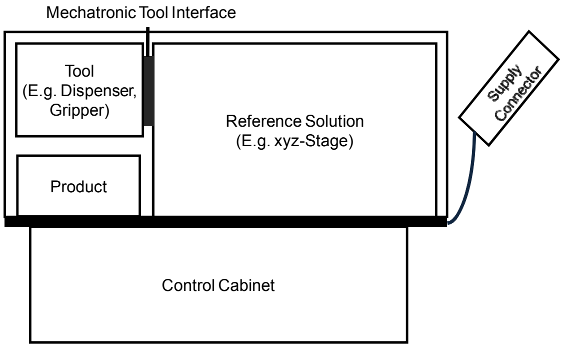


Figure 2: Process modules based on reference solution.

### 3.3 Platform for Process Modules

Now the concepts of the complex interface and the process module construction kit are introduced. These are both a prerequisite for cross-platform integration. Figure 3 shall explain how cross-platform integration could potentially look like from the authors' perspective:

- The complex interface is a thorough specification of mechanical, supply and control interfaces.
- Based on the interface specification a process module construction kit is provided, which allows development of process modules based on reference solutions.
- Process modules can be either freely developed or be derived from the process module construction kit. Each process module must meet the complex interface specifications.
- Modular machines have to feature receptacles for process modules and thus also to meet the complex interface specification.
- An independent certification body tests and certifies both process modules and modular machines to compliance to the complex interface specification.
- Once the process modules and modular machines are certified, they can be offered on the market. This can be supported by a market platform.
- Users of modular production equipment can access this market platform. They can access modular machines and process modules. This enables them to nearly freely configure and reconfigure their production equipment. If production equipment becomes obsolete, it can be refurbished and offered on the market.

This concept has implications for suppliers and users of modular production equipment.

Supplying companies can offer their products on an additional market. Developed process equipment can now be sold more than once in the form of process modules.

Companies applying modular production equipment can now purchase and integrate freely process modules by different providers. This reduces the dependency on a single company and decreases development effort.

As choice of different process modules and modular machines is drastically increased and supported by the interchangeability of process modules, a stepwise adaption of the assembly equipment becomes possible. This means that the same process modules could be applied in a 2-slot machine with manual loading, as well as in a 6-slot machine with automatic transfer system.

## 4 EVALUATION METHODS

A cross-platform integration concept has been described in the previous chapter. Within this and the following chapter modular micro-production equipment will be evaluated against a conventional special purpose machine approach from the perspective of a micro-manufacturer based on a use case. A qualitative and a quantitative method are applied to a typical product lifecycle and two use cases (Figure 4). As qualitative evaluation method SWOT and as quantitative method NPV analysis are applied.

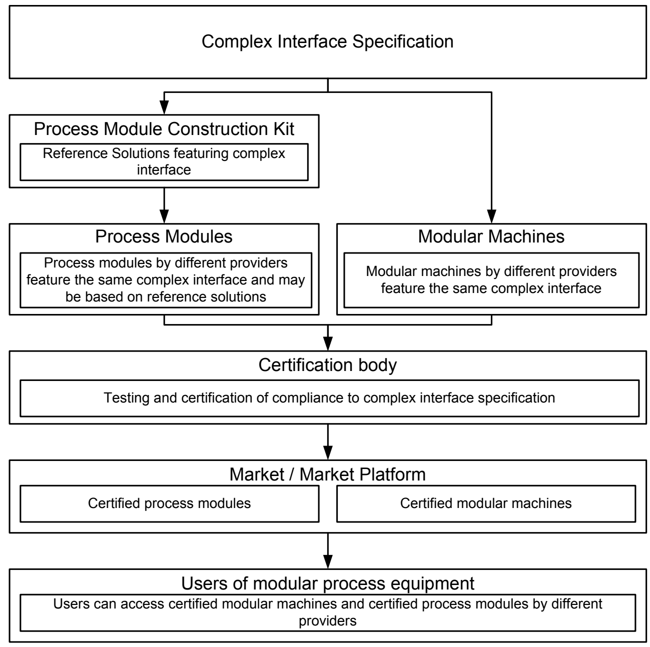


Figure 3: Concept for Cross-Platform Integration.

### 4.1 Use Case

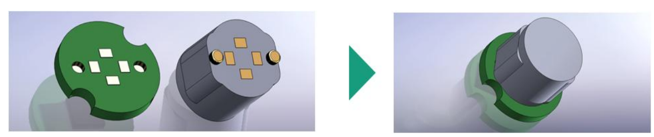

Figure 4: Demonstrator product.

The evaluation was based on a demonstrator product, a sensor module, as depicted in Figure 4. Both parts feature dimensions less than 2mm. The required positioning accuracy is <25µm.

For the analysis a process chain was designed around the product. The process sequence is: Cleaning – Dispensing – Pick & Place – Curing – Testing. For small lots an automation of dispensing, pick & place and curing processes was considered. For increasing lot sizes automation of the whole process chain was taken into account.

The special-purpose machines are considered as custom machines for a certain product within this model. This means that reconfiguration requires a constructional change and reuse of the machine for a different product is not possible.

For the modular approach, a system of process modules and platforms is assumed. This allows for reconfiguration by exchange of platform and modules. Reuse of process equipment is therefore possible.

### 4.2 SWOT Analysis

The original aim of SWOT is to identify internal (Strengths, Weaknesses) and external (Opportunities, Threats) factors for achieving a defined objective. In our case the objective is in general to produce the required quantity in excellent quality at the best cost. The strengths and weaknesses compare a modular production system (MPS) to a conventional commercially available production line (CPL). The opportunities and threats are factors for an assumed introduction of a modular production system on the shop floor.

For the product lifecycle we assume five typical stages over time (development, introduction, growth, maturity, decline) and a standard development over time. As use cases we choose the process change within a production line and the transition of an old to a new product (compare Figure 4).

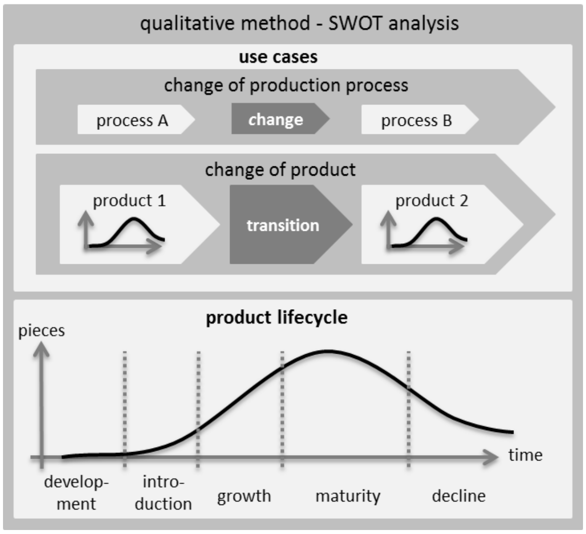


Figure 5: SWOT analysis.

### 4.3 Net Present Value Analysis

The NPV (net present value) analysis is a standard method of dynamic investment calculation to compare long-term projects from an investment perspective. To assess an investment the NPV assesses cash inflows (CI) and cash outflows (CO) when payments are made in time. Assumptions of NPV are constant discount rate (i) during whole investment, Investment time is divided into years and cash flows are made at the end of a year. It is defined as the sum of present (discounted) values of the project cash flows.

$$NPV(i,t) = \sum_{0}^{T} \frac{CI_t}{(1+i)^t} - \sum_{0}^{T} \frac{CO_t}{(1+i)^t}$$

A project is profitable if the NPV equals or is greater zero, because imputed interests are included into discount rate. [8]

In our case we made assumptions for the typical investments into a modular production system (MPS) and a conventional production line (CPL) about investment cost, volumes, prediction accuracy of volumes and discount rates. The parameters were typical for micro-technical products as described in the boundary conditions and derived from the experience with real micro-technical products. For the MPS we assume that investments are made according to the annual volume development and for CPL that the whole investment is made at the beginning of the project. Annual capacity of CPL is laid out to predicted volumes. Additional Project risks as not achieving predicted volumes, changes in production line configuration, adaption and changes of processes are covered by three different discount rates (standard 10%, medium risk 14%, high risk 18%). For modular systems we only need a standard discount rate, as we assume that modularity covers higher risk.

Five scenarios are modeled to assess indications to profitability compared to 'Standard' (compare Figure 5): 1. 'Faster growing', 2. 'Longer maturity', 3. 'Lower maturity', 4. 'Lowest maturity' and 5. 'Reduced discount rates'.

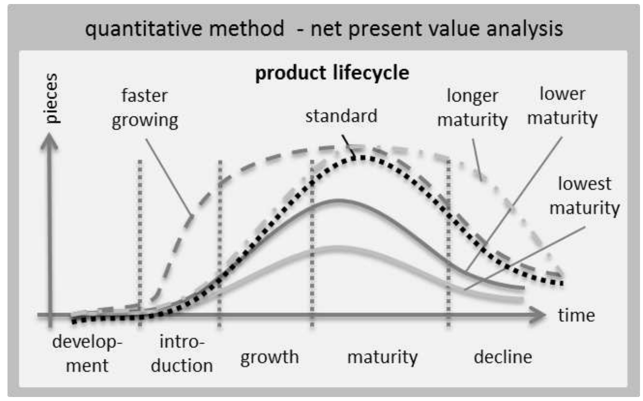


Figure 6: Quantitative Method – NPV Analysis.

'Standard ' is characterized by NPV equals zero for MPS and CPL. Investments for MPS are taken in three steps according to volume development. Higher total investment in MPS is assumed compared to CPL. But, residual value is higher for MPS, because some modules are bought later in time.

For 'Faster Growing' investments into MPS for higher automation are preponed. For 'longer maturity' investments in time are equal to 'Standard'. Only the volume peak is long-lasting. For 'Lower Maturity' the last investment to MPS is not necessary to cover annual volume and for 'Lowest Maturity' second last investment is additionally not necessary. For 'Reduced Discount Rates' discount rates are reduced by two percentage points.

## 5 EVALUATION RESULTS

### 5.1 SWOT Analysis

A SWOT analysis has been performed for each stage of the product life cycle from the perspective of a company producing micro-technical products with a wide range of products and product variants. The results have been compiled in form of a table for each stage.

| Strengths |
|---|
| - It is possible to work with a pool of process modules for quick configuration of the required processes<br>- Taking into account the availability of development platforms, the product development with close to series processes is possible |
| Weaknesses |
| - A weakness is that not one static production system is developed. Adaption and additional effort for high volume production will be necessary |
| Opportunities |
| - Simultaneous engineering of processes and product is possible without having to keep a high volume configuration in mind.<br>- Prediction accuracy of annual volumes is less relevant<br>- High investments in high volume configuration are not necessary in this stage<br>- Projects can be started with uncertainty of annual volumes and higher risks of process changes, as projects can be stopped or adjusted without having made a high investment |
| Threats |
| - A threat is waiting too long for further investment decisions, so that market requirements cannot be fulfilled |

Table 2: SWOT-Analysis Development Stage

| Strengths |
|---|
| - With MPS faster time-to-market with series processes and necessary adoptions to processes are possible |
| Weaknesses |
| - Additional planning and effort for expansion of the production line is necessary |
| Opportunities |
| - The main opportunity is to introduce products with low quality of annual volume prediction and expanding the platform according to market demands |
| Threats |
| - Late investment decisions may prevent required volumes according to demand<br>- Reduced process stability has to be expected, as processes might be adapted |

Table 3: SWOT-Analysis Introduction Stage.

| Strengths |
|---|
| - Possibility to expand and invest according to volume development |
| Weaknesses |
| - Additional planning and effort for expansion is necessary.<br>- Adaption may cause need for extraordinary qualification |
| Opportunities |
| - Growth according to market demands<br>- Rationalization by process adaption/change or platform improvements |
| Threats |
| - Fast evolution of production system is a threat to product quality.<br>- Extra effort required to assure promised quality |

Table 4: SWOT-Analysis Growth Stage.

| Strengths |
|---|
| - During maturity stage MPS are still adaptable in comparison to CPL<br>- Qualification of single process modules is possible on a separate modular “development” platform |
| Weaknesses |
| - Efficiency of MPS will always be below the optimized operating point of special purpose machines |
| Opportunities |
| - Load balancing is easier, as additional process modules can be built and used on extra platforms. So the transition of the flexibility corridor is possible |
| Threats |
| - Some customers require extra qualification of total system when platform or a process is adapted. This results in lower efficiency and higher costs<br>- Total investment for MPS can be higher |

Table 5: SWOT-Analysis Maturity Stage.

| Strengths |
|---|
| - Decline of MPS equipment is also possible according to market demands<br>- Not required modules can be reused<br>- Spare part production can be organized in job shop production or in laboratory scale and with series processes without retaining large and expensive equipment from maturity stage |
| Weaknesses |
| - Adaption of process and process equipment during decline stage can affect process stability and quality<br>- Adaption may lead to additional investments for the decline stage |
| Opportunities |
| - Equipment can be used elsewhere and configured to particular product when required |
| Threats |
| - Changes during decline may affect process stability and product quality |

Table 6: SWOT-Analysis Decline Stage.

After analyzing the implications to the product life cycle two typical use cases are analyzed. The first use case is a process change within a production, the second is a product change on one modular system.

| Strengths |
|---|
| - MPS allows plug in of new process modules into an existing production line<br>- Process improvement can be easily realized on an identical process module on a separate development system. Results can then be transferred to the productive system with short interruption<br>- Efficiency can be improved by successive automation of manual processes |
| Weaknesses |
| - Requalification of single process modules or whole system might be necessary<br>- Contracts with customers might avoid changes to MPS |
| Opportunities |
| - Engineering effort is reduced due to repetition effects<br>- Reduction of set-up and change-over times |
| Threats |
| - Possible downtimes after process reconfiguration<br>- Projected evolution of process potential cannot be achieved |

Table 7: SWOT-Analysis Process change.

| Strengths |
|---|
| - Additional modules for the new product can easily be integrated into the platform<br>- Possibility to produce both products on one system |
| Weaknesses |
| - Reduced efficiency compared to CPL |
| Opportunities |
| - Production lots of multiple products can be balanced |
| Threats |
| - Reconfiguration might affect process stability and product quality<br>- Market demands are hard to predict. This can affect production and transition planning |

Table 8: SWOT-Analysis Product Change.

### 5.2 NPV Analysis

Figure 7 gives an overview of the NPV results. On the x-axis the scenarios and on the y-axis the discount rates are assigned. The results are presented in pairs. The left one is the result for MPS and the right one for CPL. '0' is displayed if the result of NPV calculation is zero. Higher or lower results of NPV calculation are represented by plus/plusses and minus/minuses.

For MPS medium and high risk discount rates are not necessary (compare 4.2). Therefore the results are the same as for the standard discount rate.

Standard scenario with standard discount rate is valuated for MPS and CPL with zero (compare assumptions in 4.2).

| discount rate | Scenarios: standard | faster growing | longer maturity | lower maturity | lowest maturity | reduced discount rates |
|---|---|---|---|---|---|---|
| standard | 0 / 0 | ++ / +++ | ++ / ++ | 0 / -- | + / --- | + / + |
| medium risk | 0* / - | ++* / + | ++* / + | 0* / --- | +* / --- | +* / 0 |
| high risk | 0* / -- | ++* / + | ++* / - | 0* / --- | +* / --- | +* / - |

Legend: MPS / CPL; O = NPV equals zero (baseline); + = NPV is greater zero; - = NPV is less zero
*assessed with standard discount rate, because higher discount rate is irrelevant for MPS

Figure 7: Results of NPV - MPS compared to CPL.

For 'standard discount rate', NPV analysis indicates advantages in two (lower and lowest maturity) of five scenarios for MPS. The advantage of MPS is that negative cash flow for further investments are not necessary and for CPL investments are already done and production line is oversized.

'Faster Growing' has advantages for CPL. But, both systems are favorable, because of higher positive cash flow according to faster growing of annual volumes. This means if the prediction accuracy of annual volume is good, processes are well known and the annual volume is very high (mass production), special purpose machines have a higher NPV.

In two (longer maturity, reduced discount rates) of five scenarios MPS and CPL are equal. For 'Longer Maturity' higher positive discounted cash flows have a lower impact than 'Faster growing'.

For medium and high risk NPV indicates significant advantages in all 5 scenarios for MPS. This means if volume is hard to predict, but could be mass production in the future, processes are not well known and simultaneous engineering of product and processes is required, NPV always indicates advantages for the modular solution.

## 6 DISCUSSION

A concept for cross-platform integration of process equipment for modular micro-assembly systems has been presented.

This includes a complex interface between process modules and machine, a process module construction kit and a platform for modular equipment by different providers.

The concept shall be overall a first step towards a scenario which enables on one hand companies producing a wide range of micro-technical products to easily access modular process equipment. On the other hand companies supplying modular process equipment shall be able to access new markets with their equipment.

Based on this concept, modular micro-assembly systems have been evaluated against a conventional special purpose machine approach from the perspective of a micro-manufacturer. A quantitative net present value analysis and a qualitative SWOT analysis have been performed to evaluate these two concepts against each other.

As the SWOT analysis indicates, modular systems offer many strengths and opportunities. The flexibility and the continuous evolution of the production system are promising, especially if it is unclear how the product volumes and thus revenues will develop.

On the other hand process stability and thus product quality might be negatively affected, which is a serious threat. Additionally contractually or legally required process qualifications might impair the continuous evolution of the system.

On the other hand the investment risk could be reduced with the modular solution. It could be a potential approach for many micro-technical products when the economical performance is uncertain. It could help to get better through the ‘valley of death’.

It is hardly possible to make a general statement about the suitability of modular micro-assembly equipment. However, the evaluation presented in this paper indicates strong advantages towards modular micro-assembly systems when volumes are rather low (40k-600k pieces/year), the predictions are uncertain and several products and variants are planned to be produced on one highly utilised machine. In such cases investment risks are reduced whilst improving the ability to follow the market dynamics.

## 7 ACKNOWLEDGEMENTS

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# Statistical Study for Micro Forming Technologies Used for Linked Parts Production

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**Abstract**
Manufacturing and handling of micro parts is a great challenge due to their small dimensions. Manufacturing processes and the state of knowledge in macro technologies are not smoothly transferable to the micro world. This can be justified, for example, by size effects and the related, changed component behaviour. It is assumed that known statistical distributions from macro range are changed, too, concerning to the changed behaviour and changed physical regularities in micro range. For that reason quality criteria for micro cups are described. By means of these selected criteria, parts are judged. Using the findings, statistical distribution models for the simulation of ladder linked parts production are determined.

**Keywords:**
Micromachining; Deep drawing; Sheet metal

## 1 INTRODUCTION

Production of micro parts increasingly becomes more important. In automobile industries and in the telecommunication branch micro parts are integral components. In automobile industries sensorial and optical micro components are applied, for example, to achieve an increased driving comfort and a higher security level [1]. In every application field manufacturing and handling of micro parts constitutes a great challenge because of their small dimensions. According to Vollertsen [2] micro parts are smaller than 1 mm in two dimensions. Within the third dimension they have to be smaller than 5 mm. Applications and experiences from macro technology are not smoothly transferable to the micro technology world. Important reasons are size effects, which occur because of changing ratios like the ratio of the volume to the surface after scaling geometrical dimensions [2]. Challenges also are known for handling and storing micro parts. For example, exact positioning and aligning of micro parts because of the part's fragility is challenging. Figure 1 exemplarily shows some appearing faults primarily caused by mishandling. In figure 1 a) and 1 b) deformed parts can be seen. Figure 1 c) shows a dent at the cup bottom. An ideal cup is shown as reference in figure 1 d).

A possibility to avoid these difficulties is the manufacturing and handling of the micro parts within a parts linkage. When micro parts are manufactured within a linkage, using different procedural steps, the whole linkage achieves dimensions of a macro part. Two different types of linkages are the line type and the ladder type [3]. Ladder Linked Parts are especially suitable for manufacturing of parts using sheet shaping technologies like stretch forming operations [4].

For being able to provide only good parts for a production process, quality descriptions after every production step along the entire production line are necessary. There are only a few statistical models which describe quality for micro range. Existing statistical models from macro manufacturing give no unrestricted validity for micro range because of occurring size effects caused by changed physical regularities in micro range. That is why quality investigations for linked parts manufacturing and handling are necessary. The following investigations represent a pilot study for quality evaluation for the production of micro parts in linkages. The production environment and the simulation environment shall simultaneously be built up wherefore statistical data are necessary beforehand. To obtain the necessary data, studies at the existing single production steps are necessary. A pleasant ancillary effect beside receiving data for the simulation is the reception of data of the single production steps which have not yet been identified.

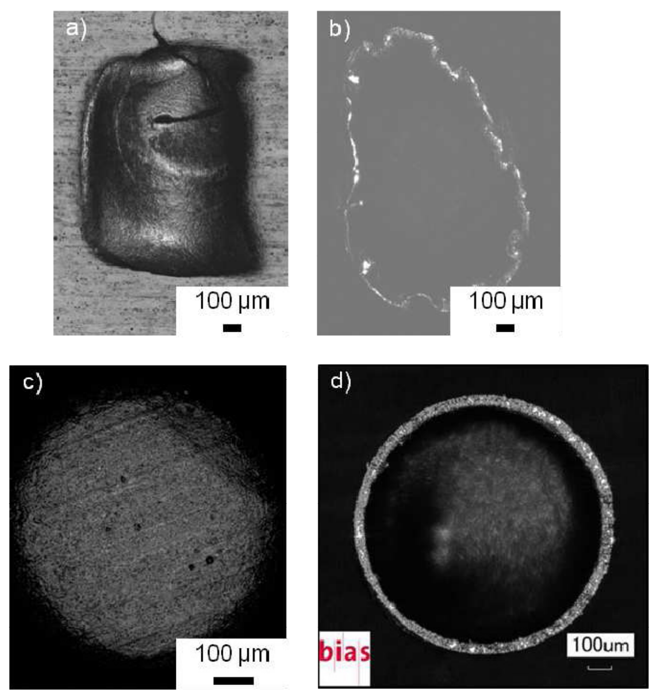


Figure 1: Faults by mishandling: a) deformed cup, b) deformed cup, c) dent, d) ideal cup (BIAS).

# 2 STATE OF THE ART

## 2.1 Examples for Statistical Models in Micro Researches

Micromachining encompasses all procedures of manufacturing engineering, whereby primarily the main groups cutting, forming and primary shaping are applied [5]. The choice of a procedure depends on the achievable process reliability but also on the feasibility and on the production task. At forming procedures micro parts are mostly manufactured using punching and bending operations. Applications of the macro range are not always directly transferrable to the micro range because of special physical micro effects [6].

In research and industry statistical models for quality description and quality assurance in micro manufacturing hardly exist. Existing models for the macro range are often not transferrable to the micro range because of special size effects. There hardly are statistical models, which are describing the geometry of micro formed parts.

Schlipf [7] for example describes a method for the statistical regulation of manufacturing processes and measurement processes for achieving a production of micro-mechanical parts with sparse variability [7].

Kennerknecht et al. [8] describe the crack propagation of micro components on the basis of different fatigue tests. Therefore fatigue experiments in positive pulsating and alternate pulsating stress were done at plane drawn micro samples (1 mm x 260 µm x 130 µm) from aluminium-bronze. With micro-bent samples (200 µm x 200 µm x 1.2 mm) from yttrium stabilizing zirconium oxide threepoint-bending-fatigue experiments were executed. The crack propagation curve shows a behavior respective to the Paris law. Its coefficient amounts to n = 23. [8]

A further model of the primary shaping manufacturing engineering is explained by Röger [9]. He describes the mechanical attributes of micro samples from silicon nitride. They are produced by pressureless hot-molding, which is applied as a rapid-prototyping-process. The investigation of the mechanical attributes ensued at more than 30 probes with the dimensions 1500 x 230 x 230 µm through three-point-bending-stress. Furthermore, the structure is examined in the cases grain size and grain structure, amount and distribution of the amorphous secondary phase and the porosity. The ascertained strengths are between 540 and 1200 MPa. For all parameters the strength can be depicted as Weibull distribution, whereby also deviations from the ideal Weibull distribution exist. [9]

## 2.2 Manufacturing of Linked Parts

Figure 2 shows the process chain of ladder linked parts with the steps preparation, deep-drawing/stretch-forming, punching and material accumulation. The function of the statistical study presented in this paper is to generate statistical distributions being able to simulate the process chain for the production of ladder linked parts. For this reason a short introduction to the process chain follows.

First of all the metal strap is prepared for the further transportation. A possible preparation is to punch the edges of the strap, so gear wheels can grip into the punching holes to convey the strip. The second process step is deep-drawing respectively stretch forming. The strip is conducted into the tool where the deep-drawing ensues in defined intervals. The third process step is punching. Here shapes between the drawn parts are punched out. At the edges of the punches the accumulation takes place. This production chain shall also be deployed as a virtual linked process chain, for being able to simulate different process chains. The statistical models of this investigation are the base for the simulation models. The cups are manufactured by using different tools at the micro forming machine of the Bremer Institut für angewandte Strahltechnik GmbH (BIAS) with kind support of the sub-project B3 of the CRC 747 (Collaborative Research Center 747). Beside the conventional tools a tool with a diamond like carbon coating (DLC) is employed. DLC-tools occupy a very hard surface, which offers an alternative to lubricants, to reduce the abrasion of the tool. The used manufacturing parameters are [10]:

- punch diameter: 0.9 mm,
- inner diameter cavity: 1.06 mm,
- external diameter blank sheet: 1.6 mm,
- sheet thickness: 0.05 mm.

## 2.3 Identification of Quality Features

Quality features in micro forming are comparable with quality features in macro forming. A distinction between geometrical features, surface features and material features can be done.

Figure 3 illustrates different characteristics of the feature deviations of roundness. Geometrical features are, for example, deviation in dimension a), shape deviations b) and deviation in position c). Deviation in dimension is defined as deviation from the desired geometry to the achieved geometry. According to DIN EN ISO 1101 shape deviations are deviations from the provided perfect shape. Examples are straightness, evenness and cylindrical shape. [11]

The deviation in position is the deviation from a desired point of line or surface of the part. Characteristics for example are concentricity or symmetry. [11]

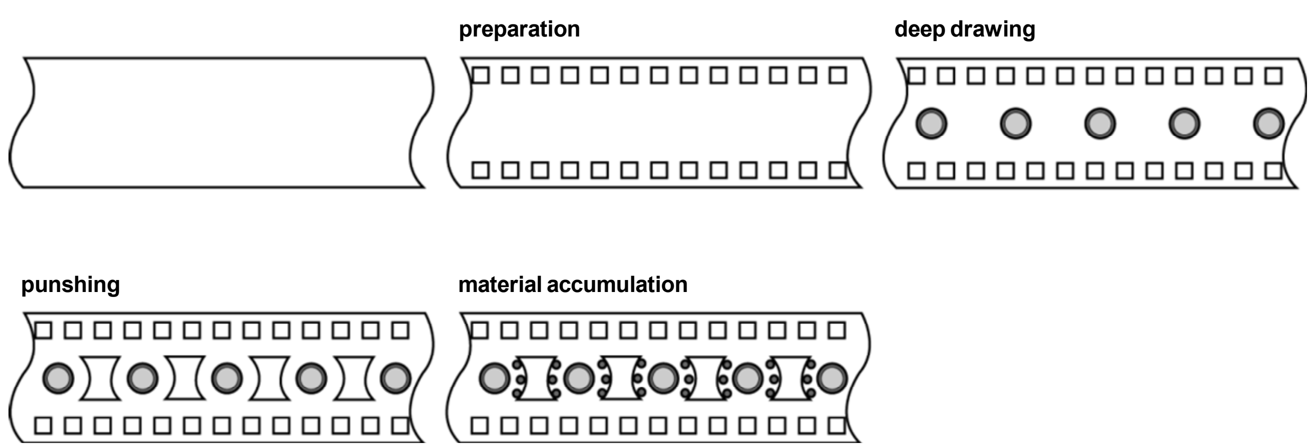


Figure 2: Process chain for manufacturing ladder linked parts.

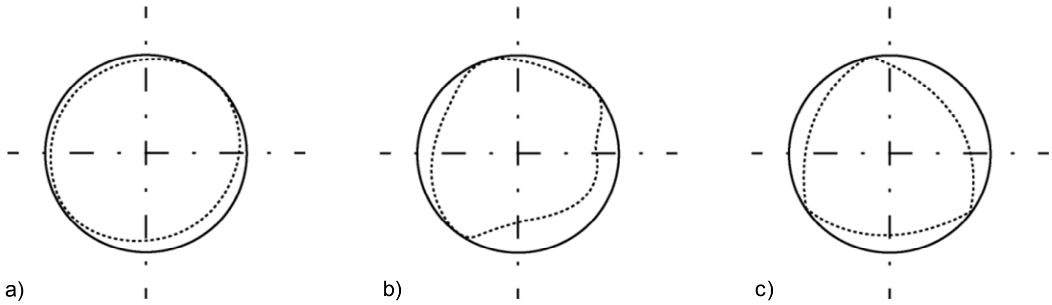


Figure 3: Characteristics of roundness deviations [11].

Part of the surface features are surface imperfections. They are described within DIN EN ISO 8785. Surface imperfections are defined regarding to the standard element or irregularity or groups of elements and irregularities of the real surface, which are emerged inadvertent or random e.g. at processing or storing [12]. The standard subdivides four types of surface imperfections: immersions, humps, combined surface imperfections, sporadically surface imperfections. Beside the surface imperfections the surface finish is described by roughness characteristics. Roughness finish is described in DIN4760 [13]:

- unevenness,
- waviness,
- grooves,
- creases, sheds, peaks,
- structural conditions and
- mesh structure.

Material characteristics like grain size, grain shape, chemical composition, texture and strength are describable using metallographic investigations. Potential mistakes which are detectable within the material are for example blowholes, pores, crystal defects and porosity. Material mistakes are described and defined within DIN EN ISO 8785 [12].

## 3 DESIGN OF EXPERIMENTS AND TEST EXECUTION

### 3.1 Products under Investigation

The machine for producing ladder linked parts is currently still under construction. But, statistical data are necessary to build up a simulation model. Therefore separated micro cups are investigated in a first step. Measurements are done at the laser scanning microscope of the Bremer Institut für angewandte Strahltechnik GmbH (BIAS). At the laser scanning microscope surface finishes, radii and creases can be determined and investigated. The products under investigation are cups made from cupper or steel. The batch size lies at round about 2500 parts. The inner diameter of a perfect cup lies at 0.9 mm, the outer diameter at 1 mm. The maximum outer diameter is 1.06 mm because of the cavity size, neglecting elastic deformation.

For example, their rib thickness, rib altitude and surface imperfections are investigated. Within the next chapters a short description of occurring deformations will be described. After that a more intensive reflection of the quality features rib altitude and rib thickness will follow. In the following the results for steel cups (1.4301), produced in different batches, are presented. From every investigated cup batch 10 objects are measured.

The ten samples of each batch are randomly selected. Following, the material and the batch are mentioned, e.g. St_01 representing steel of batch no. 1. After that two kinds of geometrical data are determined: on the one hand the inner radius of the cups and on the other hand the external radius of the cups are determined especially for being able to make a statement about creases of second order. Moreover, the edges were proofed for potentially appearing scallops as well as varieties at rib altitudes. Furthermore, an investigation of the surface, searching for surface imperfections, takes place. Cup base fractures and deformed parts are not investigated.

### 3.2 Measurements and Interpretation of the Ladder Linkage

For investigations the Keyence laser scanning microscope VK-9700 is used. It is based on the principle of confocal holography. For every cup three views (edge of the cup, inner bottom and outer bottom) are acquired by using the laser scanning microscope, which are shown in figure 4. Adjustments like enlargements, lightness and measuring range have to be set manually. The edge is acquired in its entirety by using a ten-fold enlargement. The inner bottom and the outer bottom are acquired with a twenty-fold enlargement for being able to detect quality faults. When faults are found the acquirement was repeated with a fifty-fold enlargement for being able to inspect the fault more precisely.

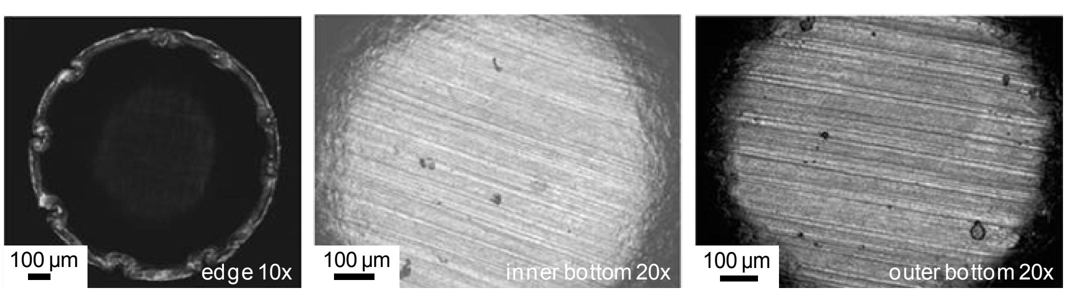


Figure 4: Edge of the cup, inner bottom and outer bottom.

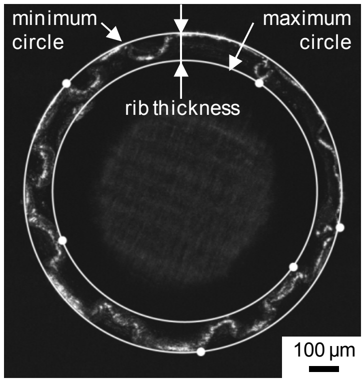


Figure 5: Determination of rib thickness.

Important, for example, is the quantification of size and characteristic of the fault. The analysis of the microscope captures is made manually. The analysis is made for the views described above. The rib thickness is determined by using the minimum circumscribed circle and maximum inscribed circle like depicted in figure 5.

The minimum circumscribed circle is the smallest circle which encases from the outside. Therefore three distinctive points at three distinctive places are set. The maximum inscribed circle is the largest circle of the inner side of the cup. Therefore also three distinctive points at three distinctive places are set. The difference of the two circle's diameters devotes to the rib thickness. The larger the difference between the two radii is the larger is the rib thickness or the bigger the rib thickness is influenced by creasing.

The variation of the rib altitude of a cup is shown in figure 6. The height profile is shown in figure 6 b). Within this diagram the highest point (2) and the deepest point (1) are chosen manually. The differences between these two points result as the variation of rib height.

### 3.3 Measurement Results Ladder Linkage

Applying excessive blank holder forces cause cup base fractures. Cup base fractures can be avoided, if the blank holder forces are adjusted and are constant during the production phase. The rib thickness should be around 0.05 mm. It can be seen that the rib thickness of all produced cups is above the desired value. Reasons for this divergence are creases of second degree. Creases of second degree occur when the retaining forces are too low.

In contrast to the copper cups the steel cups have a similar variation in the frames height. The frames strength should account 0.05 mm for all cups. Fact is that the frames strength of all produced cups is clearly higher than the expected value. Whereby the cups produced by the DLC coated tool have a better shape accuracy than the cups produced with an uncoated, conventional tool [14]. The reasons for this frames strength are creases of second degree. During production of deep-drawn parts it should be the aim that no creases neither first degree nor second degree appear. The variation of the frames strength is in this case understood as variation of fold strength. By the creation of the overview from the statistical results for copper cups the essential results of the copper cups are consulted.

### 3.4 Measurement Results of Steel Cups

Within the whole investigated sample of steel cups eight distorted parts are found, from which seven cups already appear in batch St_01. A further one exhibits a bulge in the bottom of the cup. The deformed cups were not investigated further. Only one steel cup, shown in figure 7, has a variation of the frames height from under 100 µm.

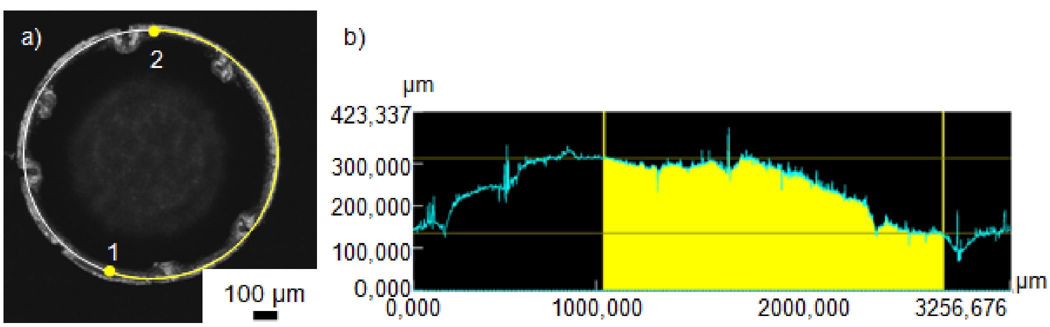


Figure 6: Variation of the altitude of a cup.

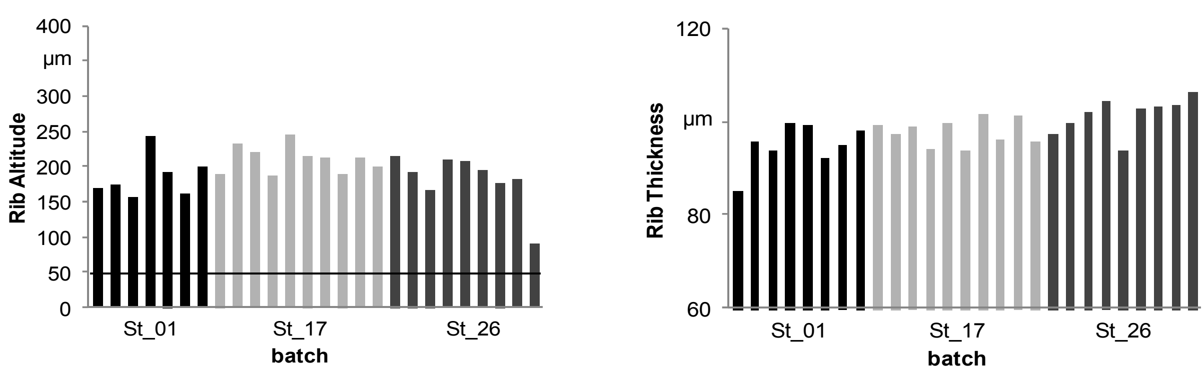


Figure 7: Steel cups: a) variation of rib altitude, b) variation of rib thickness

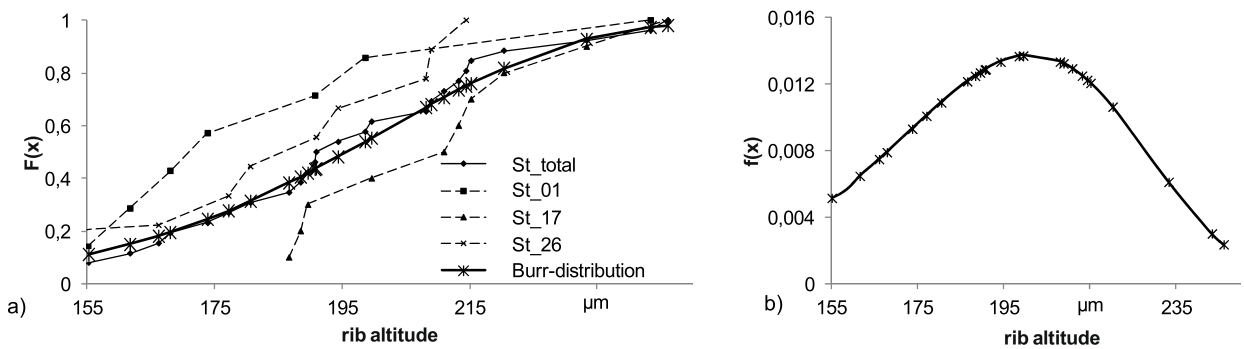


Figure 8: Steel cups – deviations of the rib altitude per part: Burr distribution function a).
Steel cups – deviations of the rib height per part: Burr density function b).

### 3.5 Deviation of Rib Height Per Cup

Measurements exhibit that deviations of the rib height can be approximated with a Burr distribution. Figure 8 a) shows the process of the deviation of rib height. Batch 17 starts with a higher deviation like the other two batches. The progress of the Burr distribution is S-shaped. That means that the rib-height deviation accumulates at around 200 µm.

In figure b) the progress of the Burr density function is shown. The highest probability of occurrence lies between 185 µm and 215 µm. The progress of the density function approximately is gauss-shaped. That means that the amount of measurement values decreases to higher and lower measurement values. An expected value of 192.99 µm and a standard deviation of 30 µm can be determined.

### 3.6 Rib Thickness

Moreover, the rib thickness per cup can be described using the Burr distribution. The progress of the batches 1 and 17 are nearly homogeneous (figure 10 a)). All cups have a rib thickness of nearly 100 µm. On the contrary, charge 26 exhibits measurements of up to 106 µm. At this batch the slope is also higher. Batch 26 shows an explicit variation. The density function, shown in figure 10 b), achieves its maximum at 99.5 µm. A considerably occurrence can be seen at 94 µm and round about 103 µm. Also here a gauss-shaped distribution is recognizable. Hence, it can be assumed that the amount of values decreases to the direction of smaller and higher values from its maximum.

### 3.7 Overview about Statistical Models

The procedure for getting the distributions for copper cups is the same like at the steel cups. Therefore, the results are described only summarizing. It can be seen that for copper cups no correlation exists between rib thickness and rib altitude. The variability of the rib altitude is describable by a generalized Pareto distribution. At the copper_DLC cups the rib thickness follows the Weibull distribution. At the copper cups the rib thickness follows the Burr distribution just like the steel cups (table 1).

## 4 CONCLUSION

Small dimensions constitute a challenge in the production and handling of micro parts. Because of the fragility and the occurring size effects handling and production processes cannot be transferred from macro to micro range. To overcome the mentioned problems linking of the micro parts is a valuable approach, because the dimensions after connecting the micro parts correspond to dimensions of macro parts. The production chain for producing ladder linked parts consists of the manufacturing processes punching, deep-drawing/stretch forming and laser melting. At the moment of the investigation a production of the ladder types was still under construction.

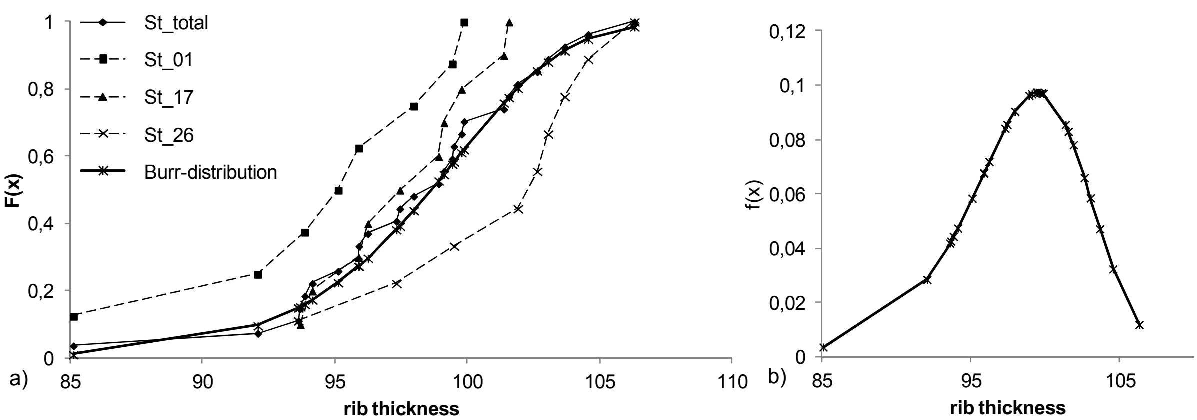


Figure 9: a) Steel cups – rib thickness: Burr distribution function.
b) Steel cups – rib Thickness: Burr density function.

| type | material | Parameter | model |
|---|---|---|---|
| ladder linkage | copper_DLC | variability rib altitude | generalized Pareto distribution |
| | | rib thickness | Weibull distribution |
| | copper | variability rib altitude | generalized Pareto distribution |
| | | rib thickness | Burr distribution |
| | steel | variability rib altitude | Burr distribution |
| | | rib thickness | Burr distribution |

Table 1: Overview about statistical distributions.

Therefore the investigations were executed at deep-drawn cups made of steel or copper with an inner diameter of 0.9 mm and a foil thickness foil of 0.05 mm. Object of investigation was the quantitative description of the rib thickness and the variation of the rib altitude for each part as well as the surface quality. At all examined cups creases of second-degree were found ascertained through the rib thickness. The rib thickness at the steel cups is between 80-100 µm. The variation of the rib height is significantly different between the three investigated cup types. Among the second-degree creases and the variations in height no coherence could be found. It is not possible to construe a uniform statistical distribution for the mentioned quality characteristics, because of the big differences and scatter among the different cups. The rib thickness (St, Cu) could be approximated with a good accuracy by the Burr distribution. With the generalized Pareto distribution the variation of the rib altitude could be described. The results build a solid basis for upcoming simulations. After building up the pilot station and the simulation model the next step will be to investigate and implement new statistical models for linked parts manufacturing. The presented results may be considered as a first approach to identify the statistical distribution of the deep drawing process which could be used within the simulation. Especially at micro deep drawing of steel cups the Burr distribution seems to be suitable for the simulation model. In addition, valuable results within the evaluation of production of piece parts using micro deep drawing are emerged. These results are used for further investigations of scattered production.

## 5 ACKNOWLEDGEMENT

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# Specification Technique for the Consistent Description of Manufacturing Operations and Resources

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**Abstract**
The design and production of mechatronic systems is an interdisciplinary and complex task. Within the integrative development process the interactions between the design of product and associated production system have to be considered continuously. The selection of appropriate manufacturing resources requires knowledge about operations, work piece characteristics and machine capabilities. Therefore, a consistent description of manufacturing resources and operations is presented that supports the conceptual design of production systems. Sets of attributes and parameters include all necessary information to match a resource with operation specific requirements as well as general requirements.

**Keywords:**
resource requirements planning; conceptual design of the production system; integrative design process

## 1 INTRODUCTION

The prevailing market situation requires companies in high-wage countries to develop and manufacture fast and cost-effective their increasingly individualized products. Today, highly flexible and adaptive production systems are used to meet the manufacturing requirements [1]. The priority action is the efficient and rational use of existing resources [2]. The decision for a principle manufacturing operation and a qualified resource is taken at an early design stage of the production system development. However, after maximizing the productivity in manufacturing, a rapid development of the production system for a product is the new challenge [1]. The conceptual design includes the operations to be performed, their sequence and the various resources. In this phase plenty of interactions between the manufacturing operations and qualified resources have to be considered. When there is more than one resource with the capabilities to accomplish the desired manufacturing operation, it is quite complex to identify the best alternative [3], [4]. All suitable resources have to be compared with regard to the process time, energy consumption and production costs. The manufacturing of raw, unfinished and finished goods involves usually more than one operation. The best possible allocation of a resource to a single manufacturing operation does not necessarily lead to an efficient manufacturing process (operation chain). For example, the set up time for resources can be reduced when subsequent operations are performed by the same machine. This could also be achieved by changing the sequence of operations, assumed the new sequence is qualified to manufacture the desired goods.

The aim of the presented approach is an assisted selection of alternate resources based on a chain of manufacturing operations. Existing approaches in this field of research show that the operations and their parameters for manufacturing must be known. Furthermore, the available or conceivable resources and their technical properties to accomplish these operations have to be considered [2]. The assisted allocation of resources to manufacturing operations requires a formal description of parameters and properties. The developed approach bases on CONSENS (CONceptual design Specification technique for the ENgineering of complex Systems) that was developed at the Heinz Nixdorf Institute. This technique describes the operation sequence by the used manufacturing technologies and further attributes. One or more operations can be mapped to a resource. The generic specification technique was adjusted to the specific aspects for an assisted mapping of manufacturing operations and resources.

## 2 CONCEPTUAL DESIGN OF PRODUCTS AND PRODUCTION SYSTEMS

In this article we focus on the early stage of the development of the product and associated production system. The product development process and the production system development process cannot be seen as a stringent sequence of process steps. It is more an interplay of tasks and iterations steps. In the first instance, the product concept highly determines the concept of the production system. With regard to the overall efficiency and manufacturing costs, the concept of the production system also influences the product concept. For this reason, the product and the associated production system need to be developed integratively.

### 2.1 Integrative Design Process

For an integrative conceptual design of the product and the associated production system of mechatronic systems a detailed procedure model has been developed (see Figure 1) [5]. It matches and synchronizes the main phases of the conceptual design of the product and of the conceptual design of the production system. The main phases of the conceptual design of the product are: **planning and clarifying the task** for the product, the **conceptual design on the system level,** the **conceptual design on the module's level**, and the **system integration**. The main phases of the conceptual design of the production system are: **planning and clarifying the task** for the production system, the **conceptual design on the process level**, and the **conceptual design on the resource level**. For the integrative design a close interaction of the phases conceptual design on the module's level, planning and clarifying the task for the production system and conceptual design on the process level is necessary.

**Planning and clarifying the task** (product): In this phase the core of the development task is identified. This is followed by an environment-analysis which investigates the most important

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boundary conditions and influences the system. The results of the first phase are documented by demands and wishes within the list of requirements.

**Conceptual design on the system level**: The main functions of the product are extracted from the list of requirements and set into a function hierarchy. In order to realize the documented functions, possible solution patterns for each function are investigated. The best solution combination is chosen and the active structure, the behaviour, and a first model of the product's shape are specified. The principle solution on the system level is the result of this phase.

**Conceptual design on the module's level**: For a closer look at the technical and economical realization of the principle solution, it is necessary to modularize the system [6]. This detailed investigation of the system also includes choosing specific product technologies. The product technologies determine the manufacturing technologies and vice versa the manufacturing technologies determine the characteristics of the product. Therefore the conceptual design on the module's level takes place in close interaction with planning and clarifying the task for the production system and the conceptual design on the process level.

**Planning and clarifying the task** (production system): In this phase the design task and the initial production system requirements are identified. Afterwards the modularized active structure and the building structure of the product are analyzed. The objective is to identify all system elements that need to be manufactured as well as their structural connection. This sets up the basis to derive the initial assembly sequence.

**Conceptual design on the process level**: The objective is to set up the manufacturing process, including all parts, assemblies as well as manufacturing and assembly operations. The elements that have to be manufactured are derived from a first building structure of the product. Next, they are linked by assembly operations to an initial assembly sequence.

The parts to be manufactured are completed by the necessary manufacturing operations to produce them from raw materials or unfinished parts. In this context on the one hand, adequate manufacturing technologies are chosen with respect to the deployed product technologies. On the other hand, these manufacturing technologies may also determine the structure or the shape of the product's modules. Thus, their specific requirements need to be taken into account for the conceptual design of the product's modules.

**Integration of the concept**: The principle solutions of the product's modules will be integrated into a detailed principle solution of the whole system. Concluding, a technical-economical evaluation of the solution takes place. Result of that phase is the principle solution that serves as a starting point for the subsequent product concretization.

**Conceptual design on the resource level**: In this phase the resources of the production system are determined. The resources realize the specified operations (cf. [7], [8]). The selection depends on the requirements witch arise from the manufacturing operations and input materials as described in the conceptual design on the process level. In this early stage of the development process the requirements include various uncertain information [2]. Nevertheless, alternative resource combinations have to obtained on this basis. In Addition, the overall economic efficiency that results from the manufacturing process and assigned resources has to be considered in the conceptual design on the resource level.

The presented procedure is not to be considered as a stringent result of single processing steps but it is marked by numerous iterations which are not shown in the figure. During the processing, the content of the principle solution of the product as well as of the production system are gradually developed and specified until there are final principle solutions in the end of the conceptual design.

## 2.2 Specification Technique CONSENS

In order to describe the principle solution of the product and the associated production system, the specification technique CONSENS was a result of the cooperative project VireS (funding period from July, 2008 to June, 2011). CONSENS provides a common language for the engineers of the different domains. The product as well as the production system is divided into several aspects, which are mapped on the computer by partial models. As the partial models are highly related to each other, the principle solution consists of a coherent system of partial models. The aspects of the product are Environment, Application Scenarios, Requirements, Functions, Active Structure, Behaviour and Shape.

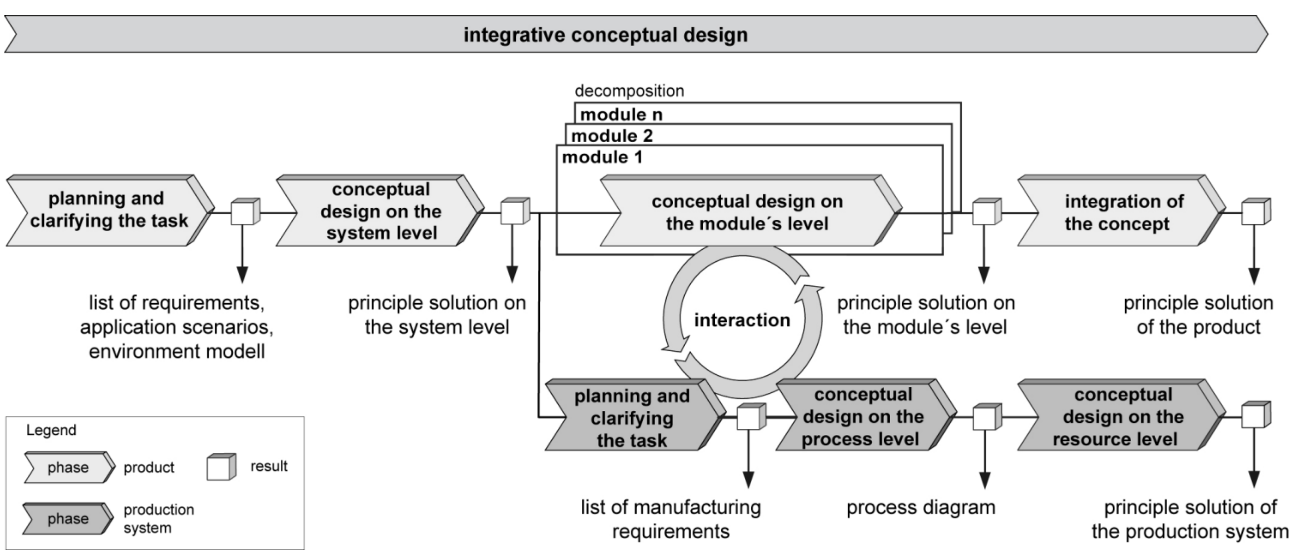


Figure 1: Generic procedure model for the integrative conceptual design of products and production systems [5].

In addition, there are four aspects of the production system as shown in Figure 2: Requirements, Process Sequence, Resources and Shape. The latter is not relevant to the presented approach.

**Requirements:** The list of requirements sets up its basis for the other partial models. It presents an organized collection of requirements posed to the production system (e.g. tolerances, number of units). Every requirement is textually described and, if possible, concretized by attributes and their characteristics.

**Process Sequence:** Depending on the concretion, a process represents an operation or a sequence of operations. It is characterized by a manufacturing function and additional attributes. During the conceptual design the manufacturing functions are concretized into manufacturing technologies. Each process always has at least one input-object and at least one output-object in the form of material elements.

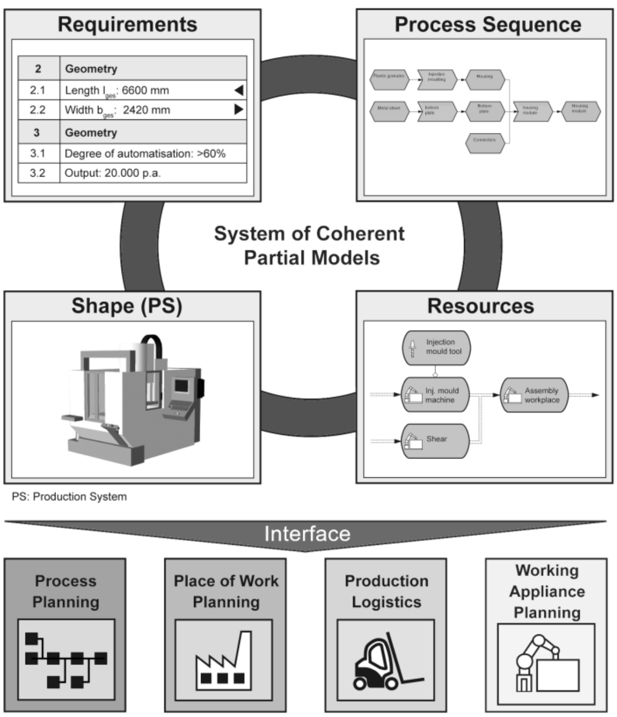


Figure 2: Specification technique for production system concepts.

**Resources:** Resources are defined as all equipment, tools and personnel that is required for the execution of a process. To every process of the partial model process sequence at least one resource is allocated, whereas it is possible that one resource realizes more than one process. In addition, a manufacturing technology can be realized by different resources. Starting from the processes, each allocated resource is described by requirements and attributes.

The specified conceptual design is the interface for the further development and planning steps within the four scopes Process Planning, Place of Work Planning, Production Logistics and Working Appliance Planning.

For more detailed information about the different partial models and the development process see [9]. In the following we will concentrated on the transition from the conceptual design on process level to the resource level and the required attributes and parameters for processes, material elements and resources.

## 2.3 Problem Analysis – Resource Allocation

Based on the first process sequence a systematic allocation of resources is required. The process specification defines the type of the necessary manufacturing technology which must be performed by the resource. More restrictions result from the process parameters and the input material elements of the process [10]. Furthermore there are general requirements like the cost per hour or the level of automation. These are not bound to a single process; instead they are valid for the whole production system. All this different restriction and requirements need to be considered during the resource allocation. The resulting list of requirements for the resource are determined by individual conclusions of experts, but they may be incomplete due to the varying expertise [3]. This non-formalised description of requirements demands a manual comparison with the capabilities of available or conceivable resources.

However, the process sequence is based on uncertain information of the product and due to this; it is not fixed [11]. Modifications on the product may change the requirements as well as the sequence of operations on the process level. This might affect the existing allocation of resources. After each change it is necessary to assure that the determined resource is still qualified. The relations between the properties of material elements and processes which leads to the manufacturing requirements are habitual not documented. Hence, when premises change in the design phase the affected requirements have to be identified manually.

Although the initial process sequence marks the starting point for the selection of resources, the resources as well may influence the process sequence. For example, the operations are rearranged to avoid machine changes and hence minimize set up times. Firstly, the restrictions affecting the potential process sequences must be known to determine valid alternatives. Secondly, all implications on the product design caused by a changed process sequences have to be considered.

The output material element describes the intermediate state of a work piece after the modification by a process. This output material element might be the input material of a following process. Resources are allocated with regard to the input material element and desired process. It therefore follows a sequence restriction due to the dependency on the material element: all processes that transform the material element and its parameters to the assumed state have to be performed previously. As a result the flexibility for further optimizations through alternative sequences is reduced.

## 2.4 Need for Action

In our understanding the allocation of resources, bases on the interactions of certain attributes of the processes, material elements and resources. The required manufacturing technology (e.g. milling) correlates with the provided resource technologies (e.g. milling and drilling). However, this is a simple example; actually the correlations that determine the qualified resources are quite complex and multifaceted [12], [3]. In the field of machining the resource must realize all tool movements as described in the process. The difference between the smallest and greatest position in the tool path correlates with the range of the axes. Beside the requirements from the process there are also dependencies to the material element that must be taken into account. Particularly the dimensions and weight of the input material element determine the possible resources.

Today the resource allocation is done by experts, who know the most common processes, resources and their interactions. Due to the wide field in production technologies, their knowledge is always incomplete and the decisions are subjective. Furthermore it is hardly possible to have all relations and effects in mind. For that reason we suppose an assisted allocation of qualified resources. All decisions must be reproducible to check their continuous validness and ensure a consistent design across the partial models. The aspired consistent description of processes and resources provides a direct feedback of decisions on other objects.

Therefore, the representation of a resource obtains the relevant requirements from the other partial models (Figure 3) and compares them with its own capabilities. For this purpose, a consistent description of manufacturing operations and resources provides the basis for verifiable decisions. This can be achieved through standardized attribute sets for the specification of the partial models [3], [13]. In the light of an increasing concretization, the processes, material elements and resources have to be described on different levels by the attribute sets and their values [10]. For example, an attribute is brown down to several finely graduated attributes; an value is concretize from a range to a fix specification.

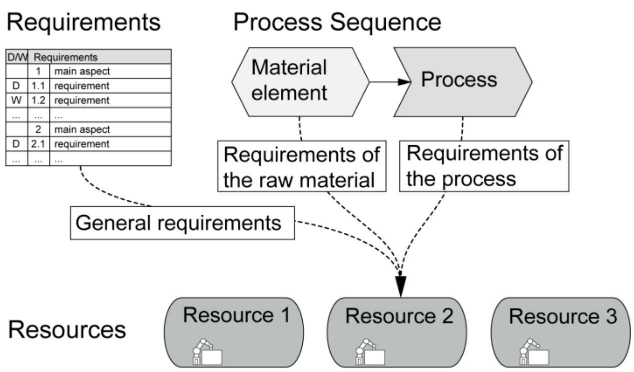


Figure 3: Requirements for the resource allocation

Besides the standardized specification it is necessary for the assisted selection to describe all relevant correlations of the attribute sets across the three partial models. Within the specification technique this should be done automatically to relieve the utilization.

In the past, different approaches for the description of manufacturing resources have been published. The NIST Manufacturing Resources Model and the ASME B5.59-2 draft focus on the requirements of manufacturing resource vendors but not on the application in operations planning, as they are lacking of the information of machining capabilities [14]. Other approaches extend the STEP-NC data model [15] to describe the resource capabilities [13], [10]. For example, the STEP-NC compliant machine tool data model (STEP-NCMtDm) described in [13] focuses on the conversation of machine independent operations described in STEP-NC to a vendor and machine specific STEP-NC program. The effort for building this detailed resource model is very high and the implementation of independencies between the operations and resources remain unclear. The same applies to the OOMRMmodel presented in [3]. Another manufacturing model was developed in the MOSES (model-oriented simultaneous engineering system) concurrent engineering environment. This model includes resources, processes and strategies, the latter are company-individual and describes how the resources and processes are organized, composed and deployed to realize manufacturing orders [16]. Although strategies are classified and subdivided into strategic decisions, the description is not formalized and so not machine readable. In general, most resource descriptions are too detailed for the early stage of the development of the product and associated production system due to the uncertain information level.

## 3 MODEL FOR THE CONSISTENT DESCRIPTION

In the following we present the approach of a data model for the consistent description of manufacturing operations and resources to support the conceptual design phase with CONSENS.

### 3.1 Basic Concept

For the consistent description the different element of the partial models are enhanced with specific attributes sets. The aim is to provide all required information to map material elements, processes and resources. Figure 4 shows the relevant objects and the corresponding sets which are divided in organisational data, descriptive characteristics and rules. The organisational data as well as the descriptive data contains a predefined set of standard attributes.

The organisational data is used for non-technical information, like identification number, delivery date, acquisition costs or machine hour rate. Some of this information is later on necessary to compare alternative manufacturing scenarios and different production system concepts to each other. The organizational data will therefore be needed to match general requirements.

Descriptive characteristics cover technical parameters for the selection of appropriate resources required for single processes. These are used to specify the material elements, the process and the resource in an adequate way. To meet the increasing planning information during the design process, general parameters (e.g. resource class) and specific parameters (e.g. specific machine type) are listed.

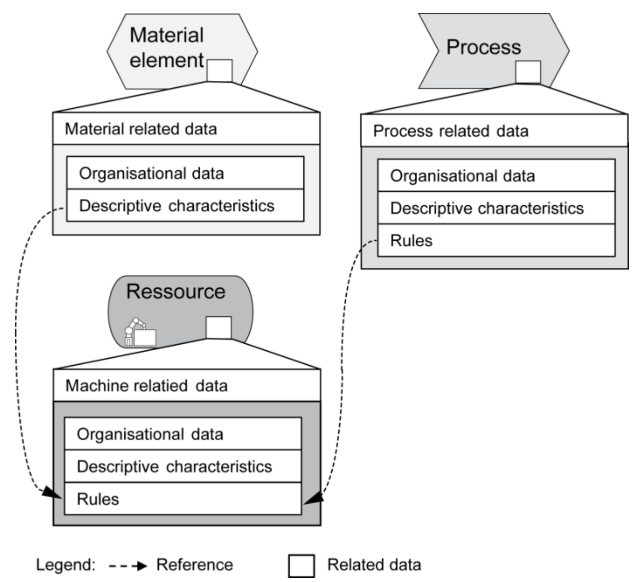


Figure 4: Basic concept of the data model.

The interactions between two or more attributes are described by rules. Rules refer to attributes of the same object as well as attributes of other objects. For example, a rule of a resource verifies if the resource is capable to execute a process. To generate this information, the attributes of the material element as well as the attributes of the processes are compared with resource parameters. As these rules cannot be generalized for all resources, each resource has its one rule. The rules represent the expert knowledge for resource selection. The allocation of rules to objects (e.g. a type of resource) solves the problem of an insufficient administration. This object orientated knowledge processing has already been approved in several commercial expert systems [17].

### 3.2 Description of a Machining Process and Resource

The consistent description is demonstrated by an aluminum plate which is machined by a milling machine. Figure 5 gives an overview of the data models for the description of material element, process and resource. For reasons of clarity only a part of the attributes are displayed. The attributes within the different sets have a hierarchic structure are represented by an AND-OR tree. According to the planning progress the attributes are specified in different levels of detail. That allows an early selection of possible resources even with few and uncertain information on process level.

The attributes are broken down until a matching with other attributes is possible. For example, the material element attribute shape cannot be matched with the machine table size of a resource. Hence, the attribute shape is divided into the attributes cuboid, cylinder, cube and so on. Naturally, the shape can only be classified by one form. These attributes are alternative branches (exclusive or) of an AND-OR tree. In this example, the attribute cuboid is true. For a matching with the table size, the attribute cuboid is described by length, width and height. These attributes represent branches with an AND operation. In the corresponding rule the dimensions and the form of the material element is used to describe the relation with the table size. The rule is shown in the resource related data and defined in a simple pseudo code. The presented rule of the resource ensures that the input material element fits on the machine table. The next rule compares the desired manufacturing technology of the process with the capabilities of the resource. Depending on the present information of the product, this is done on different levels of detail. Here, we have two levels: In the beginning, it is only known that the manufacturing technology is a cutting operation. In this stage all machine tools providing cutting operations are allocated to the process; assumed the material element fits on the machine table. Later on, the manufacturing technology on the second level (milling) is compared with the process and the previous allocated resources.

As mentioned before, the sequence of processes is not fixed, but there are a lot of restrictions. Some processes, for example the drilling of high-precision bearing surfaces, need to be executed in the same clamping position and on the same machine to accomplish the allowable tolerance. Further sources for restrictions are technological manufacturing sequences (e.g. primary forming before transforming, transforming before coating), limited accessibility and the sequence of assembly. These are described by the attribute process chain, here exemplary by the declaration of previous and following processes.

### 3.3 Application

The presented data model for CONSENS provides a great benefit for the **conceptual design on the resource level.** The utilization with the specification technique is introduced by an exemplary process sequence shown in Figure 6.

In the first step, qualified resource combinations for the first process (machining plane side) are identified. The source is the shop floor model with virtual representations of all available resources. As described above, the capability to perform a process is checked by rules which are part of the resource related data. If no resource has the capabilities, generic resources (e.g. machine class) are used to determine the requirements for new acquisitions. Once, a resource is allocated to a process, the impact on the present process sequence is determined. These requirements are also described in the resource type specific rules. As an example in the field of machining, a setting up operation is always needed when the manufactured work piece on a machine changes. As a result, the necessary auxiliary processes are added to the process sequence.

For the second process (machining front side) in connection with the known shape of the aluminium plate, we assume that there is no qualified resource available. In this case, it is necessary to check how the aluminum plate has been changed by the first process. The attributes of the intermediate material element are derived by the rules in the process related data.

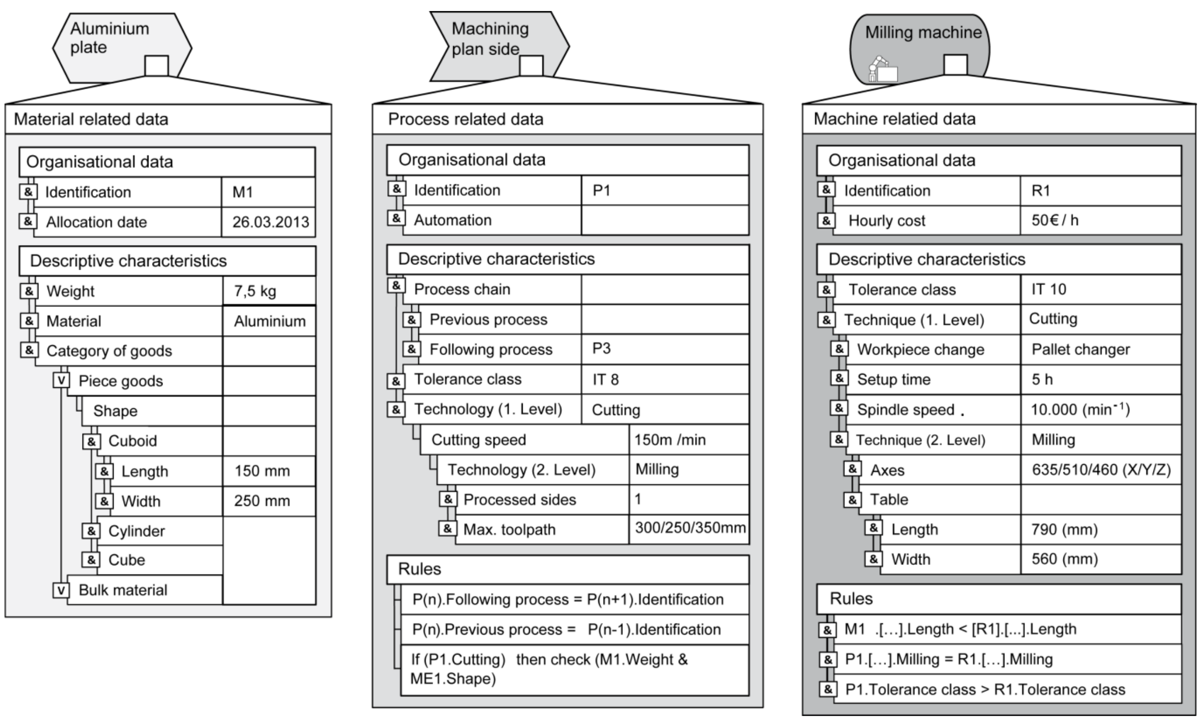


Figure 5: Example of the data model for a material element, process and resource.

Here, the attributes weight and dimensions of the aluminium plate that might have changed. As a result there are now modified requirements for the selection of a resource for the second process. Two qualified resources can be found in the shop floor model. Once, all processes are associated with one or more resources, the process sequence is optimized with the aim to minimize machine changes, transportation or occupancy times, for example. The processes are rearranged in accordance with the defined restrictions in the process data. Naturally, more degrees of freedom lead to greater savings, due to less restrictions.

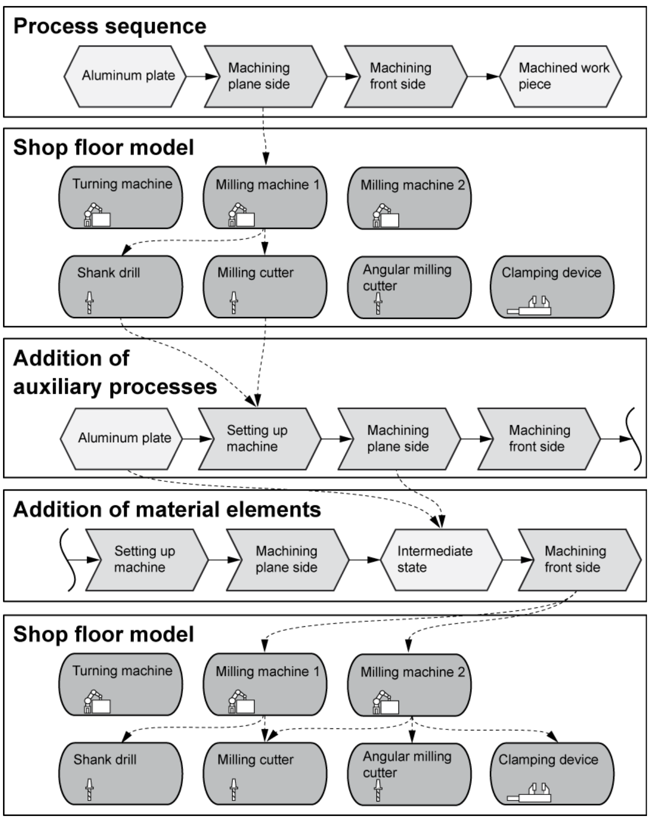


Figure 6: Enhanced procedure.

## 4 SUMMARY

The allocation of qualified resources to manufacturing operations is a challenging task during the design of a new production system. We presented a specification technique for the conceptual design phase of new production system which supports the developer during this design phases. The starting point for the resource allocation are the general requirements and an initial operation sequence. Attributes from the operations as well as the input and output elements like unfinished material elements need to be considered. Furthermore the impact of a resource selection on other operations has to be transparent for the developers. Thus, we introduced an approach for a data model for the consistent description of manufacturing operations and resources. The different sets of attributes and parameters ensure that all required information are provided.

In our future work we are going to extend the data models for supporting resources like tools and clamping device. This is necessary to allocate combined resources for example a CNC machining center. Here the possible operations depend on the machine attributes, the available tools and attributes of the clamping devices. Furthermore we will develop a formal representation in order to describe the presented objects of the partial models (material elements, processes and resources) in a computer conform way. Based on this formal representation a knowledge base will provide further support for the developers. This enables an assisted allocation of resources to manufacturing operations in the early stage of the production system development.

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# Developing Modular Manufacturing Architectures – An Industrial Case Report

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**Abstract**

The manufacturing industry needs flexibility and changeability to accommodate the increasing market dynamics and the related need for product change, variety, and customisation. Achieving such manufacturing responsiveness is the focus of Modular Manufacturing Systems (MMS). MMS have become central in research, but yet are short numbered in industry. This paper presents a case report on MMS platform development at a large Danish manufacturing company. The approach taken is based on related theory of modular product development and hence, modular architectures. The platform is developed following a six-step method and the paper provides thorough descriptions and illustrative examples of each step.

**Keywords:**

Modular Manufacturing Systems, Production Development, Modular Architectures.

## 1 INTRODUCTION

Different module based manufacturing concepts have emerged in response to the manufacturing challenges related to increasing dynamic of market requirements. These market requirements include; a need for rapid adjustment of the product assortment, high product variance, and customisation, and this concurrently with low price and high quality. In regard to manufacturing, this implies a challenge of combining manufacturing profitability with the flexibility to produce a broad product assortment and with the changeability to adjust to future products and manufacturing requirements. Previously, Flexible Manufacturing Systems have been appointed as a solution to these challenges but have not yet been widely adopted due to low system output [1], high complexity [2], and a high cost of general flexibility [3], [1].

Today the trend points towards Modular Manufacturing Systems (MMS), where components, control system, machine tools, etc. are decomposed into modules (building blocks). As illustrated in

Figure 1, the ability to add, remove, exchange, and/or update the manufacturing module(s) allows on-going change of both capacity and capability and hence, adjustment of the manufacturing system according to new products, product variants, production volume, technologies, etc.

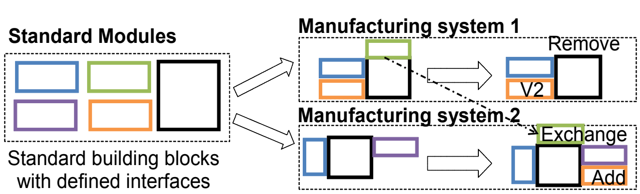


Figure 1: The responsiveness and reconfigurability concept of MMS and the suggested architecture approach to MMS development.

For companies operating in dynamic markets, this changeability entails both increased competitiveness and a risk reduction of manufacturing investments. Additionally, MMS imply a potential to increase reuse of manufacturing solutions (on module level) and, hereby, volume in the production of manufacturing systems. Among other things, this creates a basis for: cost reduction, decreasing lead time on delivery and running-in, and reduction of uncertainties on cost price, delivery time, and capacity.

In literature, modular manufacturing concepts are described as Reconfigurable Manufacturing Systems (RMS) [4], Holonic Manufacturing Systems (HMS) [5], and Evolvable Production Systems (EPS) [6]. In this paper, the term MMS is introduced as a super category of these module based manufacturing theories. MMS are listed as a focus area in the European Commission Strategic Research Program for future competitive manufacturing in Europe [7], listed in the national findings of the Danish Manufuture initiative [8], and appointed as first priority among six grand challenges for future manufacturing in the "Visionary Manufacturing Challenges for 2020" by the US National Research Council [9]. The research effort on MMS is mainly focused on potential benefits, basic principles, and enabling technologies, while industrial development of MMS has received less attention. Though, recently the MMS potentials have been demonstrated by the FESTO iFactory (learning factory) [10].

This paper is part of a research project which explores how to assist industry with efficient methods for developing MMS and hereby how to enable the desired benefits of MMS in industry. The applied approach takes its outset in related modular product development theory. The paper reports from a collaboration with an industrial company on how to develop a cell level MMS platform. The paper focuses on the development process. Initially, the paper gives a brief introduction to the selected MMS approach including the interpretation of modularity and architecture. Secondly, the paper presents the conducted case and provides an overview of the developed platform. This provides the offset for the subsequent exposition of how this platform was developed. Finally, the paper discusses the experiences obtained from the case, concludes on the findings, and discusses needs for future research in MMS development.

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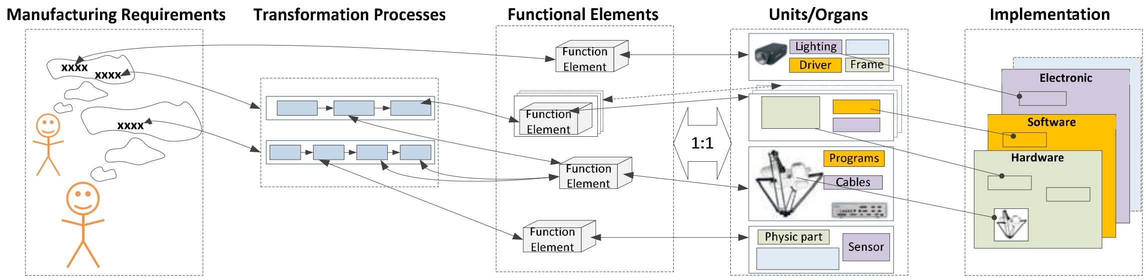


Figure 2: Relations among manufacturing requirements, transformation processes, functional elements, units/organs and practical implementation [11].

## 2 MODULAR MANUFACTURING SYSTEM ARCHITECTURES

The applied approach to MMS development takes its outset in the modular product theory known from product development and mass customisation (MC). The theoretical background of this is discussed in [12] and further discussed and tested on three industrial cases in [13]. This exploration has revealed four domain gaps: Design tradition (offset in Engineer-To-Order (ETO) instead of well-known products), product type (mechatronic instead of physical), increased complexity, and the number of products/systems to be produced. These domain differences imply a need to adjust the known modular product theory to the domain of manufacturing. A full exposition of this, including modifications, can be seen in [11] while a brief overview of the approach is provided below.

### 2.1 The Architecture Based Approach to MMS

For modular products, modular product architectures are used as a tool to develop, maintain, and manage a modular product assortment and, hereby, to obtain the variety in a cost effective manner. The term architecture denotes the scheme of how functional elements of the products are implemented into units (modules) and of how these units interact with each other [14]. A modular architecture is one such architecture characterised by modularity [14], see 0. MMS architectures are introduced as a similar tool to manage and uniform the modular manufacturing structure and its modules across the specific manufacturing system installations. As such, developing MMS based on modular product theory implies development of a MMS architecture from which customised manufacturing solutions can be designed as a specific combination of the specified modules, see Figure 1. This module combination of a manufacturing system includes, in contrary to the traditional product approach, both existing, planed, and customised modules. This approach brings manufacturing system development from ETO towards Configure-To-Order.

Literature regarding product architecture distinguishes between architectures and platforms. According to [15], a platform is a structural description of a subset of an architecture including only existing standard designs and their interfaces. For manufacturing, a similar distinction between manufacturing architectures and platforms is relevant. Manufacturing platforms are interpreted as a structural description of a subset of a manufacturing architecture including only the reusable/widely-used standard designs. This interpretation includes both existing and future standard designs, this due to the low volume of specific manufacturing systems and hereby the related use as a design platform for future manufacturing systems.

### 2.2 Manufacturing Modularity

In product development and MC literature, it is generally accepted that achievement of modular benefits depends on the applied modular architecture which should meet the customer requirements whilst still limiting the internal complexity [16], [15]. This is supported by the observations of [17], who performs an empirical investigation of the modularity effects by before-and-after modularisation measurements. With the exception of one case, positive results are reported. Later studies by [18] explain this negative observation by wrong product modularisation. These findings illustrate the potential in modularity contemporary with the importance of the applied modular structure.

A general accepted definition of product modularity takes its offset in the relation among functional elements and how the physical elements, which implement the product functions, are grouped into building blocks. Based on this mapping, product architectures can be more or less modular. At the one extreme, modular architectures consist of “one-to-one” mappings and at the other extreme integral architectures consist of complex (many-to-one or one-to-many) mappings [14]. Furthermore, according to [14] modular architectures are characterised by well-defined interactions among these building blocks which generally are fundamental to the primary functions of the product. Adjusted to encompass the mechatronic nature of manufacturing systems, this definition is found to cover manufacturing as well. Hence, manufacturing modularity depends on the relation among functional elements and how the physical, electrical, and software elements are grouped into building blocks; building blocks which possess clearly defined interfaces (physical, electronic, and software/control interfaces). This is illustrated in Figure 2.

It appears from product modularisation methods that these generally take their outset in the customer requirements and based on these define the need of functional elements including the relation among customer requirements and functional elements. Examples of such methods are Modular Functional Deployment [16] [18] and Product Family Master Plan (PFMP) [15]. This relation among customer requirements and functional elements ensures that the modules reflect customer requirements and their diversity. This entails that products can be derived from the architecture as a specific configuration in compliance with a set of the individual customer requirements. For MMS this implies that functional elements of MMS architectures should be defined on the basis of the individual requirements of the different enclosed manufacturing systems. It should be noted, that the transformation process performed by the manufacturing system falls in-between some of the manufacturing requirements and their related functional elements. Hence, the functional elements depend both on manufacturing requirements and the transformation process design. This is likewise illustrated in Figure 2.

## 3 CASE INTRODUCTION

The case was conducted in close cooperation with a large Danish manufacturing company. The case focused on development of a cell level MMS platform of a newly developed insert injection moulding technology. The case addressed both the cell level platform and all included lower level station platforms (e.g. robot handling system) and machine/tool level platforms (e.g. robot gripper platform, and specific included robots), see Figure 3.

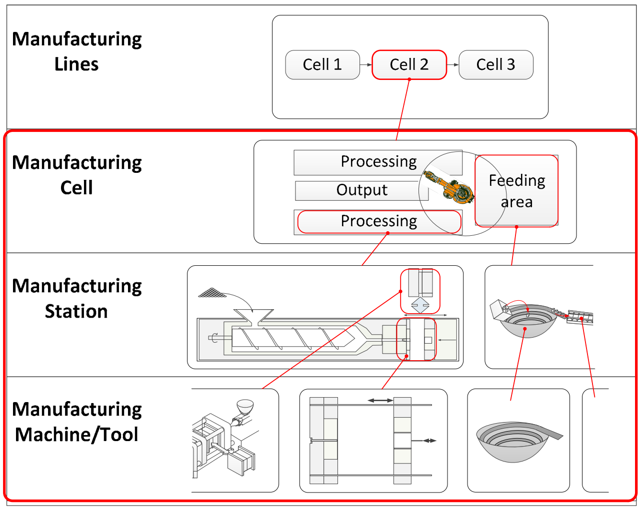


Figure 3: The manufacturing levels addressed in the case.

For all three levels, platforms were developed. These platforms define the generic composition structure of manufacturing systems at the respective level and the variants of each compositional element. As an example, at cell level the platform defines that one such manufacturing cell is composed by five sub-systems: Feeding-, handling-, moulding-, control-, and cooling system, see Figure 4. The variety of the compositional elements is defined in a classification structure, e.g. the sub-classes of the handling system which are: Manual, 6-axes robot, portal robot, and pick & place handling systems. All of these four handling system types are related to a station level platform defining how to design e.g. a 6-axes robot station. The main variants of all five cell level compositional elements are included in Figure 4.

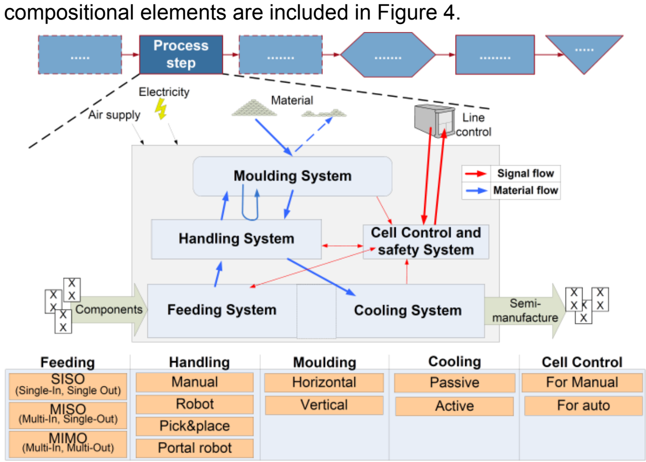


Figure 4: Illustration of the cell level platform, including its line level relation, its subsystems and its main sub-system variants.

From an overall viewpoint, cells were categorised based on their included injection moulding machine type, hence in vertical and horizontal. Furthermore, the valid cell level configurations were identified and related to determine cell parameters.

The conducted platform development revealed complications related to uncertainty of the main process technology. These complications were especially noted regarding quantification of parameters and decision making which induced a broader and more indefinite platform than needed. Hence, this platform should be revised (updated and further specified) when technology maturity has increased. The revision is expected to follow the same development process as the conducted platform development.

## 4 PLATFORM DEVELOPMENT

The platform was developed by the following six step procedure. This procedure was applied both at a cell level and to the included lower level platforms:

1. Define the focus area
2. Define the platform scope
3. Define functional elements
4. Concept generation
5. Modularisation and platform development
6. Document the platform

The development process is iterative by nature. To support this, a fast cross-level loop of step 1-4 was initially conducted to provide a holistic overview. Hereafter, full completion of step 1-6 was conducted in a top-down order which entailed that results of the cell level platform formed the outset to define focus area and scope of the station level, etc. The development of each step is elaborated in the following sub-sections. It should be noted, that these steps in practice are highly interrelated and modifications in one step tend to manifest itself in resulting modifications in the others.

### 4.1 Define the Focus Area

A black box model was sketched for each of the included platforms to define the overall focus area of the platform (the overall intended production task(s) and functionalities, the related level of manufacturing, and the main relationships to superior level manufacturing systems, e.g. how do the cell fit into manufacturing lines?). For the cell level platform, the system black-box was identified from the generic process flow of the manufacturing lines of which the platform should constitute a cell. This generic process flow was identified from the product families to be produced (group of products with certain similarities). These were analysed regarding their production processes and one or more process diagrams were drawn for each product family. These process diagrams were subsequently drawn above each other to emprise commonalities and subsequently remodelled into a generic process flow. The process-step which should be covered by the platform was identified in the generic process flow and subsequently extracted and modelled as a black box, see Figure 5. Furthermore, the generic process flow served to define a generic function description and the external interfaces of the system black-box.

The station level system black-boxes were defined directly based on existing information from their respective superior level platform. In the case, five station level system black-boxes and related functional descriptions were defined directly from the cell level platform, one for each of its subsystems (station level platform). Machine/tool level system black-boxes and function descriptions were likewise directly defined, in this case from the information of the related station level platforms.

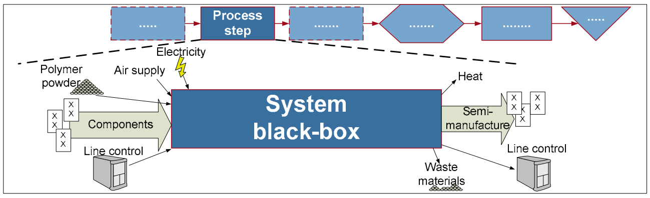


Figure 5: Identification of the cell level platform system black-box.

## 4.2 Define the Platform Scope

The scope is a requirement specification of the platform including both the total span of requirements of all included manufacturing systems and the diversity among these (need of variance). It is experienced that a broad involvement of stakeholders and manufacturing aspects should be included to ensure a robust scope and hereby a robust development process and platform. Furthermore, management support is of critical importance to obtain a robust scope. The obtained scope definition utilised the cell level system black-box model as an offset to define the platform scope, e.g. functionalities of the platform, types of incoming components, and regarding types of resulting semi-manufactures. Additional information was gathered from analysis and study of existing documents, product review, company standards, interviews with experienced engineers, etc. To obtain an overview, this information was initially modelled in a PFMP. The PFMP was found to constitute a good modelling tool to create overview, but only among people directly involved in the modelling process. To increase the ability to communicate with a broader audience, the PFMP was transformed into a graphical representation of the same information. Furthermore, this served as the scope documentation and as offset for the scope review which was conducted by delegates from production technology engineering, potential customers, module designers, etc. The scope contained information on the products to be produced, the operational condition to comply with, the installation and service conditions, roadmaps and forecasts, and on specific technical requirements and standards. An attempt was made to quantify the scope information, but this was only partly completed due to low maturity of the focus technology.

## 4.3 Define Functional Elements

The internal process of transforming the identified components, materials, etc. from their initial state into the specified semi-manufactured products was defined by a process similar to the above describe process of “defining generic process flow” (see 4.1).

In the work of doing so, all possible transformation process flows of generating the identified types of semi-manufactures from the different component types were identified. Furthermore, a selection between process flows was made and a single generic process flow was defined based on commonalities among the remaining ones. Six process elements were identified from the process steps of the generic process flow(s). The process elements represent the general transformations to be conducted and hereby the critical functionalities which should be supported by the platform. In addition, three support elements were added and together these process and support elements constitute the functional elements of the cell level platform. The identification of the internal generic process flow and the function elements are illustrated in Figure 6.

## 4.4 Concept Generation

The concept generation and related investigation of the technical solutions took their offset in the ideas and concepts of the technology development. From this, an initial cell level structure including function description of its subsystems was made.

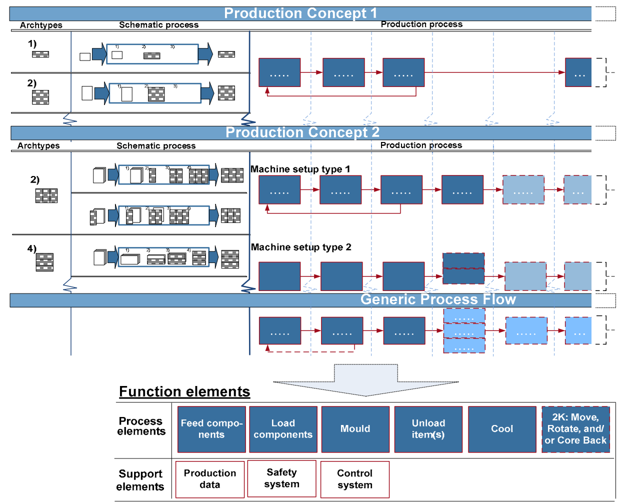


Figure 6: Identification of the generic process flow and functional elements of the platform.

Subsequent, this initial cell structure formed an offset for searching technical solutions and generating additional concepts. Furthermore, concepts were generated based on the functional elements which were experienced to add new perspectives to technical solutions and concepts, which hereby resulted in new/changed concepts, this especially regarding the non-value adding support systems. Knowledge of the technical solution was actively used throughout the concept generation, both as inspiration for new concepts and as a quick proof-of-concept. As the work was conducted, the concept information was modelled in a PFMP model [15] in an on-going process. The modelling was experienced to create a structured overview to relate concepts to the scope and functional elements, and to create a preliminary idea of the levelling structure. Furthermore, the overview was experienced to form a source of inspiration for new ideas, both regarding concepts, functional elements, and the scope. The generated concepts spanned wide and covered both layout sketches, handling strategies, feeding ideas, etc.

An attempt to select among and to validate the concepts was conducted. This was done to reduce the complexity of the subsequent modularisation and platform development activity, and to ensure that only valid concepts, with a likelihood of being realised, were carried on.

## 4.5 Modularisation and Platform Development

The task of transforming the concepts into a modular platform is a process of relating, grouping, selecting, and redesigning the concepts into a general structure characterised by: Clear relations among the specified scope and the functional elements, a one-to-one relationship between functional elements and the division in groups/subsystems, and by well-defined interfaces. A number of analyses and modelling methods have been utilised to support this transformation process. Figure 7 illustrates the relation among the applied methods and how the methods have been used to create overview of, or relating, the scope, process, functional elements, units/organs, and implementation. It should be noted that the transformation of concepts into modular platforms was conducted in a top-down approach (cell level first, then station level, and finally machine/tool level platforms), and that the methods in practice are used concurrently as input for one another in an iterative process. The methods have generally been adjusted to fit the domain of manufacturing and to the specific use in this case. The related

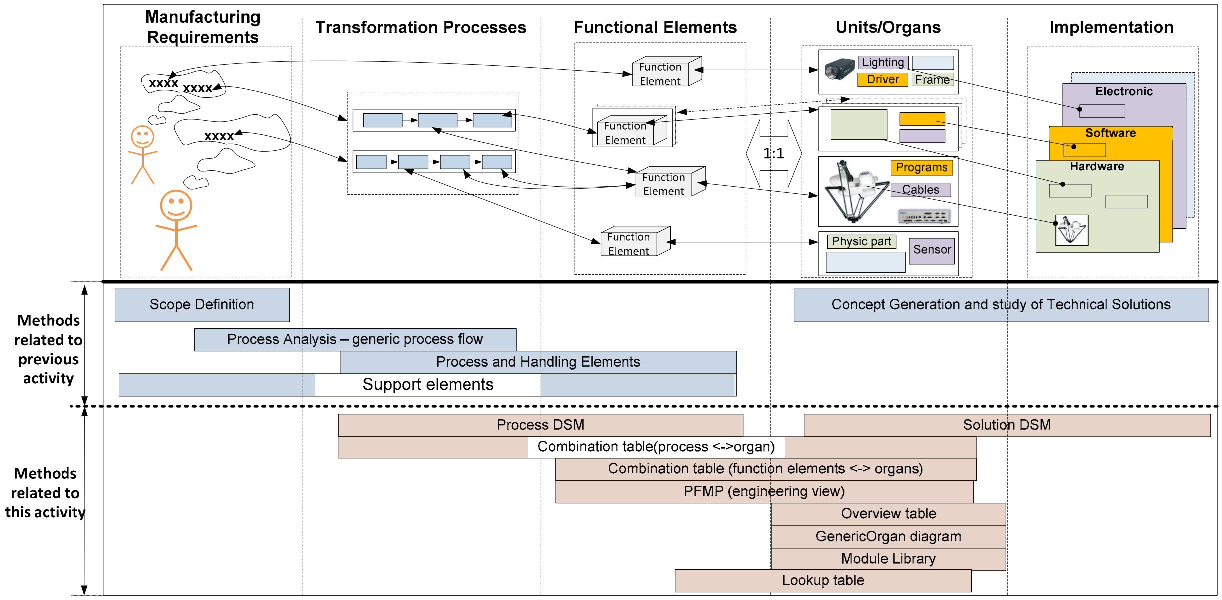


Figure 7: Overview of the applied methods and how they are used to create modular relations among the manufacturing requirements, transformation processes, functional elements, units/organs, and the practical implementation.

product development methods are: Design Structure Matrix (DSM) [19], PFMP, and Generic Organ Diagram [15]. Further details can be found in [11]. Elaboration of the use of each method is given in [11] and an example on interface specification is given below.

*Generic Organ Diagram and Interface Tables*

Interface diagrams were drawn to analyse and to create an overview of the interfaces of the different platforms. This was done by means of Generic Organ Diagrams which show the organs of the platform, organ variants, and the interfaces among organs – see example in Figure 8. In accordance with the guidelines of [15], the diagram was developed by drawing the organs and interfaces of each concept on top of one another. Toward the finalisation of the platform, interface tables were added to the Generic Organ Diagram. The interface diagrams were experienced to constitute a powerful tool to identify, highlight, and communicate both regarding modules and their interfaces.

### 4.6 Document the Platform

The platform was documented by a set of graphical platform documents. The platform documentation should be presented according to maintenance, future development of the architecture, and according to the three use cases of the platform: Module design, manufacturing system configuration, and product design for manufacturing (DFM). The platform documents were divided into:

1. Overview: Link to the overall systems (external interfaces, etc.), functional description, module/subsystem overview.
2. Architecture scope: A documentation of the scope.
3. Internal generic process flow(s) and functional elements: The internal generic process(es), the associated functional elements.
4. Concept(s): List/sketch/description of the selected concept(s).
5. Interfaces: Interface diagrams and interface tables – both internal and external interfaces should be included.
6. Module library: List of all cells/subsystems/modules/parts including advantages, concerns, and other relevant notes.
7. Configuration: How to put a production line, cell, station, or machine/tool together based on the architecture.

## 5 DISCUSSION OF FINDINGS AND CONCLUDING REMARKS

This case report on developing MMS has its outset in an architecture based approach to define, manage and uniform the structure and modules across different manufacturing system installations. This approach is highly inspired by equivalent theory and methods of modular product development, but contains a number of adjustments to fit into the domain of manufacturing. The paper reports on MMS platform development experiences from an industrial case of cell level platform development (platform is a subset of an architecture). The platform development was conducted based on a six step development procedure and the conduction of each step is described and exemplified in the paper. The suggested six step development procedure has been applicable for platform development both at cell, station, and machine/tool level. This indicates a general applicability which has to be studied further. Furthermore, the case work both illustrates usability of the presented architecture based approach to MMS and that methods of modular product development are useful in MMS development with minor modifications. Commonalities between method adjustments at cell, station, and machine tool indicate a potential to make general adjustment and hereby define a toolbox of methods for MMS development. This is a subject for further research. Finally, the conducted case revealed that platform development is time consuming and that effective platform development requires knowledge and certainty on the main technology and its capabilities.

## 6 ACKNOWLEDGEMENTS

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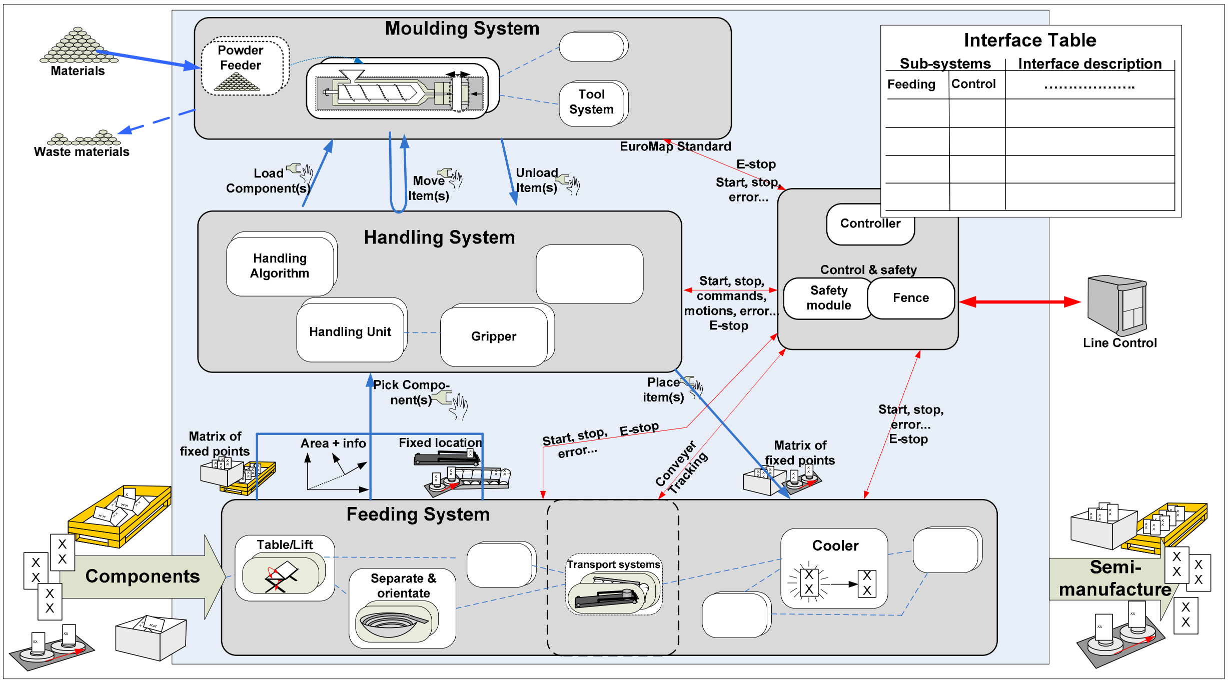


Figure 8: Cell level Generic Organ Diagram including cell level organs, internal and external interfaces, and the related interface table.

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# An Approach Framework Supporting Manufacturing System Design for a Range of Products

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**Abstract**
Mass customization and the evolution of products provide significant challenges to manufacturing system designers. Paradigms such as changeability, product process co-evolution and product platform development have been developed over the years to tackle these challenges. This research work identifies the synthesis decision-making activity in manufacturing system design to be a critical aspect of the development cycle, since many factors have to be taken into consideration. These include technical factors such as machine capability, but also uncertainty due to changing business and product elements. This research therefore aims to provide manufacturing system designers with an insight of the consequences of synthesis decisions on the range of products that can be manufactured by the evolving manufacturing system by contributing a manufacturing capability measure based on product range capability.

**Keywords:**
Manufacturing System Design; Capability; Range of Products

## 1 INTRODUCTION

Changing customer requirements and technological developments have meant that manufacturing is under a continuous state of change, this leads to the development of new paradigms for the future of manufacturing [1]. Manufacturing is a broad term that may have different definitions, but the one which is most notably employed states that manufacturing has a broader application than the term production, since it encompasses all activities and operations from product concept to servicing of past products in the field and everything in between [2].

A manufacturing system (MS), which can also be referred to as a production system or facility, is a group of technical production facilities, including humans, machinery, equipment, work stations and material flow systems, which are bound together by a common material and information flow for the production of products [2][3].

MS design is the activity involved in designing these systems. Chryssolouris [3] defines MS design as the mapping from performance requirements of the MS onto suitable values of decision variables, which describe the physical design or the manner of operation of the MS.

One such requirement is the need for MS to deal with product evolution over time. This leads to stakeholders in the MS design process to face significant challenges. As explained by Westkämper [4] factories are complex and long life products which have to be adapted to changing requirements. Therefore the need arises to develop digital tools that support the MS design decision making activity which includes uncertainty due to evolving requirements.

This paper will therefore begin by analysing the different challenges faced during MS design. A number of different approaches and state-of-the-art tools to support the manufacturing system design activity will then be reviewed. A model of the decision-making activity and the consequences of decision commitments on MS capability is then proposed. As part of this model, a MS capability measure has been developed to better visualize and understand the consequences of decision commitments on system changeability. A prescriptive approach for the support of the manufacturing system design activity for a range of products will then be explained. A prototype digital manufacturing tool based on this approach will also be presented.

## 2 CHALLENGES IN MANUFACTURING SYSTEM DESIGN

MS design is a planning level within factory planning [5]. The authors will therefore be using the term factory in the following sections to benefit from terms like factory life cycle that have been coined by several authors such as Westkämper [4], Schenk [6], Wiendahl [7], who describe the factory life cycle and the several stages of which it consists of.

### 2.1 Importance of the Early Stages of the Factory Life-Cycle

The planning stages are a critical part of the factory life cycle, and decision making is a critical aspect of this activity with many stakeholders involved. Several authors [8], [9], [10] indicate that the planning activities cycle from a conceptual level to a detailed level followed by ramp-up and production and maintenance and finally with re-planning or clearance of the factory. Since conceptual design precedes all other stages it is therefore logical that decisions taken in the early stages of design will have a consequence on later stages. This leads to the requirement of supporting the MS design process as early in the planning as possible, since it is critical to make good investment decisions at this stage.

### 2.2 Concurrent Development

As described by Constantinescu in [8] and shown in Figure 1 the factory and product are developed concurrently to each other with decisions being made during the planning phases of the independent life-cycles effecting each other. The two life-cycles then meet at what is defined as the crossing life cycles point where the product is produced by the MS.

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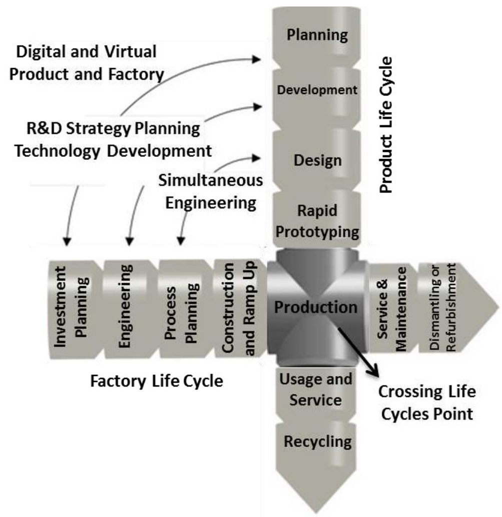


Figure 1: The harmonization of Product Life Cycle and Factory Life Cycle under the "Crossing Life Cycles Point" [8].

Several other authors highlight this concurrent or integrated [11] development with one of the main aims to include concurrent consideration during development. This concurrent consideration leads to the foreseeing of possible problems that product design decisions have on other phases such as MS design or production and vice-versa. Concurrent consideration may lead to the foreseeing of possible consequences that product design decisions have on the manufacturing system, such as the required capabilities to produce a product range. To provide effective MS design decision support it is essential to take the developing product requirements into consideration.

### 2.3 Co-evolution of Products and Their Manufacturing Systems

Furthermore, throughout their lifetime product families are continuously evolving, new features or parts may be added or replaced to the current range of products. As outlined by ElMaraghy [12] a change in product design can then be translated through a process matrix to the manufacturing domain, which would cause changes in the manufacturing system design and production processes, unless the current system capabilities are sufficient to accommodate the product changes.

This means that decisions made during the design stage of the MS have outstanding consequences on both the life cycle of the system and also on the future product range which can be produced by the system. The modified system capabilities in turn would present new opportunities for processing additional features as the products evolve.

This paradigm brings about a new complexity since products continue to evolve throughout the life-cycle of the MS, leading to a phenomena termed co-evolution [13]. This ever changing of products and manufacturing systems represents one of the main challenges in designing MSs which cope with a range of products, especially when product changes may occur during the life cycle of the MS as this adds an element of uncertainty in the decision making process.

### 2.4 Changeability in Manufacturing

As referred to in the beginning of this paper and as has been proposed by several authors [14], [15] MS are constantly changing to meet the customers' needs. One such customer need is the increase in customization which may be introduced in a company with the development of product ranges.

When product ranges are a requirement for the MS designers have to apply changeable manufacturing concepts such as Transformable Factories [16], Focused Flexibility Manufacturing Systems (FFMS) [17], Reconfigurable Manufacturing Systems (RMS) [18]. This may propose a challenge as to the level of changeability to be designed into a system. MS designers have to be supported with evaluating the level of changeability of the MS they are developing. This will allow them to take better decisions as to the level of changeability to be achieved by the MS.

## 3 CURRENT APPROACHES FOR MS DESIGN SUPPORT

Before developing a solution that could meet the challenges described in Section 2, the authors reviewed the state of the art approaches developed by other research initiatives.

### 3.1 Flexibility Measures

One method of supporting MS designers is to provide changeability metrics to evaluate the changeability of the MS. These metrics provide support by making the designer aware of the overall changeability of the system. Some of these models also consider uncertainties in changeability evaluation. An example of such a methodology is that provided by Zaeh et al. [19] who developed a tool to support the valuation of manufacturing flexibility and implemented it in PLANTCALC™ by Siemens. Karl et al. [20] also propose a methodology to evaluate Reconfigurability of Assembly Systems (RAS). This approach begins by identifying the reconfiguration needs by describing the degrees of freedom of Assembly Manufacturing Resources (AMR). A planning morphology for the reconfigurations is also introduced and this includes a set of necessary key performance indicators (KPIs). Georgoulias et al. [21] on the other hand propose a holistic approach for short, mid and long-term flexibility performance measuring and monitoring in industrial practice. In the core of the suggested approach, stands a flexibility evaluation toolbox. This toolbox is made up of five flexibility evaluation methods; The Penalty of Change (POC), the ζ-analogy method, the Desyma, the FLEXIMAC and the oscillator analogy. Other authors [22], [23] also propose measures for evaluating the capability and the capacity of a flexible manufacturing system with the goal of increasing the efficiency of the FMS. This said these measures are intended as dynamic measures of flexibility with the aim of supporting FMS planning during its operation rather than in the design aspect.

### 3.2 Economic Measures for Evaluating Flexibility

Another approach to evaluate flexibility is based on economic measures of flexibility. These methods include but are not limited to real options analysis (ROA) and the net present value (NPV). One such approach is that employed by Milberg et al. [24] who propose a method for the evaluation of the economic efficiency of flexible manufacturing systems using the real options theory. This approach proposes a structured valuation process for selecting options related to production engineering and factory planning. Based on a classification of possible modifications of a production system, options profiles are derived. An advantage of using this approach is that it considers the existing uncertainty of a company's environment whilst analysing the manufacturing system design.

A method for evaluating the economic transformability of a manufacturing system is proposed by Nyhuis et al [25]. This method not only allows the user to assess whether the factory possesses adequate and economic transformability. Zaeh et al. [26] have also developed a capacity/cost model that considers the impact of market uncertainties and the corresponding capacity flexibilities. It proposes a demand forecasting method, a modelling approach for capacity-related flexibilities and the analysis of the economical correlation between available and required capacities.

### 3.3 Product Centred Approaches

Another support to meet the challenges described in Section 2 is a product centred approach. In these approaches the focus is on the product ranges, their effect on the manufacturing system changeability requirements and how they may evolve in the future, therefore taking uncertainty into account. Schuh et al [27] developed an approach that introduces object-oriented-design to production systems. The central element of object-oriented design of production systems is the definition of objects, e.g. product functions, with homogeneous change drivers, which are consistently handled from product planning up to process design. Shabaka and ElMaraghy present an approach [28] for selecting the different types of machine(s) and their appropriate configurations to produce different types of parts and features, according to the required machine capabilities. The premise here is that the capabilities of the machines and manufacturing systems in RMS change with each configuration. In [29] ElMaraghy and AlGeddawy present a novel co-evolution hypotheses and a model for products and their manufacturing capabilities, inspired by the biological co-evolution, which uses Cladistics analysis of the historical development data of both. This approach first identifies evolution courses of products and manufacturing capabilities, then it searches for the best matching courses to ascertain manufacturing co-evolution, and finally informs future planning guided by the established co-evolution scheme

### 3.4 Decision Making Support Systems

One of the main problems in decision making is to rank alternative design options taking into account different criteria such as cost, time, quality and flexibility. This is especially true for configuring or reconfiguring manufacturing systems. For this purpose several Multiple Criteria Decision Making (MCDM) tools have been developed. Well known MCDM tools include the Analytic Hierarchy Process (AHP), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Weighted Sum Model (WSM).

As explained by Manassero et al. [30] a major drawback of AHP is that uncertainty in the judgments of the decision makers and the resulting impact on the ranking is not considered. In real situations, however, judgments based on perceived future scenarios are almost always uncertain. Therefore the authors of [30] present a complete probabilistic extension to the AHP method. The new method provides the decision maker not only with information on the ranking of the alternatives but also the probability that the ranking remains stable even in presence of uncertainty in the judgments.

Mehrjerdi et al. [31] adopt a different approach to develop a computer aided decision-making model for flexible manufacturing system (FMS) situations when multiple conflicting objectives are addressed by the management. This research gives an overview of the FMS and proposes a goal programming model for the analysis of problem. The proposed model acknowledges the randomness of customer demands for better standardization of production planning and inventory management systems.

Taha and S. Rostam [32] propose an innovative decision support system is presented for machine tool selection in flexible manufacturing cell that combines fuzzy logic programming to the analytic hierarchy process (fuzzy AHP) and artificial neural network.

## 4 MOTIVATION

The review of MS design support tools yielded that there are no approaches that provide MS capability measures that represent in detail the range of product features such as form, dimensions and materials that can be produced by the MS. Also uncertainty is only considered with the use of investment measures rather than through measures that quantify the evolution of product features. This gap in support tools therefore proved the motivation for this research to develop a MS design support tool based on the uncertainty of feature evolution in product ranges.

## 5 A MANUFACTURING SYSTEM DESIGN MODEL

To develop a tool to support MS design it was deemed critical to gain a deeper understanding of the relationships between MS requirements and the MS design process. This research therefore developed the MS design model shown in Figure 2 with this aim in mind.

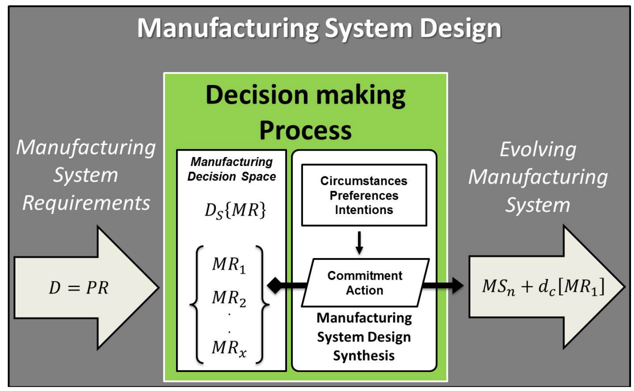


Figure 2: Manufacturing System Design Model.

As shown in this model, at the core of the MS design activity is a decision making process. The following sections will review in detail the different aspects of this model.

### 5.1 A Decision Query – MS Requirements

The MS designer begins by analysing the requirements for the system under development. These requirements include but are not limited to the product range to be produced by the manufacturing system. Other requirements may also be considered at this stage such as financial targets and floor space. The MS requirements are therefore formed into a decision query.

$D$ = Decision Query, the requirements for the manufacturing system

This research will focus on the product range requirements of the decision query.

$PR$ = Requirements of Product Range

A product can be described using a set of basic properties like material and form. This research uses the basic product properties proposed by Tjalve [33] to describe the product range requirements:

$PR = R_{PR}\{M, F, D, SF, T\}$, where:

$M$ is the range of Material Requirements

$M = R_M\{M_1, M_2, M_3, .. M_x\}$

$F$ is the range of Form Requirements

$F = R_F\{F_1, F_2, F_3, .. F_x\}$

$D$ is the range of Dimension Requirements

$D = R_D\{D_1, D_2, D_3, .. D_x\}$

$SF$ is the range of Surface Finish Requirements

$SF = R_{SF}\{SF_1, SF_2, SF_3, .. SF_x\}$

$T$ is the range of Tolerance Requirements

$T = R_T\{T_1, T_2, T_3, .. T_x\}$

*Certainty in MS Requirements Definition*

When MS designers are certain of product requirements they will know exactly what the maximum and minimum requirements for the MS are. Therefore the range of current MS requirements can be modelled using a Uniform Distribution.

$f(d)$ = The probability density function for uniform distribution

$$f(d) = \begin{cases} \frac{1}{b-a}, & when\ a \leq d \leq b \\ 0, & \end{cases}$$

Where $a$ and $b$ are the minimum and maximum product range requirements.

*Uncertainty in MS Requirements Definition*

When the product range is being developed the product designer will be uncertain of future product evolution. It is being proposed here, that the range of future MS requirements can be modelled using continuous distribution functions such as the Normal Distribution.

Where: $X \sim N(\mu, \sigma^2)$

$f(x)$ = The probability density function for normal distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right], -\infty < x < \infty$$

and $x = M \vee F \vee D \vee T \vee SF$

Figure 3 shows the normal distributed function modelled for uncertain requirements of a product range with dimension mean 100, and standard deviation 5, $D \sim N(100,25)$

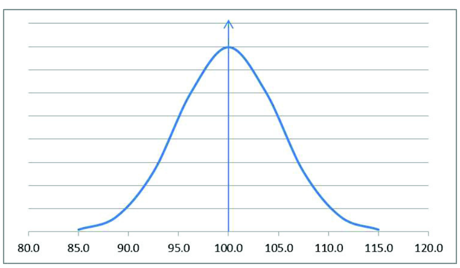


Figure 3: Normal distributed function.

This implies that the product designer has:

- a 68% certainty that future product evolution will lead to a product requirement range of 100±5mm
- a 95% certainty that future product evolution will lead to a product requirement range of 100±10mm
- a 97.7% certainty that future product evolution will lead to a product requirement range of 100±20mm

## 5.2 The MS Decision Making Process

The MS designer is responsible for designing the production to meet the product range requirements. This involves activities such as the detailed planning of the MS which includes manufacturing resource selection.

*Consequences of Product Range Requirements on MS Decision Space*

As explained by Borg [34] product design decisions have consequences on life-cycle phase elements (LCPEs). For example, choosing plastics as a material for the product range limits the manufacturing resources that can be used to those processes that can process plastics. Therefore it can be concluded that the product range requirements have a direct consequence on the decision space, $D_S$, that will be considered by the MS Designer.

$MS_n$ = Manufacturing System at a state n

If $MS_n$ is Manufacturing System capability at a state *n*, i.e. what product range features can be produced, then the $MS$ capability can be defined as:

$$MS = C_{MS}\{M, F, D, SF, T\}$$

$$MS_{min} = C_{MS}\begin{bmatrix} M_{min} \\ F_{min} \\ D_{min} \\ SF_{min} \\ T_{min} \end{bmatrix} \& MS_{max} = C_{MS}\begin{bmatrix} M_{max} \\ F_{max} \\ D_{max} \\ SF_{max} \\ T_{max} \end{bmatrix}$$

If the MS cannot produce the product range requirements, hence $MS_{min} \nleq PR \nleq MS_{max}$, a new manufacturing resource must be added to the existing MS, or an existing manufacturing resource must be reconfigured.

$MR$ = Manufacturing Resource Capability

$$MR = C_{MR}\{M, F, D, SF, T\}$$

When the product range requirements are known, for a manufacturing resource to be part of the decision space, $MR \subseteq D_S\{MR\}$, it must be capable of producing the product range, therefore $MR_{min} \leq PR \leq MR_{max}$.

The decision space is therefore made up of manufacturing resources that satisfy this rule, i.e. manufacturing resources that can produce the product range requirements.

Decision Space $D_S\{MR\} = D\{MR_1 \vee MR_2 \dots \vee MR_x\}$

## 5.3 Evolving Manufacturing Systems

The MS designer will then make a commitment to choose one of the manufacturing resources based on a set of circumstances, preferences and intentions.

$d_c[MR_1]$ = Decision Commitment

$MS_{n+1}$ is the Manufacturing System at state n+1

$$MS_{n+1} = MS_n + d_c[MR_1]$$

*Consequences of MS Decision on MS Capability*

It can therefore be concluded that MS decisions have a direct consequences on the range of products that can be produced. This is not only true for the current product range but is also applicable for future product ranges which may develop. Since there is an element of uncertainty as to how future product ranges will develop it is essential to take these consequences in consideration.

# 6 PRODUCT RANGE CAPABILITY MEASURE

Based on the understanding of this MS design model, a MS capability measure has been developed to support the MS designer during the decision making activity.

This research is therefore proposing a probability measure, $C'_{MR}$, to quantify the capability of a manufacturing resource to meet the uncertain future product range requirement:

$$C'_{MR} = P(X_{min} \leq X \leq X_{max})$$

As was explained in Sectio n0, $X$ can be modelled using a continuous distribution such as the normal probability distribution where $X \sim N(\mu, \sigma^2)$, therefore:

$$C'_{MR} = F(X_{min}) - F(X_{max}) = \Phi\left(\frac{\mu - X_{min}}{\sigma}\right) - \Phi\left(\frac{\mu - X_{max}}{\sigma}\right)$$

*Example*. For the requirements of a product range following the normal distributed function with dimension mean 60, and standard deviation 2, $D \sim N(60,4)$, a manufacturing resource $MR_1$ with:

$C_{MR_1}\{D_{min}\} = 58mm$ and

$C_{MR_1}\{D_{max}\} = 66mm$

$$C'_{MR_1} = P(58 \leq D \leq 66) = F(58) - F(66)$$
$$= \Phi\left(\frac{58-60}{2}\right) - \Phi\left(\frac{66-60}{2}\right)$$

$C'_{MR_1} = 0.84$

Therefore the probability that manufacturing resource $MR_1$meets the uncertain product range requirement is 84%.

The decision space, $D_S\{MR\}$, is therefore made up of a set of manufacturing resources for which the capability metric $C'_{MR}$ has been calculated. An example of a decisions space for several manufacturing resources is illustrated in Table 1.

| | 54.0 | 56.0 | 58.0 | 60.0 | 62.0 | 64.0 | 66.0 | |
|---|---|---|---|---|---|---|---|---|
| σ | -3 | -2 | -1 | 0.0 | +1 | +2 | +3 | |
| Φ | 0.2 | 2.2 | 15.8 | 50.0 | 84.1 | 97.7 | 99.8 | $C'_{MR}$ |
| $MR_1$ | *min* | | | *max* | | | | 49.8 |
| | *0.2* | | | *50.0* | | | | |
| $MR_2$ | | | | *min* | | | *max* | 49.8 |
| | | | | *50.0* | | | *99.8* | |
| $MR_3$ | | | *Min* | | *max* | | | 68.3 |
| | | | *15.8* | | *84.1* | | | |
| $MR_4$ | | *min* | | | | *max* | | 95.5 |
| | | *2.2* | | | | *97.7* | | |

Table 1: Decision space and manufacturing resource capability metric.

## 7 AN APPROACH TO SUPPORT MS DESIGN

Based on the MS design model described in Section 5 and the product range capability metric proposed in Section 6 a prescriptive approach to support MS designers was developed. This approach was modelled using the framework shown in Figure 4.

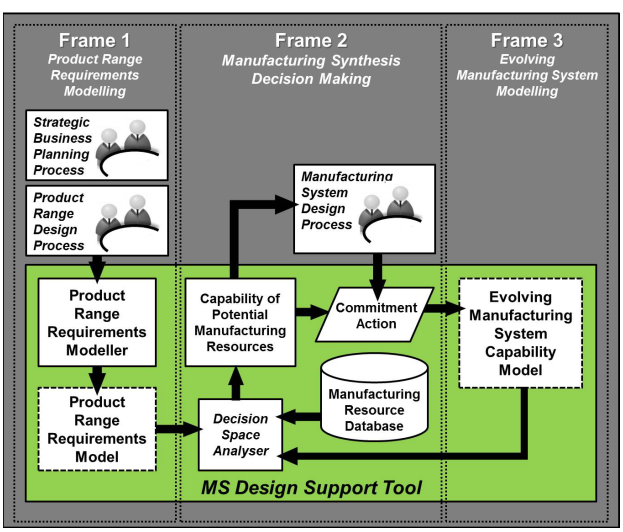


Figure 4: A framework for supporting MS design.

### 7.1 Frame 1 – Requirements Modeling

The process begins in Frame 1, were the product designer enters the product range requirements. These requirements are based on a knowledge of the current product requirements and the possible evolution of future product ranges based on marketing, business plans and customer requirement knowledge.

### 7.2 Frame 2 – Synthesis Decision Making

In Frame 2 the MS decision making process takes place. A decision space analyser compares the inputted product requirements with the current MS capability. If the requirements cannot be satisfied with the current manufacturing resources a new resource must be selected. The decision space analyser therefore searches a database of manufacturing resources for resources that may satisfy the product range requirements.

Following the database search the manufacturing resources relevant to the decision making problem are selected and their capability metrics are calculated. The MS designer may then make a commitment to choose one of the manufacturing resources by comparing the capability metrics $C_{MR}'$ of the different manufacturing resources.

### 7.3 Frame 3 – Evolving MS Modelling

Frame 3 then models the evolving manufacturing system capabilities so that these can be used when analysing upcoming product range requirements.

This framework was then used as the basis for developing and implementing a prototype digital support tool. Screen shots for the user interface for Frames 1 & 2 of the approach framework are shown in Figure 5.

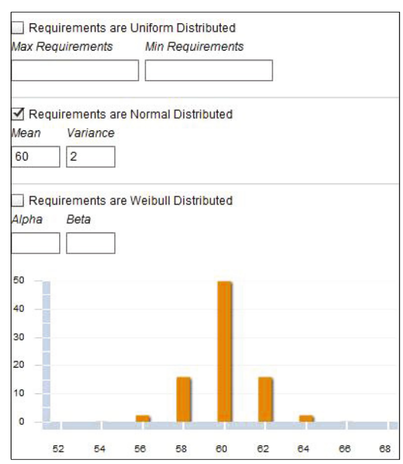


Figure 5: Screen shot of MS design tool implementation.

## 8 FUTURE WORK AND CONCLUSIONS

This research work has contributed a MS capability measure that will help MS designers to better visualize and understand the consequences of decision commitments on system changeability and the range of products that can be manufactured by the evolving manufacturing system.

Future work will involve further development of the MS capability measure to include economic functions, such as the cost per product or investment cost of the manufacturing resources. The implementation of the design tool will also be improved and tested using industrial use cases.

## 9 ACKNOWLEDGMENTS

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# A Generic Control Concept for the Simulation-Based Verification of Reconfigurable Transport System Models

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**Abstract**
Simulation models of transport systems must have reality-compliant electric inputs and outputs to test original controllers in the context of emulation and virtual commissioning. Usually, these models are hard to verify. We present a new control concept for the fast verification of such models. All components of the model are automatically connected to a virtual controller. A one-time created and manufacturer-specific PLC program is used to drive the model and even reconfigurations of it. Engineers can visually verify the functioning of the model before emulation itself starts. The concept has been implemented and used successfully in several applications.

**Keywords:**
Reconfigurable Transport Systems; Model Verification; Emulation

## 1 INTRODUCTION

Carrier-based transport systems are common parts of automated manufacturing plants. Engineers often want to verify controller programs for such plants before they are built – especially in the planning phase for a new plant or when a plant shall be changed or reconfigured. Such verification can be done using simulation. This requires that the transport systems are modelled using model library components with reality-compliant I/O interfaces.

In this paper, we focus on the verification of transport system models built for the purpose of emulation. A simulation expert creates these models using detailed low-level components. Then the expert passes the model to the controller expert to test the original controller programs against the model. Here, the problem arises that the simulation expert can hardly verify the model before giving it away. This is, because even most trivial simulation runs require complex controller programs which may not yet exist. However, the simulation expert must ensure that the model is correct. Branching and merging points must function and carriers can reach every part of the system. If the model is not verified it will not be clear whether an emulation session will reveal errors of the controller as intended or just errors of the model.

## 2 MOTIVATION

Emulation is defined as “A model that accepts the same inputs and produces the same outputs as a given system.” [1] Verification in general is defined as “The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with validation.” [2] In this paper, we address the problem that arises when trying to verify simulation models for emulation. The problem arises from the following facts:

- For emulation, we need simulation models which must have all I/Os just like the real plant to be able to test the real controller.
- For complex simulation models, we cannot have an easy controller program to verify the models.

Verification is often considered a formal process which then highly depends on the semantics which are used to describe the model to verify [3] [4] [5]. A comprehensive overview of verification techniques is given in [6]. But no matter how the models are formally described, they all have one characteristic in common: they offer an interface to connect controllers for emulation.

In contrast to other methods of verification, we will take advantage of this attribute and use a controller based concept to verify the models. Actually, we will use a generic concept based on a PLC program. The idea of this approach is described in [7] for the first time. In this paper, we will go into detail.

## 3 EMULATION AND CONTROLLER-COMPLIANT MODELLING

This paper is not about emulation itself. However, we will shortly explain the functioning of emulation and the special nature of simulation models suitable for emulation. Details on emulation and a differentiation from simulation can be found in [8].
Emulation always includes a controller to drive the model. There are many ways to incorporate such a controller. The most common case is the use of PLC controllers. These may be either implemented within the simulation system or externally coupled to it. For our concept, both internal and external PLCs can be used.
Figure 1 shows how emulation works for an external controller coupled to a simulation system. Communication between the server and the client can be established using different protocols – a very common one is OPC. The most important aspect of the emulation concept for the subject of this paper is the following one: all I/Os of the component models must behave just like the real I/Os to allow the controller to function properly. For example, if only one single output of the model does not return the correct result, the controller will most likely get stuck at a certain point in the controller program when the corresponding controller input is evaluated.

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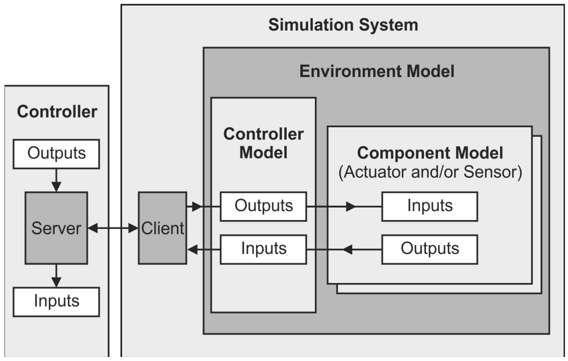


Figure 1: Emulation with external controller and simulation system.

The exchange of I/O values between a controller and the field devices is usually executed over a field bus system. In the following, we will omit to explicitly consider the field bus as it only packs and unpacks I/Os.

Correct functioning of all the I/Os is ensured by controller-compliant modelling. This means that the model's reaction to a changed input is answered in one of the following ways:

1. Dynamic response based on 3D simulation
2. Dynamic response based on electric circuits
3. Static response
4. No response

Figure 2 shows the information flow for the first case. A controller input is connected with a sensor output and the sensor may detect mechanical changes of the 3D model during simulation. This is the most flexible modelling. It offers the widest range of user experiments during simulation to build up the engineer's confidence in the model. Then again, it requires complex modelling.

Figure 3 depicts a less time-consuming modelling based on electric circuits including e.g. logic operators and delay elements. Modelling becomes less complex but the range of experiments is reduced as the model moves away from the real behaviour.

Figure 4 illustrates the simplest model response. Component outputs are set to constant values without evaluating the inputs. This possibility does not allow for any experiments at all as there is no dynamic response. Anyway, this modelling may be useful for outputs which are required for the functioning of the controller but which are not explicitly examined. For example, such outputs may be outputs indicating the presence of air pressure for a plant.

The fourth case – not responding to changes – is the easiest to do, but only works if model reactions are not relevant for the controller.

## 4 THE GENERIC CONTROL CONCEPT

Figure 5 depicts our new generic control concept. We use pre-build model libraries of transport components and carriers which correspond to manufacturer's catalogues. This way, we provide low-level components like lift-units, stoppers, and sensors instead of e.g. ready-built fork assemblies. Using these models, an engineer can build up complete transport systems.

Our concept bases upon two major ideas: First, each manufacturer-specific model library contains a virtual controller and newly designed generic control programs that are pre-built using original development environments. Second, we provide a method which allows for the automated connection of I/Os of field device models with the corresponding I/Os of the virtual controller. We will explain this automated wiring in detail later.

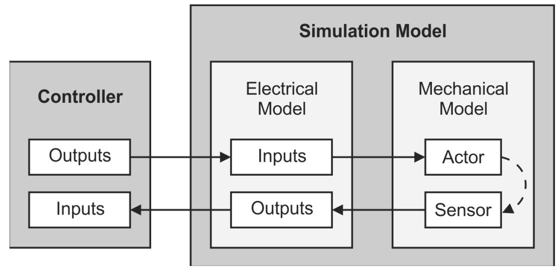


Figure 2: Dynamic model response based on 3D simulation.

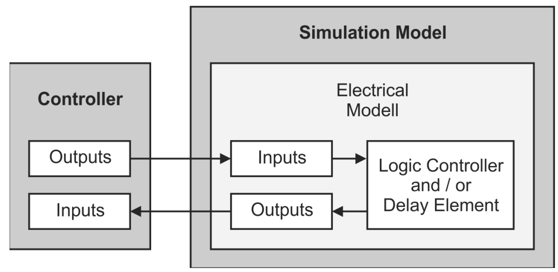


Figure 3: Dynamic model response based on electric circuits.

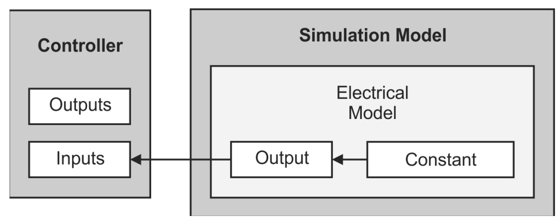


Figure 4: Static model response.

If the engineer adds a virtual controller and performs an automated wiring he will immediately be able to run the simulation and watch carriers move according to a default strategy. A simple routing policy ensures that all sectors of the transport system are visited by directing carriers at a fork to all possible directions consecutively. This way, the transport system model can be tested and thus be verified in a short time. If the model is reconfigured, just another automated wiring will allow for the next simulation run.

The controller program consists of three layers: a downlink layer, an internal processing layer, and an uplink layer. In the downlink layer, state machines handle all the connected field devices on the lowest possible level of abstraction, i.e. reading sensor signals and initiating actuators. The internal processing layer contains data buffers to achieve an asynchronous decoupling of the downlink and the uplink part. This is necessary as the downlink layer works with a fixed and small cycle time. The uplink layer provides a command interface to which superordinate controllers can connect and thus influence the control behaviour of the downlink layer.

On the right, figure 5 shows an outlook how the uplink layer can be used. From the given transport model, a suitable algorithm gathers the topological structure of the transport graph and exports this into a common data format e.g. XML. This logical information is the input for a downstream controller generator which creates a superordinate controller. This controller can connect to the uplink layer and thus control the transport model. We will describe these ideas in detail in a future paper. Anyway, the controller program must be designed to meet these requirements.

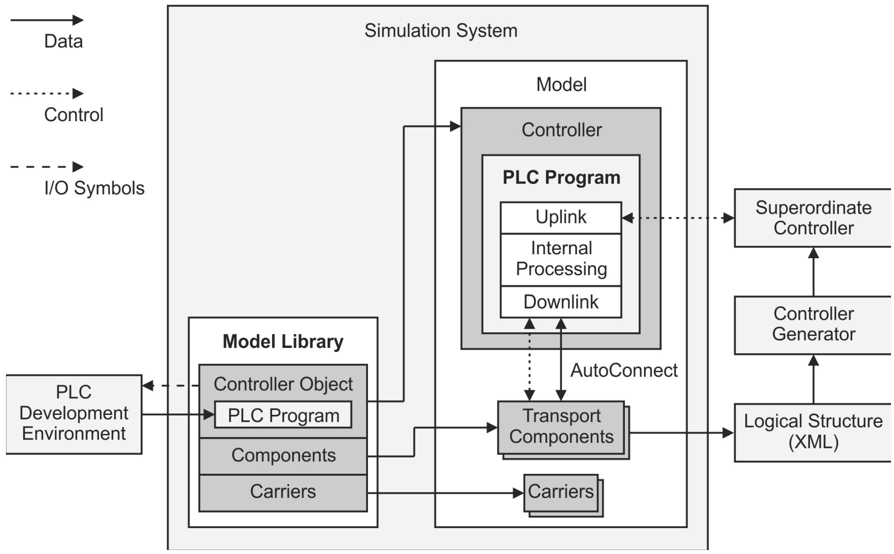


Figure 5: Data flow and control flow of the control concept.

### 4.1 Structuring Transport Systems

We will now classify the different parts of transport systems with regard to their logic function and call them **logic component types**:

1. Sources, at which carriers may be inserted;
2. Sinks, at which carrier may be removed;
3. Sensors, to detect and identify carriers;
4. Additional devices, to change position or orientation of carriers e.g. lift-units;
5. Stoppers, to stop or separate carriers;
6. Crossbars, for the 90° lateral transfer of carriers;
7. Transits, at which the only possible way to go requires control;
8. Forks, to branch carriers;
9. Merges, to merge carriers.

The instances of the logic component types are called logic components. Logic components may be parts of other logic components. For example, a fork may consist of one stopper with one sensor at the incoming, a crossbar at the main area, and one sensor at each outgoing. A stopper may employ a sensor at the incoming and a sensor at the outgoing. Additional devices and crossbars can only appear as integral parts of other logic components.

Except for sources and sinks, every logic component is also a **control element** of the controller program i.e. the functioning of the logic component requires a control action.

### 4.2 Automated Wiring

As mentioned above, the automated wiring shall connect all I/Os of all field component models within a transport model with suitable I/Os of the virtual controller. To achieve this, both virtual controller and field component models must be designed to match each other, i.e. they must come from the same model library.

The basic idea to match field component I/Os with virtual controller I/Os is to give them similar symbolic names which can be matched by a suitable algorithm automatically.

In the simplest case, one output of the controller is connected to one input of one or more components. This case may be called global control. It can be achieved by giving the same symbolic name with a certain prefix to controller and component I/Os e.g. “Global_PowerOn” or short “G_PowerOn”. If I/Os of the controller shall be connected to components for individual control of the local component, the prefix “Local_” or “L_” can be used. In this case, the symbolic name has to be assembled according to a specified pattern. The I/O names of components consist of:

- The name of the superordinate logic component type $i \in \{1 \dots 9\}$ according to the numbering in 4.1.
- The consecutively numbered index $j, 1 \leq j \leq n_i$ of the sub logic component within the logic component of type $i$ with $n_i$ being the total number of logic components within a logic component of type $i$.
- A descriptive symbolic name of the I/O.

With this pattern, the names of I/Os of components look like this:

```
L_<LogicComponentType>_sub_<j>_<I/O name>
```

For example, the input of the stopper at the second incoming of a merge may be:

```
L_Merge_sub_02_StopperOpen
```

Corresponding to this pattern, the I/O names of the virtual controller consist of:

- The name of the superordinate logic component type $i \in \{1 \dots 9\}$ according to the numbering in 4.1.
- The consecutively numbered index $k, 1 \leq k \leq m_i$ of the current instance of the logic component of type $i$ with $m_i$ being the maximum number of instances of logic component type $i$.
- The consecutively numbered index $l, 1 \leq l \leq n$ of the current logic component with $n$ being the total number of logic components in the model.
- A descriptive symbolic name of the I/O.

With this pattern, the names of I/Os of the controller look like this:

```
L_<LogicComponentType>_<k>_sub_<l>_<I/O name>
```

For example, an output of the controller for a stopper at the second incoming of a certain merge number 7 may be:

```
L_Merge_007_sub_02_StopperOpen
```

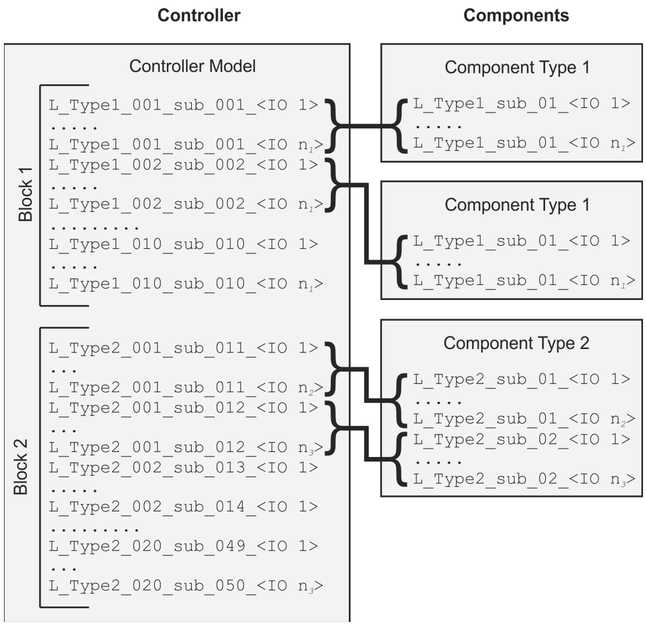


Figure 6: Automated wiring of components and controllers.

Figure 6 illustrates the matching of the component I/Os with the controller I/Os. For every logic component type $i$ there are $m_i$ blocks of I/Os in the controller. Each of these I/O blocks can connect to exactly one logic component. Thus, $m_i$ determines how many logic components of the same logic component type can exist in the model. A trivial matching algorithm searches components and connects these to the next free corresponding I/Os block.

As there may be multiple virtual controllers in a model, each component needs to carry a tag to which controller it shall be connected by automated wiring.

## 5 THE GENERIC CONTROLLER PROGRAM

After a model has been created and the automated wiring has been executed, a generic controller program can be started. Figure 8 shows the structure of the program and separates it into the three layers (downlink, internal, uplink) which have been introduced above. The program can run in one of two different modes:

- In mailbox mode, the uplink layer is active and the program communicates with a superordinate controller.
- In test mode, the uplink layer is inactive and the program works autonomously.

In this work, we will mainly describe the test mode. The mailbox mode will be explained in detail in a future paper.

Each logic component type requires control by an individual finite state machine. In a PLC program, such a finite state machine can be represented by a function block (FB). Every logic component, i.e. every instance of a logic component type, in the model is a control element to the program. For every control element there is a data block (DB) providing required local data e.g. the I/O address range. From the data block for a control element and the function block of the corresponding logic component type, a new function block for the control element is instantiated. This FB executes the finite state machine and controls the component in the model. All FBs for all the logic components in the model are executed in parallel.

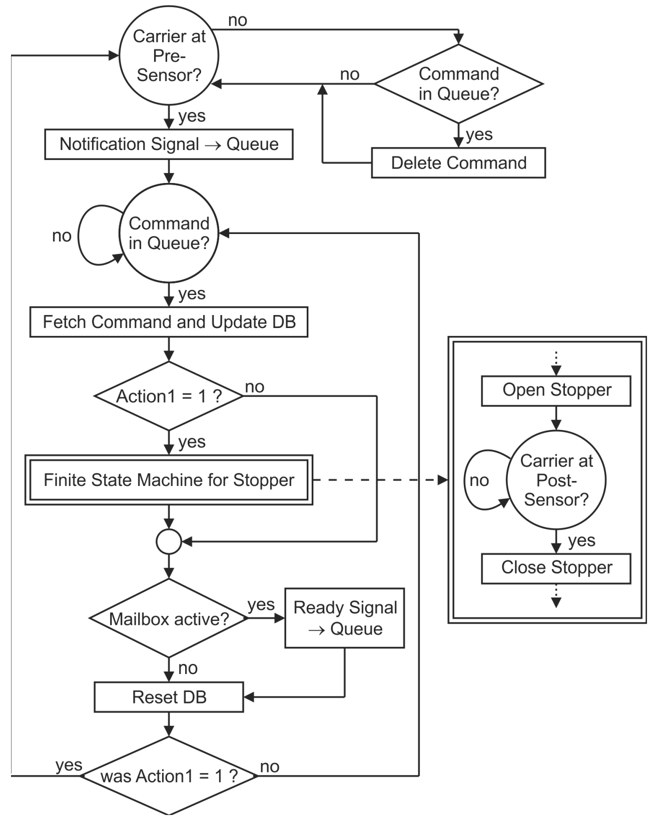


Figure 7: Typical controller program function block for a stopper.

We will now give a simple example of what may happen during simulation and during the course of the controller program. Figures 7 and 8 illustrate the example. A carrier runs into a stopper at a work station and a sensor detects and identifies the carrier. In test mode, we just want the carrier to stop and then go on immediately. The stopper, the sensor and even the sensor behind the work station belong to the same logic component of type “stopper”. The corresponding FB creates a location notification and writes it to the notification queue. The notification handler runs the notification standard routine and creates a command to open the stopper. The task “open” for the stopper is coded using the parameters Action1 and Action2. Actually, this is very simple for just a stopper but there will be more possible tasks if e.g. one or two additional devices like linear or rotational axes are added to the stopper. The command just created is then added to the individual command queue of the current control element i.e. the stopper with the sensors. The FB fetches this next command and executes the finite state machine for the actual stopper process i.e. opening the stopper, waiting for the sensor behind the stopper and closing the stopper. After this, the FB emits a ready signal into the global ready signal queue.

Even in test mode, the internal layer of the controller program is fully active and data is stored into and received from the queues. Actually, these queues will provide the asynchronous decoupling in mailbox mode when the uplink layer is active.

The controller program is usually created in the original development environment of the controller manufacturer. Most modules of the program are identical for all applications i.e. for all transport system techniques. Only the function blocks for the logic component types have to be created individually.

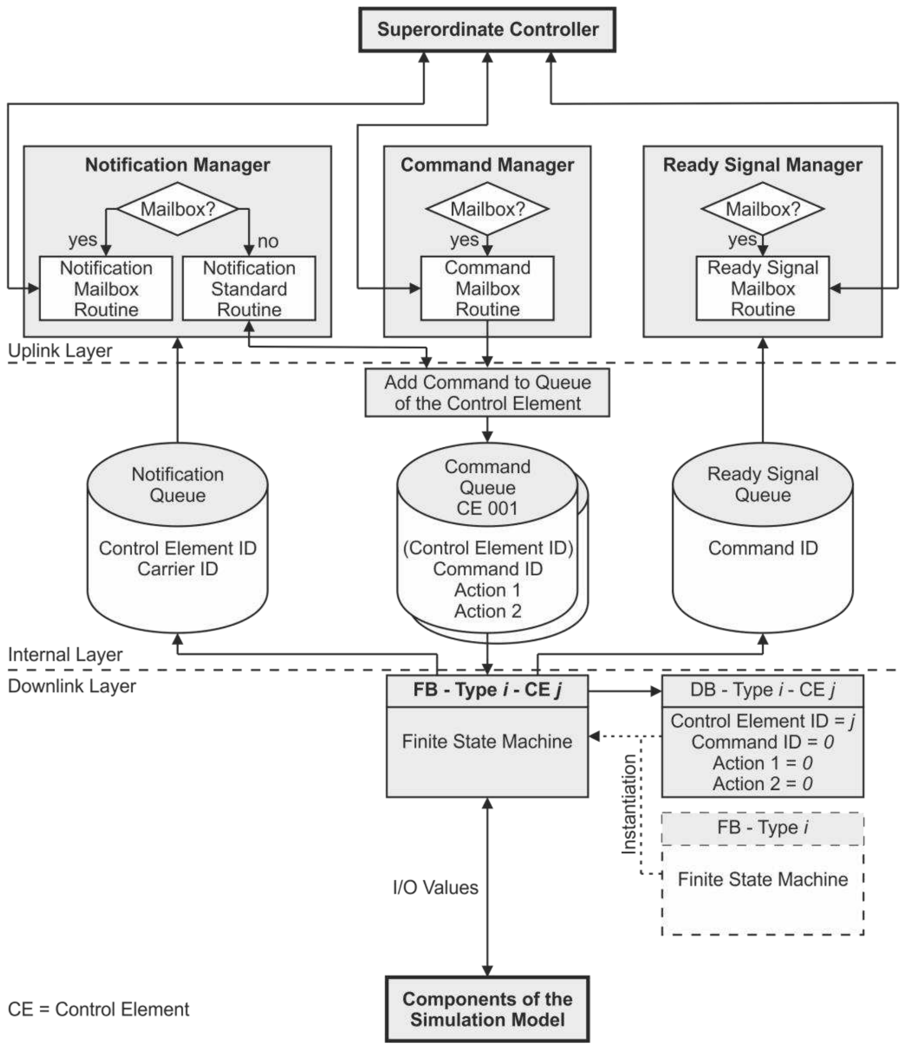


Figure 8: Structure and function of the controller program.

## 6 APPLICATIONS

We have implemented the new generic control concept for a 3D simulation system [9]. We decided to write the controller program for the widely used Siemens S7 PLC. Furthermore, we used the original SIMATIC development environment to create STEP7 code. As mentioned above, the predominant part of the program is identical for all applications. However, the implementation of the finite state machines for the logic component types varies with the transport techniques used by the different manufacturers.

As shown in figure 5, the PLC program belongs to the virtual controller which is an integral part of the model library of transport component models of a certain manufacturer. To verify our concept, we have implemented a model library and a controller program for two very different transport techniques. We decided to consider the industrially relevant systems Bosch Rexroth TS 2*plus* and ASYS TECTON (formerly Grässlin).

The transport technique of the Bosch Rexroth TS 2*plus* system is characterized by the fact that carriers may change their front face at forks, merges, and turns. Figure 9 shows a fork modelled with stoppers, sensors, and a lift-traverse unit. As carriers are diverted by 90°, the front face may change. Compared to others, this transport technique requires more complex control programs as more sensors and actuators are necessary for forks, merges, and even curves. Finite state machines have been implemented for all logic component types and complete test models have been built successfully.

We also implemented a model library with a special controller program for the ASYS TECTON transport system. In contrast to the Bosch transport technique, carriers will never change their front face as they are rotated at forks, merges, and turns. Figure 10 shows a complete transport system which has been built from the model library. By automated wiring, all components are connected to the virtual controller. Then, the controller program is emulated within the simulation system during simulation. The simple default routing strategy ensures that carriers at forks are routed straight on or to the side alternately. This way, carriers should reach every single branch of the transport system. By pressing just one button, the engineer can observe and verify the 3D simulation model.

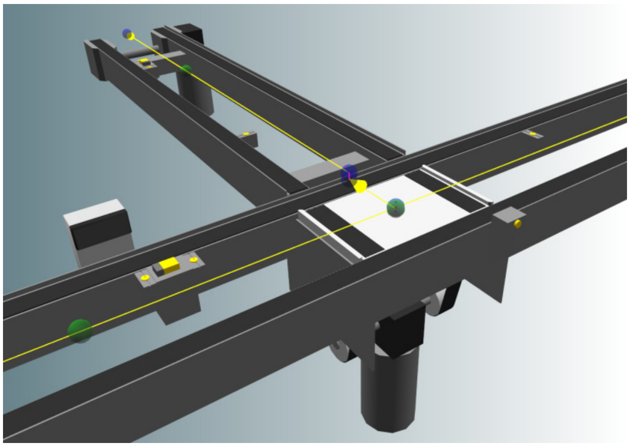

Figure 9: Fork modelled with Bosch Rexroth TS 2*plus* components.

The model shown in figure 10 is also used in the ongoing German research project AutoProBe [10]. In this project, we will analyse, identify, and export the logic components of this and arbitrary other models to create human machine interfaces automatically.

Figure 11 shows another transport system which is used to move carriers between work stations. The setup is a model of an educational plant by FESTO Didactic GmbH. The control program for the Grässlin components provides the uplink layer and a superordinate controller controls the logic components of the model.

## 7 SUMMARY

We have developed a new generic control concept for track-bound and carrier-based transport systems. The elements of transport systems are classified into logic component types. In a simulation model, each logic component of the model is automatically connected to a virtual controller. The controller program is capable of controlling an arbitrary number of logic components. In test mode, the program executes a simple routing strategy which enables an engineer to verify the model immediately. In mailbox mode, superordinate controllers can connect to the controller program which then translates high-level commands into low-level PLC behaviour. The concept has been implemented for a 3D simulation system and two industrially relevant transport systems.

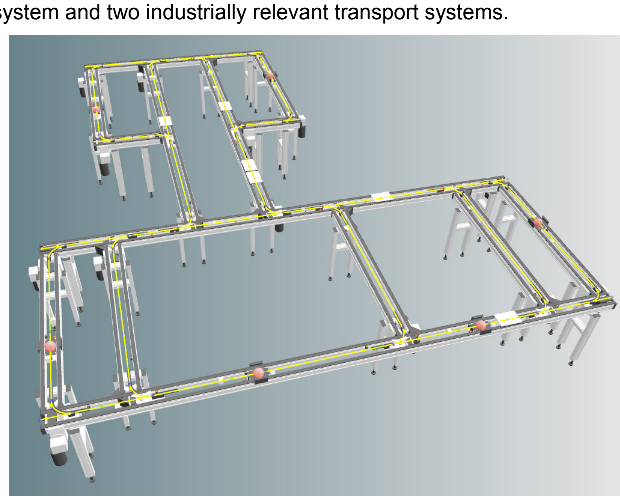

Figure 10: Transport system with ASYS TECTON components.

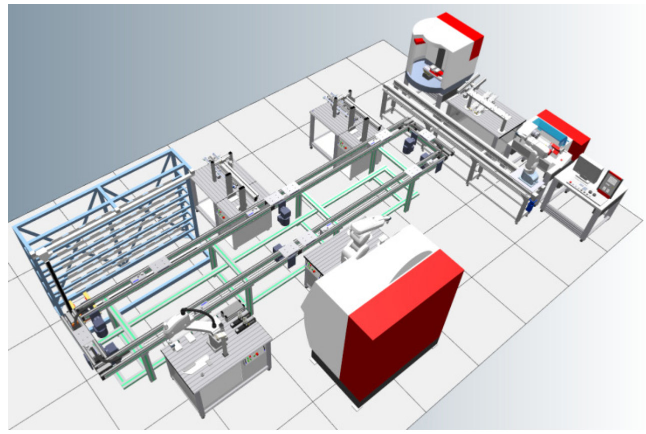

Figure 11: Transport system used in educational software.

## 8 ACKNOWLEDGMENTS

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# Forming Plastic Shields on a Reconfigurable Tooling System

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**Abstract**
State of the art in producing 3-dimensional formed plastic shields is the use of mould blocks that are milled on machining centers. This paper describes the replacement of traditional mould blocks through a novel automated reusable mould and tooling system, providing good forming results and low investment costs. The reconfigurable tooling system replaces commonly used mould blocks. Two major issues will be adressed. The first target is to find principles for low tooling costs, while the second target focuses on the improvement of the forming process suitable for the system. Therefore the system will be applicable for a broad range of products.

**Keywords:**
flexible forming; reconfigurable tooling system; thermoforming plastics

## 1 INTRODUCTION

Plastic shields more and more tend to replace the conventional glazing material glass mainly due to the potential of weight reduction. Also weight reduction is of primary importance using plastic resin on the one hand, also the design freedom of this material is a major criterion on the other hand. Plastic shields are well known to be used in helicopters, machine tools, as visors and for glazing components of cable cars. Currently the market tends to replace the shields in working machines as well as in private vehicles. For mass production these components are in general injection moulded or injection compression moulded. When it comes to form parts for small series and prototypes, thermoforming is applied. Moulds for thermoforming processes are cheaper than those for injection moulding [1]. The process costs are mainly determined by the mould costs. Applying a different contour a new mould is needed, which has to be machined by a milling process. This time-consuming process results in high costs of labor, material and equipment. Depending on its size and the material used, for example polyurethane or aluminum, the mould can cost up to 12,000 €.

A growing demand for moulds is furthermore generated by the dynamization of product life cycles and mass customization which results in decreasing batch sizes and increasing product variants [2]. Meeting the market requirements and saving resources and labor costs, reconfigurable tooling concepts seem a promising choice. Therefore the total milling process of the form can be skipped and furthermore storage of the moulds causing further costs can be avoided.

That is why the scope of this research project is the development of a reconfigurable tooling system replacing the time- and cost-consuming process by a tooling system able to provide a desired 3D-contour. As the system should be applicable for a broad range of thermoplastic materials and affordable for small and medium sized thermoforming companies it should provide low investment costs and the possibility of forming parts with high optical quality.

First of all different approaches have to be examined finding the ideal reconfigurable tooling system for such applications. Secondly the solutions found have to be examined regarding economic principles. The system that is finally built is validated by forming tests using Poly(methyl methacrylate) (PMMA) and polycarbonate (PC).

## 2 PROCESSES FOR THERMOFORMING PLASTIC SHEETS

State of the art in producing 3-dimensional formed plastic shields is the use of mould blocks, milled on machining centers. The final shape of the shield is obtained by thermoforming a plastic sheet with drape forming, stretch forming, vacuum forming, blow forming, or positive-negative forming, on the mould.

With drape forming, simple 2-dimensional forms can be realized. The plastic sheets are heated in an oven. After heating, the warm plastic sheet is applied to a mould, which is covered with a friction-reducing material. With a stretched cloth, a distributed load is applied on the whole surface, to press the material on the form (Figure 1a). In this manner e. g. prototypes for automotive windshields made of acrylic glass (Figure 2a) are formed. Due to the low forces of this process, the moulds can be made of wood or polyurethane foam, which are cheap materials.

By stretch forming, more complex parts can be formed. The heated material is clamped in a clamping frame and stretch-formed over the mould (Figure 1b). The material can flow and thus thins itself out in the process. This is necessary to prevent folds in the forming result. The method is used to produce 3-dimensional caps (Figure 2b). The moulds are usually made of polyurethane foam. It therefore is a medium cheap solution.

With vacuum forming, also parts containing a depression can be manufactured. The method differs from the stretch-forming by the fact that additional vacuum is applied. The vacuum draws the material to the mould (Figure 1c). This process can generate sharp edges and form depressions in the material. With this method, parts like shown in Figure 2c can be formed. The moulds are usually made of aluminum and therefore cause high costs.

Another method is blow-forming. It is similar to the vacuum forming, but here a negative mould and compressed air is used instead of vacuum (Figure 1d). The shape accuracy is in this case located on the outer side of the formed disc as there is the direct contact to the form. In case of vacuum forming it is located at the inner side.

A further process is positive-negative forming. In this process the material is brought between a positive and a negative mould (Figure 1e). The method is used to form parts with a simple geometry. The forms may consist of cheap materials, such as wood and polyurethane foam, as well as higher quality material, such as aluminum.

Each listed process can also be used in combination. This will not be discussed further.

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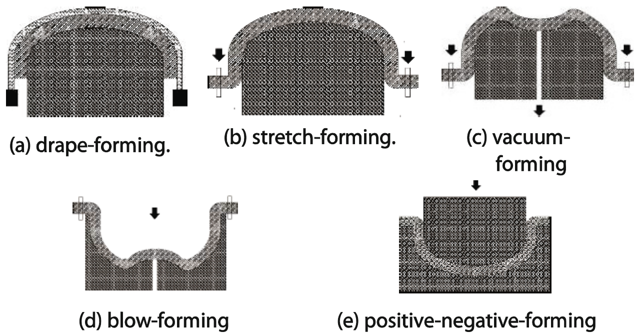



Figure 1: Processes for Forming Plastic sheets.

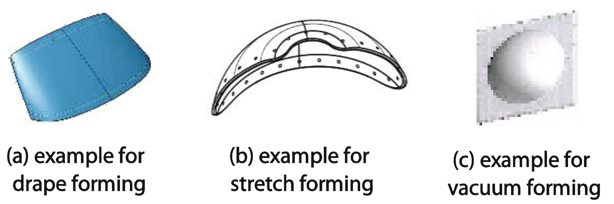



Figure 2: Several forms which are formed with different processes.

Besides different processes, it is also necessary to differentiate between the temperatures at which the forming process is applied. Moulding operations above the glass transition temperature run with a higher speed. At temperatures below the glass transition temperature, the forming process requires more time. Both, forming processes below and above glass transition temperature are part of the paper. Drape forming, stretch forming, vacuum forming and positive negative forming are considered. In each case the process and the temperature is indicated regarding the obtained results.

## 3 RECONFIGURABLE TOOLING SYSTEMS

### 3.1 Method Provided

Various approaches to build reconfigurable tools have already been examined and evaluated to find an optimal concept. The method found provides a discrete surface similar to a bed of needles or a pincushion. The pincushion will also be denominated as a stamp matrix throughout the paper.

Approaches to create flexible tools through a pincushion have been applied in the sections injection moulding and metal forming in past research. Two approaches to obtain form flexibility in this field are introduced at this point.

### 3.2 Other Reconfigurable Tooling Systems

At the TU Eindhoven a form flexible system for deep drawing of metal sheets was built [3]. A stamp matrix with 1846 elements is used in a 40 x 50 mm surface area. Each stamp has a maximum lift of 25 mm. The used stamps are rounded at the top. During the forming process an elastic counter-mould presses the metal in the cavity. No heating is provided during the process. The metal sheet is shaped at room temperature. The prototype of the developed flexible tool system is shown in Figure 3.

At the “Technischen Universität München” a form flexible tooling system for injection moulding was developed (Figure 4) [4]. This is characterized similar to the system of TU Eindhofen by a high resolution. Therefore it can also be used for small geometries only. If it was scaled up for larger geometries, the high resolution of the flexible mould would cause high costs. To establish a system that works more efficiently, this paper describes a system which can be used to produce larger discs.

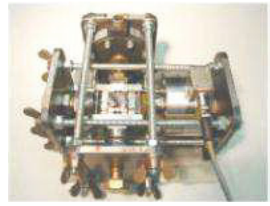


Figure 3: Flexible tooling system for metal at TU Eindhofen.

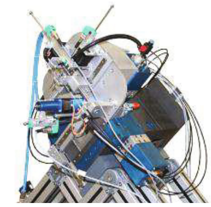


Figure 4: Flexible tooling System for injection moulding at “Technische Universität München”.

The solution presented works with a larger distance between each of the individual stamps. Therefore it was necessary to develop a new type of adjustment mechanism. A big advantage of the developed system is that this form flexible tool is much cheaper to produce, but it also shows some applications limitations. These are caused by the individual height-adjustable pins.

## 4 EXPERIMENTAL WORK

### 4.1 Setup for Experiments and Simulation for Forming Plastic Sheets above Glass Transition Temperature

At this point, basic experiments and simulations are described. The experiments were carried out before beginning with the design of a form flexible tool system. In experiments and simulations knowledge was gained to achieve optimal forming results on the form flexible tooling system. The experiments and simulations were carried out above the glass transition temperature. The processes drape-forming, stretch-forming and vacuum-forming are considered.

*First Experiments*

The stamp matrix can only rebuild the mould with discrete levels. For an optimal quality a continuous curve is necessary. Several process optimizations have to be made, in order to create a continuous curve. To reach this aim, there are two specific approaches. On top of one single pin there is a stamping head to reduce waviness. Furthermore an interpolation layer of silicon is used to smooth the discrete levels. As there is only little experience concerning flexible thermoforming of plastic discs, the described preliminary tests were conducted on a test platform to gather experience. The test platform is a perforated plate, with manually height-adjustable screws. Different types of stampingheads and interpolation mats were tested on it.

The experimental setup is designed to be compatible with thermoforming machines of an industrial user. The experimental setup can be placed into a wooden frame. The top of the construction then is flushly aligned with the wood edge. The fitted base plate of the experimental setup is shown in Figure 5.

Figure 5: Experimental setup in a thermoforming machine.

The perforated plate is the basic structure of the experimental set-up. On the plate, 85 holes with internal fine pitch threads are inserted. Screws can be placed in the holes, in order to map a 3-dimensional surface. The fine pitch threads have been chosen to make use of the self-locking design and to increase the load capacity in the longitudinal direction of the screws. To improve the position tolerance of the screws in the hole, these can be fixed at the underside of the perforated plate with nuts.

The perforated plate has a squared base with 240 mm side length and is 10 mm thick. The fine pitch thread screws (ISO 8676 M8 x 1.0) inserted into the perforated plate allow the adjustment of the stamp field. As screws are available in lengths 80 mm, a maximum height difference of 60 mm can be reached. This value results from the thickness of the plate, and from the mounting of the nut.

The heads of the screws are hexagonal and allow the mounting of the stamp heads. The stamp heads are manufactured in two different variants. Through the two variants with different degree of elasticity, the behavior of the interpolation mat is influenced. Thereby, the shape of the plastic disc is affected. Both stamping head variants are made of polyamide (PA) 2200 and are manufactured with the additive laser sintering process.

The interpolation mats are made of casted silicone (Elastosil RT 622 A / B) and are available in three different thicknesses (5, 10 and 15 mm). The thickness has great impact on the elasticity. Due to the manufacturing process, the two sides of the interpolation mat differ in their surface quality. One side is fitted with much more pores on the surface than the other. Therefore, care has to be taken during the forming process, so that the side with the non-porous surface is orientated to the top and so towards the plastic disc.

Figure 6 shows the full test platform described above. Recognizable in the picture are the perforated plate, the fine pitch thread adjustment screws, the lock nuts, the stamp heads and the interpolation mat. The results obtained on this test platform are described later on in the Topic "Results".

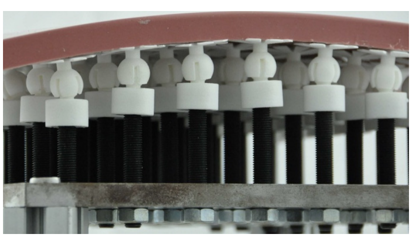


Figure 6: Stamp heads and interpolation mat on the perforated plate.

*Computer-Based Simulation*

The modeling and simulation of complex problems with tools of the finite element method offers great potential to accelerate the development process. Using numerical methods, mechanical models are constructed and calculated. The results of these calculations serve as a basis for decisions and help to increase the understanding of the system. In case of the newly developed reconfigurable tooling system, forces can be determined by using the simulation. Furthermore the whole formed geometry is calculated. The result is displayed in a graphic way (see Figure 7). In a further step the simulative results of the formed geometry are automatically compared with the previously constructed target form. The implemented automatic analysis in Matlab provides quantified device parameters within seconds. With the exact characterization of the simulated formed parts, it is possible to choose the process parameters of the forming process optimal, even before the physical start of the form flexible tooling system begins. Production can thus start faster.

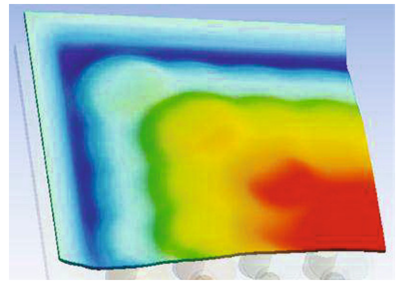


Figure 7: Simulation of vacuum forming on a flexible tooling system.

In the simulation, a subsystem of the reconfigurable tooling system is modeled. In this method symmetries are used to keep the calculation time within acceptable limits. The existing simulation consists of a system with 16 stamp elements with stamp heads, the elastic interpolation mat and the plastic disc. Each stamp head is mounted on a ball bearing, which ensures a very variable adjustment of the surface. In the simulation, the stamps are considered as solid bodies. The interpolation mat, as well as the plastic disc is modeled as hyper-elastic materials during the forming process.

The simulation allows both the simulation of stretch forming, as well as the vacuum forming process. During the forming process, the height of the stamps is varied until they reach the target position. Simultaneously a planar compressive force is applied to the plastic disc to replicate the vacuum. In this way the realistic form of the components is computed in the simulation. To study the behavior of the materials for plastic discs during the thermoforming process on a flexible tool system, several simulations were performed with different parameter settings. Both, the stamp heads used, as well as the thickness of the interpolation mat, and the thickness of the plastic disc, were varied. All settings were tested for different target geometries.

Based on the data records of the shaped geometry the automated analysis begins. The analysis is the basis for the evaluation of the process parameters. The simulation is thus a calculation tool to predict the final part geometry. The Simulation can be modified for different applications thanks to its modular structure. Thus, already in the planning phase of a new part, the virtual forming of it can be made. Hereby production-related effects can be taken into consideration already in the construction and planning phase.

### 4.2 Latest Setup for Experiments

With the knowledge gained from the experiments and simulations, a larger demonstrator is designed. Currently planned is a demonstrator with a stamp field, large enough, to have industrial relevance. The planned size is approximately 1.0 m x 0.5 m. The spacing between two stamps is 3 cm. All in all this results in a field of 578 stamps. The surface is composed of two identically designed modules of 0.5 m x 0.5 m. For later use, any number of modules can be combined. Therefore, shapes in almost any order of magnitude can be achieved with little effort. The planned demonstrator can be seen in Figure 8.

It is a new, innovative concept that is implemented. The concept results in a new application which benefits are low costs and high potentials. To achieve a high resolution of the resulting stamp matrix, various approaches have been investigated within the project. Concepts in which the stamp height is controlled by individual pneumatic, hydraulic or electric cylinders are not used because of the high costs. A system that is composed of a threaded pin and an underlying portal robot with a screwing head, is not applicable due to the long setup times for the whole stamp field. A good compromise between response time and costs is realized with the following system. The stamps are on a common platform which is movable in the vertical direction. That platform moves up first and then down in the next step. The stamps are following the platform. When a stamp has reached its desired target position, it can be held in place by a specially designed clamp mechanism.

In order to smooth out the discrete levels between the stamps, the stamps are equipped with the best suitable stamping heads. On top of these, the interpolation mat is applied to avoid the slack between the stamp heads and prints of them. The selection of the optimal stamp head design is described in the results section. The design of the interpolation mat applied to the stamping heads is carried out using a finite element simulation. By simulating, the elasticity of the mat can be calculated, considering all external influence factors. So an optimized interpolation mat can be built to realize the desired radii and simultaneously the tolerated sag. Also the prints of the stamps, in the plastic material, can be minimized.

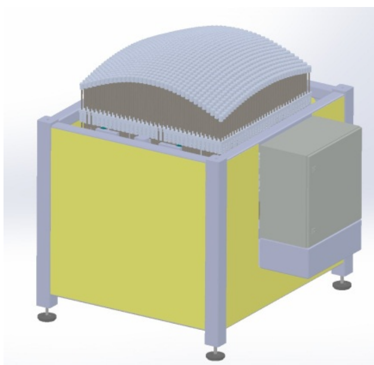


Figure 8: Latest setup for experiments.

### 4.3 Setup for Experiments for Forming Plastic Sheets below Glass Transition Temperature

Besides polymethylmethacrylat (PMMA) also polycarbonate (PC) was formed on the reconfigurable mould. Forming PC requires low and homogenous forming temperatures to obtain parts with high optical quality. Therefore research focuses on locally heating and cooling possibilities within the interpolating layer.

For producing high optical quality parts, creep forming below the glass transition temperature of polycarbonate was carried out. Therefore heating wires (Block RD 100/0.3) have been integrated within the flexible silicon layer to prevent the system from high temperatures and therefore to avoid the increase in costs for the whole components of the system. The required force was applied by a female mould. The heating wire used provides a resistance of 6.930 Ω/m. For silicones the maximum power of 0.8 W/cm2 should not be exceeded. The prototype of the flexible heating layer has a surface area of 277.5 x 277.5 mm2. The heating wires are placed at a distance of 6 mm one to each other in the middle of the silicone layer having a total thickness of 17 mm. The resulting total length of the heating wire is about 15 m providing a total resistance of 103.95 Ω. Applying a voltage of 230 V, a power of 508.90 watt is achieved. The temperature contribution was measured by an IR camera (ThermaCAMTM S60, Flir Systems) resulting in a total temperature difference of 4 °C. Furthermore the temperature drop from the middle of the layer to the outer zone was measured between two silicone layers using a PT 100 foil sensor (FP x685, Ahlborn) resulting in a total temperature difference of 0.5 °C for a temperature of 120 °C (lowest forming temperature) and 3.3 °C for 143 °C (highest forming temperature), respectively. The implementation of coolant bores was already described elsewhere [5].

In order to apply the required force for creep forming of polycarbonate, a female mould was developed using the given height values of the already existing pin cushion. The stamps of the female mould are clamped all together by moving the middle plate against the stamps. The schematic is shown in figure 9.

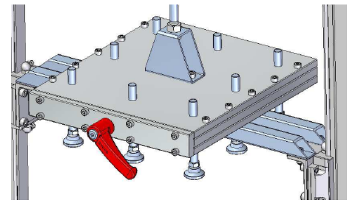


Figure 9: Schematic of a female mould.

For the experiment extruded sheet material from polycarbonate (Makrolon AG2677, manufactured by Bayer MaterialScience AG), 5 mm thick, was used. The extrusion process causes anisotropy within the material resulting in different (mechanical) properties in x- and y-direction. Before the forming process each sheet was baked in an oven at 120 °C for at least 10 hours for dehumidification to avoid bubbles when heated up to higher temperatures. The polycarbonate sheet was then clamped within the reconfigurable tooling system between the two flexible silicone layers having already the desired temperature. The resulting springback due to this forming technique was already investigated elsewhere [6]. The optical quality regarding distortion was investigated using a zebra pattern with each stripe being 12 mm wide according to [7]. The shield was placed in front of the background in an angle of 72 degrees. Therefore distortions can be made visible also in the as-received state. Distortions occur due to the surface waviness of the material. The distortion in windshields is a crucial criterion regarding the optical quality. The procedure of the analyzation of the distortion is shown in figure 10. To analyze the distortion resulting from the forming process, the as-received as well as the formed material have to be observed. Placing the material in front of the zebra pattern distortion occurs and results in a waved pattern. The subtraction of the background (undistored) provides a scale for the surface waviness. Obtaining an almost black picture will be the result of a very smooth surface. The more white pixels the more distortion occurs and therefore result in poor optical quality. The applied forming parameters for the investigations of the surface waviness are shown in table 1. A face-centered-central-composite-design was used.

| A: Temperat-ure [°C] | B: Radius [mm] | C: Ratio of Radii | D: Anisotr-opy |
|---|---|---|---|
| 120 | 960 | 0 | In direction |
| 132 | 1906 | 0.5 | Right angles |
| 143 | 1433 | 1 | - |

Table 1: Forming parameters.

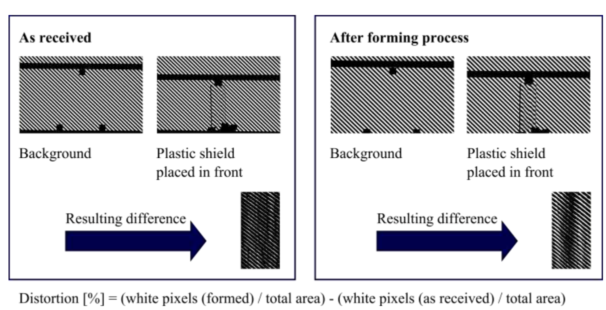



Figure 10: Procedure for investigating distortion.

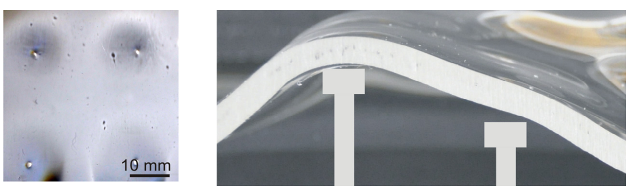
# 5 RESULTS

## 5.1 Forming Plastic Sheets over Glass Transition Temperature

*Results Through First Experiments*

To examine the effects of stamping heads and the interpolation layer forming tests were carried out on a vacuum forming machine to study the effects of stamping heads and the interpolation layer on the test setup decribed before. We found that the amount of vacuum applied is crucial for the waviness of the formed part. Experiments showed good results for simple forming and stretch forming.

The reason for the huge influence of vacuum lies in the pressure engaging all over the surface area. The vacuum draws the plastic disk and the interpolation mat through the gaps between the stamp heads. In Figure 11 the slack between the stamps is shown. The darker areas are more lofty than the lighter areas. In the illustrated example the influence of the air holes in the interpolation mat can be seen. They are randomly at the same position as the mid of the stamp heads. The darker color is at these points unrelated to the air holes. Clearly visible is the sag of a sectional image, as shown in Figure 11b. The component was cut apart for this picture, this test is therefore a destructive test. The positions of the stamps are clearly visible in the illustrated part. Even if the sag is clearly visible as a ripple in the material in the cross section, it is hard to measure it by simple mechanical methods. To measure the sag, higher optical methods have to be used to determine the ripples on the surface of the plastic disc quantitatively. In practice, the quality assurance is usually done by an experienced worker.




a b

Figure 11: Results through experiments.

*Results through Simulation*

A diagram comparable to the real forming results can be produced as an output in Matlab using simulation. The section line lies diagonal through the simulated part cutout. Figure 12 shows the curves of the two geometries shown. The solid line shows the section of the desired geometry, the dashed line represents the section of the simulative formed geometry.

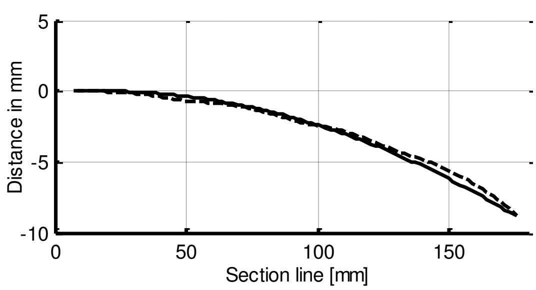
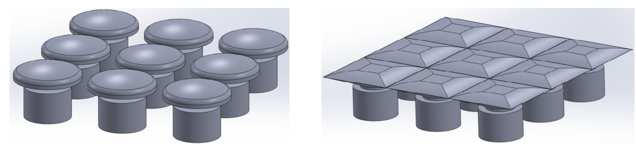



Figure 12: Set curve and actual curve in a section diagram out of the simulation.

For transparent plastic panels, high demands on the optical quality of the forming are given. Through the developed automated evaluation method, it is possible to evaluate the quality of the formed parts quantitatively through simulation methods. Thereby settings for values are identified and can be varied. In this way, it is possible to find the optimum process parameters, before start of production. It is even possible to perform a virtual start of the form flexible tooling system. The differences shown in Figure 11 may be reduced considerably. With appropriate adjustment of the process parameters of the presented system, very good approximations of the lines shown in the figure are possible. For an optimized system, the actual and target geometry can be distinguished hardly. The quality of the forming result can therefore directly be improved by the proposed method.

The simulation is used to predict the forming results and to optimize the geometry of the stamp heads as well as the mat thickness. Figure 13 shows two different stamp head variants. On the left picture there is a round stamp head and on the right one there is a squared one. In Figure 14 and Figure 15 the corresponding intersections out of the simulation are shown. The squared head design shows much better results. To get an idea about the impact of stamp head geometries, a total of 20 variants were simulated under various environmental conditions. Finally the simulation showed, that the optimum stamp head geometry is the squared one.



a: Round variant b: Squared variant

Figure 13: Different stamp head variants.

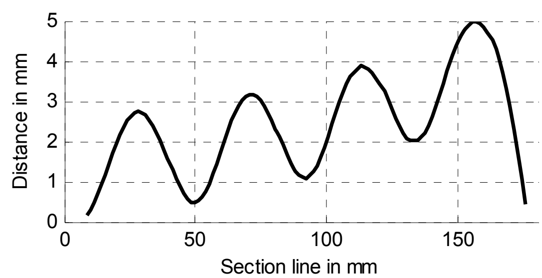



Figure 14: Difference between set curve and actual curve in a section diagram out of the simulation for round stamps.

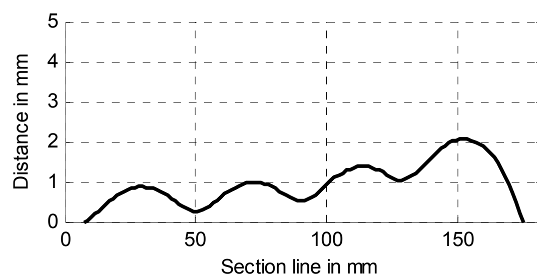



Figure 15: Difference between set curve and actual curve in a section diagram out of the simulation for squared stamps.

According to the analysis, the thickness of the interpolation mat has only minor influence on the target sizes. With a thicker interpolation mat, the order of magnitude of the sag and the geometry accuracy are influenced positively. The elevation increases slightly with the thickness of the interpolation mat. With the knowledge from experiments and simulation, a good compromise could be found. The value for the thickness used is 10 mm.

To detect potential limits of the formflexible tool using the squared stamps different radii varying from 800 mm up to 300 mm for the 2D and 3D geometry were tested. The results showed that 2D geometries up to a forming radius of 300 mm can be formed with the formflexible tool without a decrease in the accuracy of the formed shape of the plastic panel. For the 3D geometry a decline was detected for radii bigger than 600 mm.

### 5.2 Forming Plastic Sheets below Glass Transition Temperature

Figure 16 shows the resulting distortion over the four different forming parameters. The highest effect on the distortion is generated by the ratio of radii showing a nonlinear negative effect of -0.26. This means a 2-dimensional part is more crucial regarding distortion than a 3-dimensional part providing the same curvature in x- and y-direction. The anisotropy is nearly of the same importance order as the temperature. Both parameters show a positive effect of 0.1425 and 0.116, respectively. Nearly no influence is shown by the radius (0.05).

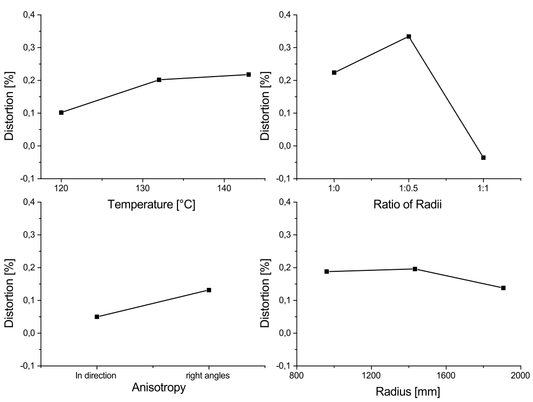



Figure 16: Plots of distortion over forming parameters.

Regarding the interactions the results are shown in table 2. Due to the DoE the interactions are mixed. Nevertheless it is shown that the interactions of the temperature and the ratio of radii and the radius and the anisotropy, respectively, show a negative interacting effect of – 0.2075. According to the main effects it can be assumed that the effect arises from the interaction of the ratio of radii and the temperature. This effect is almost as high as the main effect of the ratio of radii. Both show a negative effect and therefore increase the effect on distortions. Changing the ratio of radii at the same time as the temperature high optical results can be obtained. Regarding the interactions the results are shown in table 2. Due to the DoE the interactions are mixed. Nevertheless it is shown that the interactions of the temperature and the ratio of radii and the radius and the anisotropy, respectively, show a negative interacting effect of – 0.2075. According to the main effects it can be assumed that the effect arises from the interaction of the ratio of radii and the temperature. This effect is almost as high as the main effect of the ratio of radii. Both show a negative effect and therefore increase the effect on distortions. Changing the ratio of radii at the same time as the temperature high optical results can be obtained.

| CD/AB | BD/AC | AD/BC |
|---|---|---|
| -0.0225 | -0.2075 | 0.0775 |

Table 2: Interactions of forming parameters.

## 6 SUMMARY

Form flexibility can save resources. Increasing resource efficiency in production provides a high financial and material potential. Flexible tools provide the ability to adapt to the changing demands of product design and therefore allow to manufacture small quantities economically. The Fraunhofer Project Group for Resource-efficient Mechatronic Processing Machines in Augsburg and the University of Applied Sciences Munich developed therefore a reconfigurable tooling system for the thermoforming of plastic discs. The new tooling system allows the replication of the traditional mould blocks for forming plastic discs through an adjustable field out of a mass of single stamps. Machining of the mould block is no longer necessary. When using flexible tools, the quality of the final shape geometry is a crucial factor. For this reason, the studies of material behavior of plastic discs being thermoformed on a flexible tool are of paramount interest.

As results of practical experiments and simulations, the process parameters for an improved forming result could be found. This means that already before the actual forming process on the tool recommendations to adjust the machine in an optimal way are delivered. Also the limits of the process could be identified and expanded. All in all, the experiments and simulations were used to enable optimal forming results.

Through the development of the application described in this article, lots of resources can be saved. Herewith the researchers want to make a contribution to a responsible treatment of the environment and to a reduction in costs in the forming industry.

## 7 ACKNOWLEDGMENTS

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# Developing a Vision for Multi-site Manufacturing System of Systems

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**Abstract**

Multi-site manufacturing system of systems (SoS) are complex systems of geographically dispersed manufacturing organisations that self-organise in response to customers' needs, dissolving once these needs have been satisfied. This paper presents results from the EU FP7 project, Road2SoS, which has developed a roadmap of multi-site manufacturing SoS in order to explore the potential pathways to a future vision of a globally reconfigurable manufacturing SoS. The most important drivers, benefits, and challenges for the implementation of this vision are described, and the implications of these results for different manufacturing business models are explored.

**Keywords:**
Multi-site manufacturing; system of systems; SoS, roadmapping

## 1 INTRODUCTION

Systems of Systems (SoS) are complex systems which comprise operationally and managerially autonomous systems. Due to this, manufacturing networks and production environments can be regarded as SoS for production. Those manufacturing SoS span a range of governance modes, from directed SoS such as supply chains in which a central organisation co-ordinates the SoS, to acknowledged and collaborative SoS modes such as virtual enterprises.

New technologies help to decrease the effort for establishing, joining, or managing SoS and herewith are making it possible for collaborative SoS to form more rapidly and for smaller manufacturing enterprises to participate at all. However, significant socioeconomic and technical barriers remain to their wider adoption and for a vision of globally reconfigurable manufacturing SoS to be realised. For this reason, a roadmap for multi-site manufacturing SoS has been developed during the EU FP7 project Road2SoS.

This paper describes the development of the manufacturing SoS vision and the roadmap, going on to introduce the most important drivers, benefits, and challenges for the implementation of this vision, and to explain which technologies, capabilities, and enablers could help to overcome these issues. Building on the results of the roadmapping process, the paper discusses the influence of business models to the implementation of SoS and vice versa.

## 2 WHAT ARE SOS IN MULTI-SITE MANUFACTURING?

An SoS can be classified as having one of four different governance modes: directed, acknowledged, collaborative or virtual [1]. These governance modes are distinct in the degrees of power and influence that particular organisations exert within other members of the SoS. In the case of multi-site manufacturing SoS, supply networks are acknowledged SoS; the 'customer' in the supply network acts as the designated manager of the SoS, with the suppliers retaining "their independent ownership, objectives, funding, as well as development and sustainment approaches" [1]. Meanwhile, other forms of multi-site manufacturing such as virtual enterprises, distributed manufacturing, dispersed network manufacturing, cloud manufacturing and manufacturing-as-a-service can be classified as being either acknowledged or collaborative SoS modes. As in supply networks, there may be an end customer that determines the outputs. However, in a collaborative SoS mode it may be that the individual systems interact voluntarily and with equal authority in order to satisfy agreed-upon purposes [1].

Prior research into SoS has identified five common characteristics: autonomy, belonging, connectivity, diversity and emergence [2]. How each of these characteristics is exhibited within multi-site manufacturing is considered in the following sections.

### 2.1 Autonomy

Firms are the systems within a manufacturing SoS, with each firm pursuing its own objectives of capturing value, maximising its own returns and developing competitive advantage. Firms within a manufacturing SoS can be described as having both operational and managerial autonomy that define an SoS [3]. The former refers to the ability of the systems to independently fulfil customer-operator purposes on their own, while the latter refers to the ability of such systems to continue to operate outside the SoS boundary [3]. Other manufacturing SoS can exist where the SoS comprise subsidiaries of larger firms, in which case there is only partial autonomy.

### 2.2 Belonging

A common feature of each of these manufacturing SoS are their temporary nature. Manufacturers self-organise into collaborative networks in response to customers' needs, dissolving once these needs have been satisfied. The constituent firms within the manufacturing SoS decide to belong to it because it satisfies their own needs, beliefs or fulfilment [4]. The SoS possesses "a dynamic system architecture that changes itself correspondingly in order to achieve the purpose of the SoS and its constituent systems in a cost-effective manner" [5]. The terms of involvement are

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contractually determined upon entering the SoS, which will also include the terms of their exit from the SoS.

### 2.3 Connectivity

The need for social functionality is integral within a manufacturing SoS as firms collaborate in the delivery of goods and services to downstream customers [6]. Such collaboration requires communication capabilities between the constituent firms, including both human-to-human and machine-to-machine interactions. The need for this interaction requires that the firm's manufacturing systems are interoperable with those at different geographical locations, and that each firm uses compatible ERP software and related processes. Without this compatibility the firm will not be able to operate as a fully functional participant within the SoS. The use of compatible ICT software is also required to transmit and share information across the network, using agent-based and auction-based systems to distribute the total production load.

### 2.4 Diversity

Few manufacturing industries are vertically integrated. Instead, manufacturing SoS comprise a variety of different types of firms with specific capabilities and competences. When integrated, the SoS can deliver the products and services to satisfy customer requirements. This heterogeneity of capabilities is an essential component of an SoS, which must include “distinct or unlike elements or qualities in a group” [2]. Firms benefit from participation in the SoS as they access complementary capabilities and competences that they would otherwise find costly to develop.

### 2.5 Emergence

All systems generate emergent properties as a result of the relationships between the system elements. In the case of the manufacturing SoS the emergent property is the satisfaction of the customer's needs in the form of products or services, something that would not be realised by a single firm operating independently. Furthermore, the emergence property can be seen in the structures and behaviours exhibited within the manufacturing SoS, which are often transitory in nature following the satisfaction of the customer's needs. The firms' capabilities and competences are affected by participation in the SoS and trust is developed between firms. This gives rise to the potential for new collaborations to be established or even for the SoS to take on new configurations following the completion of the initial SoS' objectives.

## 3 THE EVOLUTION OF MULTI-SITE MANUFACTURING SOS

Facilitated by emerging ICT and driven by the geographically dispersed character of production and consumption, the nature of manufacturing is shifting from acknowledged SoS governance modes to collaborative and virtual modes. Given these changes, two questions emerge that provide the motivation for this study:

- What is the vision for multi-site manufacturing SoS?
- What are the challenges to this vision being realised?

These questions have been explored as part of the EU FP7 project, Road2SoS (http://www.road2sos-project.eu/). Within this project, desk research, two surveys, an expert panel meeting, and a roadmapping workshop have been conducted. The desk research and surveys sought to provide a baseline understanding of anticipated drivers, needs, opportunities and challenges. These were first reviewed with industry experts at the expert panel meeting, at which the first version of a multi-site manufacturing vision was proposed. Following these research activities, a preliminary roadmap was developed, which was then used as the basis for the roadmapping workshop that followed, and which involved the participation of 14 industry and academic experts. During the roadmapping workshop, the trends, drivers, needs, technologies and enablers of change in multi-site manufacturing SoS were explored using standard roadmapping workshop processes [7]. For this roadmap, the workshop considered four key aspects: (1) trends and drivers, (2) domain needs, (3) technology developments, and (4) enablers.

The roadmapping workshop was based on a revised version of the vision of multi-site manufacturing SoS. This vision for multi-site manufacturing entails a global network of interoperable factories, allowing the dynamic allocation of manufacturing. In such a scenario, manufacturing enterprises will be able to assign production to available capability and capacity, wherever it may be.

Investing in production capabilities can also be very costly and in some sectors the ability to outsource production to the manufacturing SoS may reduce the barriers to market entry. The ability to ‘switch-on’ production at such factories can enable companies to respond more rapidly to changes in customer demand as they do not have the sunk costs associated with capital equipment. To do so, such factories will need to be both reconfigurable and adaptable, with communication interfaces to the outside world that are globally accepted. This will allow greater customisation and improvements to product quality.

In summary, in this vision, the global manufacturing network will bring about increased transparency on available manufacturing capacity and capability, allowing greater participation from SMEs, and fostering a more efficient manufacturing system in which competition drives down costs.

## 4 TRENDS, DRIVERS, AND NEEDS FOR SOS IN MANUFACTURING

The roadmapping activity enabled the identification of the trends, drivers and needs that are providing the incentives and opportunities for manufacturing SoS to be realised. The following two sections consider these each in turn.

### 4.1 Trends and Drivers

The top layer of the roadmap pertains to the wider social, technological, environmental, economic and political trends (STEEP) changes that are envisioned that will affect the multi-site manufacturing domain. The 10 most important trends and drivers are:

- Reduce lead times to produce and deliver a product
- Need to increase interoperability of systems/data across factories
- Faster, more flexible factories
- Handling higher complexity and customer requirements
- Local adaptation/manufacturing close to markets
- Track and synchronise information, materials, products and their status
- Flexibility in supply chain participation (e.g. appropriate infrastructure and methods)

- Geographically distributed manufacturing
- Autonomous systems
- Increase product and process quality

Of these 10, six are economic and four are technological in nature, reflecting the commercially-dominated focus of this domain. The five most significant trends and drivers are described in the following sections.

*Reduction of Costs and Lead Times*

The need to improve the economics of production, reducing costs and lead times, was identified as the most important trend that is driving change in multi-site manufacturing. These are ever-present drivers, which in recent years have been emphasised through the implementation of lean manufacturing principles and just-in-time production.

*Need to Increased Interoperability of Systems/Data Across Factories*

Multi-site manufacturing requires the interconnection of systems across these multiple sites. As manufacturing has become more interconnected and global, this need for interoperability has become of increased significance. The interoperability of systems and data across production networks has to be ensured throughout various layers of the related IT systems. This starts with the vision of adaptable, integrated equipment and systems which enable the implementation of “plug and produce” and involves standardised interfaces for supply chain integration on business, manufacturing process and engineering levels. These have to address not only message-level communication, but also data-level alignment, e.g. by means of semantics.

*Handling Higher Complexity and Customer Requirements*

Manufacturing has become more complex, in terms of the organisation of the supply network, the degree of product customisation and satisfying customer requirements. The increasing complexity of the supply network means that a company must improve its partner management, while the global nature of manufacturing networks means that it has a wider range of potential partners.

Greater attentiveness to customer requirements means the customisation and personalisation of the product, so increasing the product complexity, and also affecting the supply network configuration as a greater number of manufacturers are involved in the delivery of such products. In combination, these factors require improved transparency of the overall production systems and its related interdependencies.

*Faster, More Flexible Factories*

With the need to deliver customised and personalised products, factories are becoming more flexible in order to rapidly adapt to changing market demands. This not only means that respective interfaces and knowledge about the facilities’ capabilities has to be available on-demand, but also that common master data (e.g. to enable the control of product changes across manufacturing environments) has to be synchronised throughout the production network.

*Local Adaptation/Manufacturing Close to Markets*

A further trend which has been identified is the local adaption of production, i.e. manufacturing close to customer markets. This, together with the reduction of waste and resource/energy consumption, contributes to the improved environmental sustainability of production systems. Of course, SoS are not the only way to address these trends, drivers, and needs in manufacturing. However, they can help to overcome the related challenging by providing appropriate architectures and services.

### 4.2 Domain Needs

The second layer of the roadmap pertains to the domain needs and benefits of a multi-site manufacturing SoS. The sub-layers describe key SoS characteristics, including adaptability, autonomy, interoperability, resilience and security.

The 10 most important domain needs are:

- Reduced waste and energy consumption
- Complexity management
- Reduced manufacturing costs
- Increased control of product changes across supply chain
- Adaptable, integrated equipment and systems that can be readily configured
- Safe autonomous systems (when constantly adapting)
- ICT-enabled intelligent manufacturing
- Very well distributed, mandatory standards for suppliers and OEMs
- Increased global competitiveness
- Shorter time-to-market

As in the previous section, the five most important items are now described in more detail.

*Reduced Waste and Energy Consumption*

The recognition of the need for improved environmental sustainability is reflected in the need for reducing waste and energy consumption in manufacturing systems being the highest priority. The need to reduce waste and energy consumption is also an economic imperative. The existence of waste means that there are opportunities for superior production processes and inventory management, opportunities that may realise financial benefit. Manufacturers also need to reduce energy consumption as the cost of energy increases and carbon taxes are introduced that penalise the consumption of non-renewable energy.

*Complexity Management*

There is complexity throughout the manufacturing SoS, from the technical complexity of managing a manufacturing system across multiple sites, to managing the relationships with other manufacturers within the system, and sharing the information across all of these sites. Managing this complexity is a key need as manufacturing systems transition from being a complex system to an SoS, and if the dynamic reconfiguration of the manufacturing SoS is to be realised.

*Reduced Manufacturing Costs*

To remain competitive, manufacturers need to operate efficiently and reduce their manufacturing costs. In existing manufacturing systems, lean principles can help reduce costs. In SoS, lean principles can also be extended to consider the wider network of manufacturing partners.

*Increased Control of Product Changes across Supply Chain*

Changes in another part of the supply chain affect have consequences for the activities of a manufacturer, with organisations needing to ensure complex value delivery across the multiple locations within the supply chain. One approach involves developing and producing goods as close of the customer as possible, aiming to exploit the 'economies of small scale' that arise when production and consumption are closely situated. Techniques for anticipating changes include real-time market analysis and response, and systems to reduce development time. This may require the closer integration of manufacturing, design and marketing, particularly in relation to the standards and regulatory development process, and by engaging users earlier during development.

*Adaptable, Integrated Equipment and Systems That Can be Readily Configured*

If a dynamically reconfigurable manufacturing SoS is to become a reality then the network must be capable of reconfiguration, as must the manufacturing sites within the network. It is this latter need that has been highlighted, with adaptable, integrated equipment and systems necessary that can be rapidly reconfigured in order to respond to the changing requirements of the network and end customers. At present, adaptive manufacturing comprises single step, flexible reconfiguration and process technology. Such technology can be adapted for different types and compositions of feedstock, and mass customisation techniques.

## 5 ROADMAP: HOW TO REALISE SOS IN MANUFACTURING

In order to address the trends, drivers, and needs explained in the previous section, technologies, capabilities and enablers where identified and assigned. In the following subsections, it is explained why and how those technologies, capabilities, and enablers help to support the trends, drivers, and needs by means of the four priority innovation opportunities identified in the workshop.

### 5.1 Key Innovation Opportunities Identified in the Domain

*Integration and Communication Standards*

Standards need to be developed to provide integration across multiple manufacturing sites so that diversity can be included and heterogeneity mitigated, so that knowledge can be shared more easily, and so that manufacturers can become more agile to changing customer requirements. Standards supporting these features would contribute to more effective set-up and management of multi-site manufacturing SoS by means of simplifying communication among people, processes, devices, etc. with regard to syntax and semantics. The latter are required within the manufacturing SoS, along with a constraintless factory demonstrator to show how the communication standards can be applied in operation. As integration and communication standards help to make information exchange more effective and easy, they also contribute to the handling of complexity, increase flexibility and interoperability and help to deal with product changes across the supply chain.

Large enterprises with de facto standards are significant barriers to the creation of such standards as they protect their existing products, including lobbying activities to influence the development of standards and regulations. Public-private partnerships and joint ventures within the industry may enable these barriers to be overcome.

*Enterprise-Wide Performance Assessment Analytics and Models*

Improved analytics and models offer the potential for better collaboration between different SoS, the ability to reconfigure the manufacturing system based on real-time data, and higher end-to-end reliability. A skills deficit is a barrier here, with systems engineers requiring multi-disciplinary design skills. Furthermore, the availability of necessary information has to be overcome in order to enable those enterprise-wide features, as well as the integration of related systems.

The development of these analytics and models can be limited by the short term views of management, with organisational buy-in essential if support for the cost of development is to be found. The formation of pre-competitive consortia using public funding may be one way of ensuring their development as it reduces a single organisation's risk exposure.

*Service-Oriented Control System Architecture for Dynamic Reconfiguration*

The creation of service-oriented control system architectures for dynamic reconfiguration will allow more open engineering and manufacturing, with engineer-to-order reducing time to market and improved control of product changes. Achieving this is difficult because there is a lack of intelligence in the system, in terms of both people and processes. Knowledge transfer is also a barrier but better infrastructure could allow it to become an enabler in the future.

The intention of such an infrastructure is to enable dynamic reconfiguration of assembly, production, and transportation, and herewith to react faster to changing market demands. However, also the IT systems behind should be reconfigurable in order to put together functionalities as needed, to scale up or down functionality and performance, and to ensure reliability. Those technologies and capabilities are known in principle from IT concepts. However, they are often not implemented in manufacturing environments as they would have to be integrated with existing systems.

*Digital Factory and 3D Interoperability between Design and Manufacturing (3DMBE)*

A completely integrated digital factory environment for the whole multi-site manufacturing SoS would enable and accelerate the joint planning of new products, optimisation of production, and herewith to increase competitiveness of the SoS, also be reducing costs or development effort.

However, at present no integrated set of tools and processes exists for the simulation of manufacturing operations. The availability of consistent data will allow integration and reconfiguration, and the added benefits of greater reliability and security. The absence of SoS thinking in this area is leading to local optimisation, with seed funding thought necessary to define the interfaces and standards.

### 5.2 Enablers

In order to overcome these issues, it is necessary to develop appropriate tools / technologies on the one hand, but also to clarify open issues with regard to IP or acceptance of SoS in multi-site manufacturing. Especially the latter is a single-point-of-failure for SoS in manufacturing as stakeholders have to know about SoS concepts and advantages which results in a need for respective education.

The enablers for SoS in multi-site industrial manufacturing which have been identified during the roadmapping process are mainly of non-technical nature. These include sub-layers on skills and knowledge, business models and concepts, infrastructures and architectures, and other enablers outside of those categories. Such enablers are essential for the establishment of SoS in production as they are a pre-condition for their acceptance in many cases.

*Education – Customer and Engineers*

Education of SoS applicants and users is a high-priority enabler for SoS in production as it is the pre-condition for understanding and acceptance of SoS. Especially in the manufacturing domain, a conservative mind-set is present which tells stakeholders to never change a running system and to be very sensitive with regard to IP and security issues. This can only be overcome by education which tells stakeholders about the advantages of SoS applications and how issues they regard as critical are resolved there.

*Global Expertise*

In order to apply SoS in global production networks, expertise is needed with regard to the roll-out and operation of multi-site manufacturing SoS on a global level. This is based on knowledge about global supply chains in general, but has also to include knowledge about SoS-specific technologies and capabilities. The global aspect is important for this point as manufacturing SoS are setup globally and there exist differences among regions with regard to level of automation, application of IT systems and their acceptance, education of stakeholders, etc.

*Intercompany Integration of Processes/Systems*

Multi-site manufacturing SoS do not only require technical integration of production sites / systems but also integration of the related business and production processes in order to achieve an comprehensive and efficient manufacturing execution throughout the whole network. This means that all organisations related to the network should be connected to it and implement compatible business processes, complementary manufacturing processes, and interoperable IT systems.

*Clear IP*

As in multi-site manufacturing SoS organisations are sharing knowledge about manufacturing processes, product design, cost models, etc., it is essential to define clear frameworks for handling this intellectual property. So it has to be specified, to which level of detail information is provided, who will get access to it and who not, what parties that get access are allowed to do with this information, and which penalties are applied in case of violating those agreements.

But also other legal issues like the responsibilities for warranties, maintenance etc. towards the customer have to be agreed in multi-site manufacturing SoS.

*Other Enablers*

Further important enablers for SoS in multi-site industrial production which have been identified are:

- Research in advanced coordination and control of complex processing systems and fragmented modeling and integration technologies as there exists a lack of appropriate algorithms, models, integration standards, etc. that are adapted to each other.
- Reference implementations that demonstrate SoS in manufacturing, their advantages, principles, concepts, etc. to potentially interested parties.
- New business models to realise superior value systems. Those business models should give guidance on how to operate SoS in production and therefore provide comprehensive information e.g. about technical concepts, standards, legal issues, education, etc. for a set of application cases like mass production vs. individual products, large global companies vs. virtual organisations set up by SMEs, etc.

## 6 INTERPRETATION OF THE ROADMAP FOR DIFFERENT BUSINESS MODELS

The overall business model of an SoS has considerable impact on the implementation of such a roadmap described. This means that the setup of enabling technologies or capabilities differs depending on the degree of automation in the production processes existing in the SoS, the variety of products, or the power relations within the network. In the following, some examples are given for the influence of business models to the roadmap realisation.

### 6.1 Degree of Automation in Processes

The degree of automation in the production processes of a manufacturing SoS directly influences the ability to gather data from the production systems or, vice versa, to control production systems from higher level IT infrastructures. For processes which are executed manually, the integration to a manufacturing SoS is only possible via additional user interfaces that transfer the process related data to the software systems that are integrated to the SoS. For fully automated processes, it is possible to integrate all equipments and control mechanisms directly to the SoS infrastructure which enables much faster information exchange among the systems. However, in this case the effort for integrating the production environment to the SoS is higher when relying on state-of-the-art technologies.

The adaption of enablers like common integration and communication standards, service-oriented control system architectures for dynamic reconfiguration are the main enablers that support the optimisation of SoS establishment and management for those systems.

In comparison to that, the education of the process executors plays a key role for the integration of non-automated processes into manufacturing SoS since they have to understand and accept the principles and advantages of the respective SoS in order to support its operation.

### 6.2 Mass Production vs. Individualised Products

Within SoS that are focused on mass production, product configurations and herewith processes to be executed remain the same. In opposite to that, the manufacturing of individualised products requires on-demand adaption of production, e.g. with regard to process parameters. For this reason, individualised production comes with the demand for fast and secure communication of order-related product specifications among SoS participants which requires harmonised integration and communication standards and digital factory and product specification interoperability between design and manufacturing as the information about each product to be manufactured vary and have to be processed consistently throughout the production network. Furthermore, a well defined set of intellectual property rights ensures complementary to the technical enablers that product features or characteristics like certain functionalities or design can really be shared in the production network in order to execute the production process jointly.

Compared to that, mass production is more focused on efficiency of the production and, for this reason, requires production-network wide performance assessment analytics in addition to the well-defined communication standards.

Mass customisation, as a combination of both where mass production is executed for pre-defined product variants, also combines the requirements on the SoS infrastructure.

### 6.3 Timely Constant SoS vs. Continuous Reconfiguration

The timely arrangement of an SoS goes almost in line with the previous item. This means that for production networks which are set up for a short time, many parallels can be found to those for individualised products. Additionally, short term production networks come together with the demand for fast (re-)configuration which can be achieved by service-oriented control system architectures for dynamic reconfiguration.

Long term co-operations, on the other hand, share many principles with mass customisation setups as they exist long enough to optimise performance step by step which means that SoS wide performance assessment analytics and models may considerably support their operation.

### 6.4 Power of Singular Companies in the Market

The strengths of singular organisations in a manufacturing SoS mainly influences the degree of co-operation in such a network. For buyer market related SoS where a strong OEM controls its supply network and herewith has a very strong position within the SoS, it may appear that e.g. integration and communication standards are not harmonised but strictly defined by this actor. All suppliers have to adapt to the standards of this player if they want to participate which applies also for other enabling technologies like the exchange of product specification data or performance assessment analytics and models. For this reason, the technologies used may likely not support the interests of the overall SoS, but put priority on the existing infrastructures and preferences of the key players in the network which may lead to disadvantages especially for smaller participants like SMEs.

In contrast to that, virtual enterprises are associations of SMEs which decide to co-operate in order to create benefit for all participants, e.g. by jointly strengthening market positions, highly depend on common integration and communication standards which can easily be adopted by each participant. For them it is essential to have well-defined co-operation rules, also including agreements with regard to IP, which consider the needs of all members as the latter will only join when they see the benefit for them. This is also why education of stakeholders may be a key enabler for the establishment of this kind of manufacturing SoS as decision makers have to be aware of the concepts and advantages of SoS before participating.

## 7 SUMMARY

This paper gives an overview on system of systems in the multi-site manufacturing domain. After first defining an SoS in multi-site manufacturing, a vision of multi-site manufacturing SoS has been presented, before describing results of roadmapping activity aimed at identifying potential steps towards this vision. The roadmap has identified trends, drivers and needs for manufacturing SoS, with the most important being cost and lead time reduction, and dealing with increasing complexity and customer requirements. The roadmap has also identified key innovation opportunities and enablers, including common integration and communication standards, service-oriented control system architectures for dynamic reconfiguration, and the education of stakeholders. The enablers and key innovation opportunities have been discussed with regard to their relevance for different business models in the manufacturing industry, including individualised production, mass production, highly automated and manual production execution. From this discussion, it can be extracted that the implementation of the roadmap towards SoS in production, i.e. its key innovation opportunities and enablers, is not sufficient to address the needs identified by the roadmap. It is even more important to consider the overall situation of the manufacturing SoS with regard to its objectives, products and processes in order to really be able to point out appropriate measures from the list of options provided by the roadmap.

## 8 ACKNOWLEDGEMENTS

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# Classification, Modelling and Mapping of Skills in Automated Production Systems

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**Abstract**
The ability to enable a quick modification and system-change is one of the essential requirements of future production systems. The two basic steps to adapt an automated production system to a new task are the reconfiguration and the re-programming. Against this background, the central objective of this paper is the discussion of a concept to simplify the programming. Assuming the use of standard industry devices, there is a lack in the ability to gather the necessary information about the available equipment automatically. Each device allocates its inherent skills through different functions, commands and interfaces. A classification and a method to map the devices' skills to the program of automation systems have been developed to handle and interpret these skills. The concept and its application are described in this paper.

**Keywords:**
Flexible Manufacturing Systems; Vendor-independent Programming; Task-oriented Programming

## 1 INTRODUCTION AND REQUIREMENTS

Enterprises all over the world have to deal with the shortening of product lifecycles and an increasing product variety [1]. To meet these challenges is one key factor to stay competitive in globalized markets. While changes in the manual or hybrid production are achievable with lower invest and effort, they have a high impact on automated production systems [2]. The change process of the technical equipment is still one significant restraint [3] and is concatenated with high financial effort and manpower [4].

The main restraints in the reconfiguration process of an automated production system are the manual effort and the necessary expert knowledge. Examples are the I/O-mapping, the setup of the communication or the vendor-specific programming languages of industrial robots. This paper describes a vendor-independent possibility to access the skills of devices. Today, experts have to interpret the skills of a device and how to address these skills through its functions [5][6]. An example is the control of a gripper with two ports. One port opens or closes the gripper depending on the signal and the other one displays the distance between the gripper jaws. The programming expert has to interpret the skills which are related to the ports and how they are addressed. An abstract description or model of the skills of a device could enable the programming on a higher abstraction level. The concept of the task-oriented or implicit programming, especially for robot systems, is well known in the research community. The main benefit is that the user doesn't have to specify "how" the robot should fulfill a task but "what" task it should perform. The user also doesn't need programming-language knowledge [21]. A requirement for a task-oriented programming system is a model or description of the abilities of the production system. In existing concepts the modelling is done manually and application-specific. Three main aspects have to be considered: What kinds of skills are possible in a production system? How are they modelled? How can they be mapped to the device functions?

An approach to fill the absence of a generally applicable concept is outlined in this paper. The concept is designed for standard devices in automated production systems. After the state of the art concerning the classifications and modelling of skills and functions, the main aspects of the new approach are introduced. It consists of a classification schema and modelling rules for skills as well as possible concepts to map skills and controllable device functions.

Several requirements have to be considered in a generic concept. The classification of skills has to be unambiguous with a description for every skill and expandable for new technologies. It is assumed that not every relevant production skill is represented in an unambiguous skill taxonomy. This problem has to be concerned in the solution for example by a concept to combine skills. A standard device like a gripper could contain several other functions like sensor functions, away from the main function of gripping components. This aspect has to be considered in the allocation of a skill to a device. To achieve a high usability, the classification should be based on engineering standards that are well known and used in the industry. The modelling rule of skills has to offer abstraction levels that are suitable for all possible skills. The main requirement is the possibility to map the control functions or interfaces to the abstract skills in order to create application-programs by using the skills. The modelling rule must also facilitate an automatic mapping of skills to device functions. The expansion of the skill model for complex device interfaces, for instance for the image processing of a camera system, is another requirement.

## 2 STATE OF THE ART

Along the steps of the configuration sequence of an automated production system several approaches as well as available and required information could be allocated. In the following chapter the possible information and approaches are analyzed and described. Figure 1 illustrates the according main steps [7].

In the first step, the physical stage, the physical connection of the production system is established. Therefore knowledge about the physical interfaces, that is mostly not relevant for the scope of the paper, is necessary.

Device profiles like EDDL [8] or XIRP [9] define communication interfaces and could be allocated to the second step, the communication stage. According to [10], the functionality of a device could be deduced from the interface but this is not an explicit part of the

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device profiles. A concept of a functional model of automated devices and their communication objects is described in [11]. Devices are combined to device classes on a meta-layer that offer defined functions. This mental model is transferred into a logic model using a formularization. Functions are separated in the meta-profiles applicable and administration. The concept is based on existing device profiles and allows a functional view on devices. It didn't contain a concept to classify the generic skills or functions of a device that could be allocated to the production process.

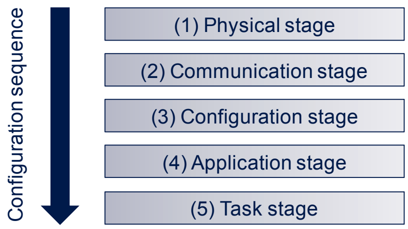



Figure 1: Steps in the configuration sequence (Own figure based on [7]).

A different approach for the topic is presented by [12]. He describes a concept to enable Plug & Produce for robotic systems. The approach is focused on the communication, configuration and application stage. A method to automate the setup of the communication and configuration is the main part of the concept. This is enabled by a state model that represents the current configuration using a driver-based concept to handle different device descriptions. The state model also contains information like CAD-data and kinematics. The programming of an industrial robot is supported by providing programming-commands for the vendor-specific robot control and automatic setup of offline-programming tools.

Several approaches that could mainly be allocated to the application and task stage are given below. As described, [5] states that the programming expert has to interpret the skills of a device and how to address them through communication interfaces. Therefore an approach to describe skills of a device had been developed in the SIARAS project. Skills are modelled through state graphs, but modelling rules are not defined. Existing engineering standards are proposed for a classification of skills, while their usage stays unexplained. Within the EU-projects SMErobot™ and ROSETTA skills a modelled in a similar way but they are not described in detail [10][13]. The main goals were the development of a modular Plug & Produce concept for robot systems and the automatic generation of robot applications by a knowledge integrated framework. Within the finished SFB 562 a skill-primitive- based approach had been defined to reduce the human interaction with the programming system or even automate the whole programming process [14]. The skill primitives are designed by experts and represent the elementary skills which are necessary to apply a defined robotic production sequence and are not allocated to a device.

The programming of assembly tasks by using skill levels is shown in [15]. The state space of a task is described by four levels: Control primitive level, control skill level, skill level and task level. The lowest level is defined by the sensor state concerning a task object. The higher levels are built by combining the lower levels. The task level represents the target state of the objects. The control primitives and skills are not designed to map them with devices and their controllable functions.

The usage of skills to link the manufacturing process and the manufacturing equipment is delineated in [6]. Emergent behaviour and skills are deemed as one main enabler of future production systems. The modelling of skills is not focus of the concept.

In summary it can be stated, that there is no concept to achieve an unambiguous mapping and modelling of skills to a certain device. Possible skills in production systems had not been defined in the past. There is also no concept to assign a generic skill to the communication objects or controllable function of a device. A concept to solve this issue is outlined in the following chapters.

## 3 APPROACH

### 3.1 Definitions

In order to achieve a clear understanding about terms used in this paper, short definitions will be given.

Skill: A skill is the ability to perform an activity or operation that is necessary to support the production process [16], for example welding on a fixed point. Two or more lower skills can be combined to complex skills if it is required for the production process, for example welding along an outline that could be combined by welding on a fixed point and moving the welding tool.

Function: A function is the communication object or interface of a device. Depending on the type, a write or read access to the function is possible. It could be used in order to control the device or to gather information from the device. An example is a welding tool, whose voltage or wire speed can be controlled through a software interface.

### 3.2 Classification and Modelling of Skills

In the first part of this chapter the classification of skills is explained. In the second part the use of this classification to model skills is outlined.

As described, a skill is defined as the ability to perform a production process. Therefore, engineering standards like [17][18] and related ones, that describe processes in production systems, are a suitable way to classify skills. In a first step their content was analyzed for redundancies. An example is the skill “insert” [19], which also could be described as a combination of the handling skills “retain” and “position” [18]. For a general skill concept, these redundancies have to be resolved. Otherwise the mapping might not be possible, especially if a device covers only a part of a process in the engineering standards. These overlaps were identified by comparing the processes respectively the required skills in the standards. The overlaps mostly concern the movement which is integrated in other process descriptions. An unambiguous list of elementary skills was developed based on the result of this analyzes. To achieve an easy extension for new skills, the skill list was clustered and overall skills were defined according to the engineering standards. The skills are arranged in a tree structure with different hierarchical levels. The tree structure is called unique skill structure (USS) in the following. This means, lower skills are a sort of higher skills. These higher skills are not used for the mapping, but they ease the search of suitable skills. Besides the skills that are directly accountable for a productions process, skills that have an indirect influence also have to be considered. For instance a robot “can attach” a gripper and a gripper “can be attached”. Thus direct and indirect skills are distinguished on the highest layer. The classification of direct skills is the focus of this paper. Other indirect skills are necessary for the communication and coordination between controls, the initialization and error-handling of devices. These control-specific skills are not a focus of the classification in this paper. A way to integrate these functions in device profiles and to delineate a functional classification is described in [11]. This approach is proposed to provide these functions in a programming system. A combination of this approach with the method presented in this paper is one aim for research activities in the near future. A small part of the USS is shown in Figure 3. For each skill in the USS, explicit definitions were developed. They are based on the mentioned engineering standards. The mapping of a skill to a certain device is only possible using this description.

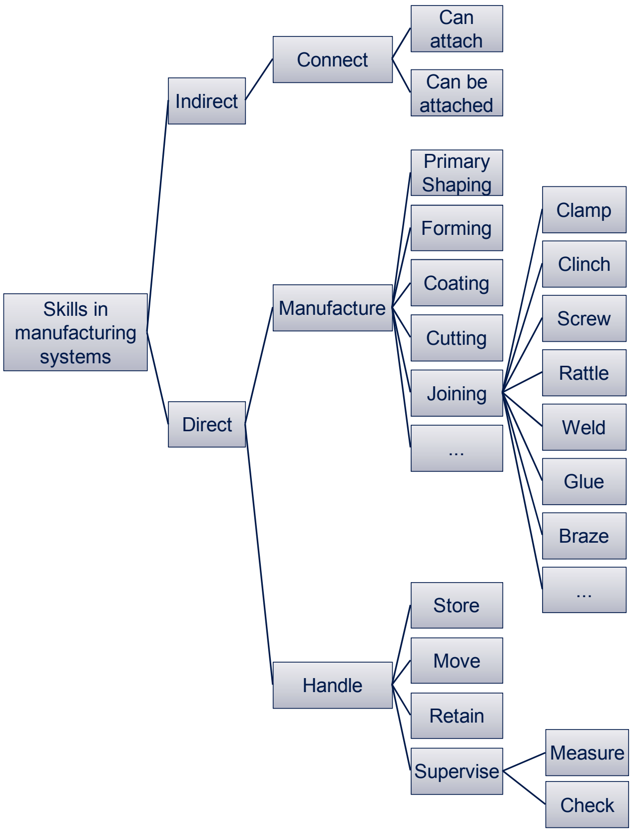



Figure 2: Excerpt of unique skills in production systems.

To cover all possible processes in a production system, also a complex skill structure (CSS) can be built. In this structure, complex skills are defined that consist of two or more skills in the USS. The CSS therefore has references to skills in the USS and can be extended by using these skills. The CSS is not used for a direct mapping of a certain skill to a single device. It is linked indirectly using its references by mapping a skill in the USS.

Some notes considering this concept are described in the following. At first, the possible skills of devices are limited to the skills that the device was designed for. For example a gripper could also be used to press one part in another by pushing with one jaw. It is assumed that these skills are not relevant for the production process. Devices are not designed for this use and damages may occur. It is not specified when such damage could occur. Apart from that, a programming expert wouldn't use such "skills" of a device.

The number of skills in the USS of a device is not limited. With this approach also high integrated devices could be represented. Additional sensor functions such as force-measuring of a gripper can be represented this way. This is an advantage in comparison with a class based concept that is used for example in AutomationML [20].

Existing concepts had been analyzed for the modelling of skills [5][6][10][11][16]. What attracts attention is the absence of precise modelling rules in these approaches. The state graph was chosen to model skills in this paper. At first, the states of each skill and a rule how they can be identified for new skills have to be defined. States are defined as the "action state" of a device that represents a process. To give an example, "welding" is the action state of a welding torch. The initial state of each device is the opposite of the action state. It is defined as "idle" state for most skills but for the skill "retain" it is differed in fix and release. The transitions between all states have to be mapped to the device functions. Therefore, the device function could be seen as triggers of the transitions. For the "action" and the "idle" state, one or more transitions that refer back to the "action" or "idle" state are optional. An example for a device function that changes the "action" state but doesn't trigger the transition from "idle" to "action" is the velocity in a movement. It is not possible to use them for every device, only if there is a device function to identify the transition to these states.

If there is no device function that triggers the transition from "action" to "idle", transitions without triggers are possible. For instance a clinching device accomplishes only one clinching operation after its allocation. In this case, the transition back to the "idle" state is triggered automatically after completion of the clinching process.

Figure 3 illustrates the modelling rules for the skill "weld". Only the two transitions $t_1$ and $t_2$ from the "Idle" state to the action state "Weld" and back are mandatory. The transition $t_n$ and $t_m$ are additional and not necessary for each device but could exist several times.

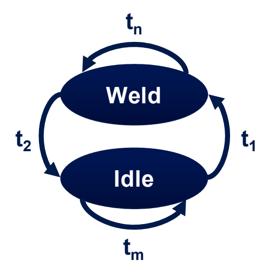



Figure 3: State graph of the skill "weld".

For each skill characteristics have to be defined. The main aspect is the operating range or point of a skill that is given relative to the device coordinate system. Other characteristics are the range of values for functions or the offset vector if the device can be attached. The characteristics also have to be mapped to the real device values.

The use of the presented classification and the modelling rules, to represent a device on an abstract level, is outlined in the following chapter.

### 3.3 Mapping of Skills

Up to this point, this paper gives a method to classify and model skills. By the use of this method, a database of known skills is build up. The next step has to be the mapping of these known skills to the functions of the installed devices. To give a simple example: the skill "retain" must be linked to the device "gripper". Two different approaches are conceivable: to map the skills manually, or (semi-)automatically. But before the mapping itself, the installed devices have to be recognized. This is not treated in this paper. Instead, other approaches, like an automatic configuration of robotic systems via Plug & Produce could be used to obtain the necessary information [12]. After the recognition of an undefined skill, as much information as possible has to be gathered about the device and its functions. These include, but are not limited to, interface-descriptions, device-specific driver, manuals, applications notes, data sheets and CAD-models.

Afterwards, the mapping takes place. In the first case, if the assignment is done manually, the implied knowledge of the human is used. The already existing hierarchic structure of known skills (graphically represented) as well as the collected information about the device will be helpful for choosing the according skill. A possible use case is that an integrator implements the mapping for all typical used devices in his application field by building up drivers. For the design and programming of a new system, no additional effort will be necessary. Another use case is that the device supplier distributes every device with its mapping.

In the second case, the assignment is done (semi-)automatically. The first step here is to bring the gathered information into a proper data format for the search-algorithm. Then the algorithm tries to match the already known skills, which are classified within a hierarchic structure, with the device-skills. Criteria to find the belonging skill can be a description in the manual, the name, ranges and units of the in- and outputs, the CAD-data and many more. Until now, the reliability of the automatic mapping was not evaluated. Because of that, the algorithm only provides a proposal. The human user has to check and eventually adjust the result.

Mapping in the presented method implies not only the skills, but also the functions, to give an idea of the difference, the following example is given in Figure 4: A gripper-device, which is able to perform the skill "retain", has to provide the interfaces or functions "close gripper" and "open gripper" (compare Gripper 1 in Figure 4 a.). Such interface or function can be a simple binary input/output (compare Gripper in Figure 4 a.), a function call (compare Gripper 2 in Figure 4 a.) or even a sequence of signals. After identifying the skills (compare Figure 4 b.) and functions of a device, every function has to be mapped to a trigger for a transition of the skill-according state-graph (compare Figure 4 c.). The specific function of the device remains unseen and the abilities of the device could be used on a higher abstraction level for example by combining several state transitions to a production process.

To enable task-oriented programming, the overall system can use the complex skills in the CSS that are linked to the unique skills. A higher skill for example could be "force-controlled gripping", if a gripper is able measure the force, which is applied to an object while closing the gripper-jaws. In this example, the device "gripper" has two linked skills, "retain" and "measure force", like Gripper 2 shown in Figure 4 b.

## 4 APPLICATION

In this chapter the usage of the described classification and modelling rules are outlined.

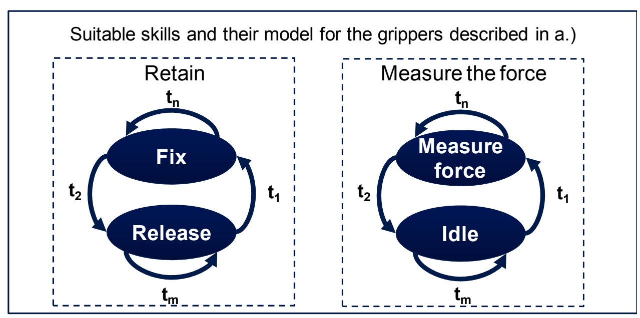
Task-oriented programming systems are a frequently addressed topic in the research fields of production and robotics. In the last years, a variety of such programming methods was introduced, often specialized to handle a specific process much easier. All these systems need a model of the equipment and its environment, which includes the according skills, to work properly. Almost every time this model has to be built by experts and because of its complexity, requires a significant amount of time. Due to this, the advantages of task-oriented programming, lower setup time and reduced necessary expert knowledge, is negated by the effort to model the production system and its environment. The introduced method could overcome this issue by enabling the (semi-)automatic generation of the required models especially when combining it with the automatic generation of the state model [12]. With the state graphs of skills in production system and the CSS, the method offers an easy way to enable the link from abstract task descriptions to device functions.

Another aspect of the approach is the possibility to build vendor-independent programming systems, because the user only accesses the skill, not the device itself. Replacing a gripper by a device of a different manufacturer doesn't have to result in a change of the application-program anymore. This saves time for integrating new devices in the case of a malfunction. At the same time, the consumer – looking for a replacement of a broken piece of equipment – can choose and compare by means of features and quality, instead of being bound to one manufacturer because the present production system supports only a proprietary interface.

**a. Two different types of grippers**

| Gripper 1 | Gripper 2 |
|---|---|
| **Description:**<br>Gripper 1 is a standard pneumatic 2-finger parallel gripper | **Description:**<br>Gripper 2 is a pneumatic 2-finger gripper with a sensor to measure the force between the jaws |
| **Interface for functions and meaning:**<br>• Input 1 == true<br>→ *open gripper jaws*<br>• Input 1 == false<br>→ *close gripper jaws* | **Interface for Functions and meaning:**<br>• command_release() {<br>communication_channel_open(2)<br>send('open gripper')<br>communication_channel_close(2)}<br>→ *open gripper jaws*<br>• command_fix() {<br>communication_channel_open(2)<br>send('close gripper')<br>communication_channel_close(2)}<br>→ *close gripper jaws*<br>• get_force() {<br>communication_channel_open(2)<br>send('measure force')<br>force = read()<br>communication_channel_close(2)<br>return force}<br>→ *measure the force between the gripper jaws* |

**b. Skills**




**c. Mapping of gripper functions and skills**

| Mapping Gripper 1: | Mapping Gripper 2: |
|---|---|
| **skill "Retain":**<br>$t_1$ = (Input 1 == true)<br>$t_2$ = (Input 2 == false)<br>$t_n$ = inexistent<br>$t_m$ = inexistent<br>**skill "Measure force":**<br>Not supported by Gripper 1 | **skill "Retain":**<br>$t_1$ = command_fix()<br>$t_2$ = command_release()<br>$t_n$ = inexistent<br>$t_m$ = inexistent<br>**skill "Measure force":**<br>$t_1$ = get_force()<br>$t_2$ = no trigger<br>$t_n$ = inexistent<br>$t_m$ = inexistent |

Figure 4: Mapping of skills for two different grippers.

## 5 SUMMARY AND OUTLOCK

A classification and a method to map skills in production processes were outlined in this paper. Modelling rules for defining skills based on existing engineering standards were defined. This approach was designed to be an enabler for task-oriented programming as well as vendor-independent and accelerated set-up of production systems.

Building rules for complex skills and rules to combine unique skills for a device will be the next step. Afterwards the automated mapping will be optimization. In addition, the method will be evaluated on various applications which include different device classes. A demonstrator scenario, consisting of several industrial robots and other automation equipment, is build up at the moment.

## 6 ACKNOWLEDGMENT

The authors of this paper would like to thank the German Federal Ministry of Education and Research (BMBF) and the Project Management Agency Research Center Karlsruhe (PTKA-PFT) (Funding code 02PR2081) as well as the German Research Foundation (DFG) (Project “Automatic Configuration of Industrial Robots using State Models”) for the sponsoring.

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# Transient Analysis of a Re-entrant Manufacturing System

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**Abstract**

Transient and dynamic analysis of manufacturing systems is becoming important especially during ramp-up periods and for systems with frequent changeovers. In this paper, the transient and dynamic behavior of a simple re-entrant manufacturing system is studied. The behavior of the system is analyzed for six different cases with different relationships between the operations' processing times. The parameters included in the study are the operations' processing times and the number of pallets in the system. The analysis identifies cases where complex behavior takes place as well as the parameter values controlling that behavior.

**Keywords:**

Modeling Manufacturing Systems; Transient Analysis; Re-entrant system

## 1 INTRODUCTION

Most of the analytical tools used in the analysis of manufacturing systems such as Markov chains and queuing theory deal with the steady state behavior of the system, and the analysis of their transient behavior is almost non-existent in the literature [1]. In manufacturing systems and specifically manufacturing lines, transients occur during the ramp-up stage after the installation of the system and until the system reaches a steady state. In today's market under the influence of globalization, manufacturers are in constant competition over market share. This competition has forced manufacturers to introduce new products more frequently and thus line changeovers take place more often. Consequently, the production ramp-up period is occurring more frequently and is occupying increasingly longer time. Therefore, efficient management of the ramp-up period is becoming important, and this cannot happen without proper understanding of the dynamics of the manufacturing systems during the transient state.

Managing the ramp-up period efficiently requires analyzing the transient behavior with the objective of answering questions such as: when does the system reach steady state? , which parameters affect the transient behavior? , and can these parameters be changed to decrease the transient behavior? Although discrete event simulation (DES) can answer some of these questions, such as when does the system reach steady state, it does not give any insight into the dynamics of the system unless hundreds of simulations are conducted and the results analyzed, a process which is tedious, time consuming, and inefficient.

In this paper the dynamic behavior of a simple re-entrant manufacturing system is analyzed to gain insight into the transient and steady state behavior. The system under investigation consists of two machines that perform three processing steps. This system can represent a simple semiconductor manufacturing facility [2] and can also represent a storage retrieval manufacturing system [3].

The investigated system is assumed to be completely deterministic and reliable. The first assumption is acceptable if the line is fully or semi-automated with synchronized line motion. The second assumption is also acceptable given a small period of observation. The parameters taken into consideration are the processing time of the three processes and the number of products allowed in the system (number of pallets). The transient analysis of the system shows the effects of these parameters on the behavior of the system prior to steady state, and gives insight on how to minimize the transients period. Discrete event simulations on FlexSim [4] are used to verify the results.

The organization of the rest of the paper is as follows. Section 2 presents literature review. Section 3 presents the system under investigation and the different cases of operation. Section 4 presents the analysis of the system and section 5 derives the conclusions and future work.

## 2 LITERATURE REVIEW

A re-entrant manufacturing line is a manufacturing flow line where products visit all or some parts of the line more than once before exiting the system. Re-entrant manufacturing lines are most widely used in semiconductor manufacturing, where finished products are composed of several layers. Since all layers require similar operations, the wafer is circulated in the manufacturing line more than once [5] [6] [7].

Even the simplest re-entrant manufacturing systems can show very complex behavior. This complex behavior motivated many researchers to compare them to chaotic dynamic systems [7-9].

The simple re-entrant model used in this paper was studied in [2]. The paper concluded that the steady state behavior is always periodic and that chaos cannot exist in this system. However, only the steady state behavior was analyzed, and the focus was on proving the periodicity of the behavior.

ElMaraghy and Manns [10] presented a synchronization methodology that limits the number of different inter-arrival times of a re-entrant manufacturing system and controls the length of inter-arrival time periods. By doing so the predictability of the system's states increases and the unanticipated states that can lead to system failures is eliminated. In a later publication Manns and ElMaraghy [11] presented an analytical approach to model the inter-arrival time behavior of a re-entrant system. They employed a

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queueing-situational decomposition that helps the manufacturing system designer avoid the resulting decrease in capacity and reliability due to increased system complexity and unpredictability.

## 3 MODEL

The model under investigation, Figure 1, consists of two machines, A and B, performing three processes. Processes one and three are performed on machine A while process two is performed on machine B. Each process has a dedicated queue which for simplicity is assumed to have infinite capacity. The sequence of the processes is fixed, so each product will have to visit machine A, then machine B, then machine A one more time.

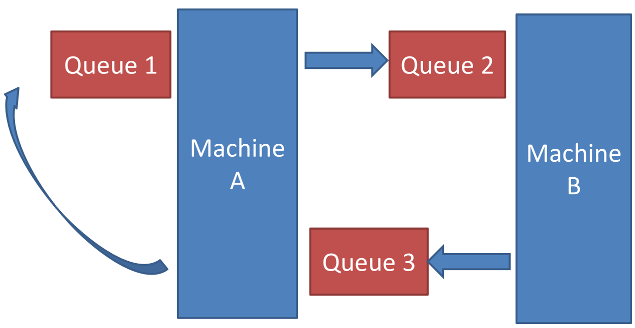



Figure 1: A Simple Re-entrant Manufacturing System.

In the case of having products waiting in queues 1 and 3 at the same time, priority is always given to queue 3. This policy can be regarded as a SERPT (shortest expected remaining processing time) or a LBFC (last buffer first serve) policy. This policy provides the least cycle-time for the system [5].

If the processing times for processes 1, 2 and 3 are T1, T2 and T3 respectively, then the system can have one of six distinctive cases of operation. The six cases are:

a) $T3 < T2 < T1$

b) $T2 < T3 < T1$

c) $T2 < T1 < T3$

d) $T1 < T2 < T3$

e) $T3 < T1 < T2$

f) $T1 < T3 < T2$

The cases where processing times are equal are included in these six cases and will be highlighted within each case.

Without loss of generality, the system is assumed to be palletized with the number of pallets circulating the system equal to N, where N is greater than or equal to two. This assumption makes it easier to regard the system as circulating pallets rather than different products entering and exiting the system. It should be understood that with every process 1 a new product or work piece is mounted on the pallet and by the end of every process 3 the finished product or work piece is un-mounted.

In-coming jobs are assumed to be always available and waiting to be mounted on pallets in queue 1. Travelling time between queues and machines is also assumed to be negligible/zero.

The behavior of the system is measured by the arrival time of the first finished product $\tau 1$ and the inter-arrival time of finished products $\tau n$, where $\tau n$ is equal to the time between the arrival of finished product number $n$ and finished product number $n-1$.

In the next section, these cases are analyzed to show their transient and steady state behavior.

## 4 SYSTEM ANALYSIS

In each case of the above mentioned cases, the behavior of the system is analyzed to show the effect of the processing times and the number of pallets on the system.

The system is assumed to always start with machine A starting process number one while machine B is idle. The number of products in the system (N) is assumed to be greater than or equal to two.

### 4.1 $T3 < T2 < T1$

Since T2 is less than T1, the first pallet in the system will always complete the second process and wait in queue 3 before the second pallet ends the first process. Given that queue 3 has a higher priority than queue1, the system will never have more than two pallets circulating the system at the same time.

Accordingly, the system will go to steady state right after the arrival of the first finished product. The system inter-arrival time of finished products in this case can be described by equation (1). Figure 2 shows the inter-arrival time of finished products for T1=15, T3=10, and 10<T2<15.

$$\tau n = \begin{cases} 2 * T1 + T3\, , n = 1 \\ T1 + T3\, , n > 1 \end{cases} \quad (1)$$

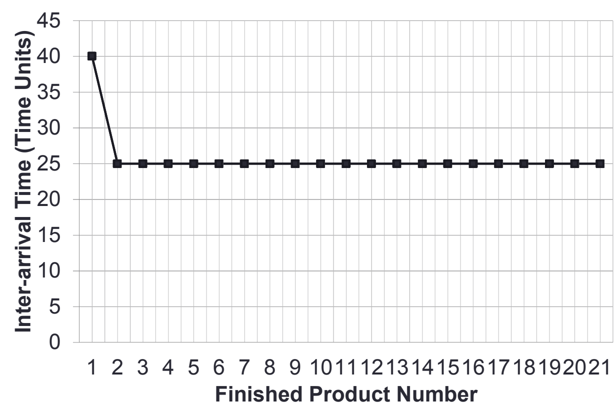



Figure 2: System Response for T1=15, T3=10 and T3<T2<T1.

Because process 3 has higher priority than process 2, the case of $T3 < T2 = T1$ will produce the same results and thus should be included in this case.

### 4.2 $T2 < T3 < T1$

As in the previous case, because T1 is greater than T2, the first pallet will complete process 2 and wait in queue 3 for the second pallet to finish process 1. Consequently process 3 on the first pallet and process 2 on the second pallet will always start at the same time, and since T3 is greater than T2, the first pallet will finish process 3 and start process 1 before the second pallet completes process 2. Therefor also in this case, a maximum of only two pallets can be circulating the system at any point in time.

The system goes into steady state right after the arrival of the first finished product, however; the steady state is not a constant inter-arrival time. At steady state, the inter-arrival time of finished products is periodic and reciprocates between the two values ($T3$) and ($2 * T1 + T3$). The inter-arrival time in this case is described in equation (2).

$$\tau n = \begin{cases} T3 \text{ , n is even} \\ 2 * T1 + T3 \text{ , n is odd} \end{cases} \quad (2)$$

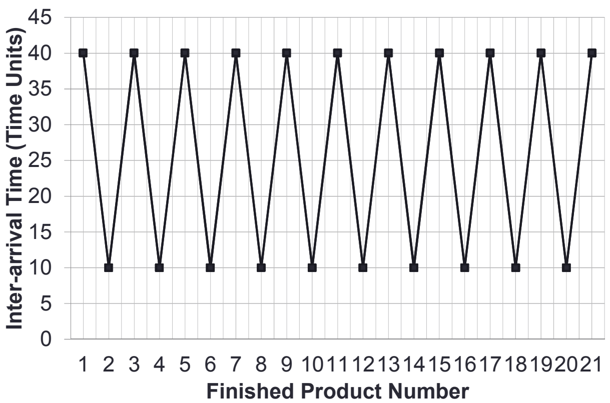



Figure 3: System response for T1=15, T3=10, and T2<T3.

Figure 3 shows the system response for T1=15, T3=10, and T2<T3.

Included in this case are the cases: $T2 < T3 = T1$, $T2 = T3 < T1$, and $T1 = T3 = T2$.

### 4.3 T2 $< T1 < T3$

In this case, the behavior is exactly the same as the previous case. The reason is that the behavior is affected by the relation between T1 and T2 and between T3 and T2, and both relations are the same in this case and the previous one. The only difference is the relation between T1 and T3 and it does not affect the behavior.

The inter-arrival time in this case is can be described also by equation 2.

### 4.4 T1 $< T2 < T3$

This case differs significantly from the three previous cases because T2 is greater than T1. This property means that while the first pallet is on machine B for performing process 2, machine A completes process one for the second pallet and starts processing a new pallet with process 1. In this case a new variable is required to describe the behavior of the system. Let $k = \frac{T2}{T1}\Big|$ where the single right bracket means rounding up to the nearest integer. For example if T2 equals 7 and T1 equals 6, then $\frac{T2}{T1} = 1.16$ and $k$ is equal to 2.

As incoming jobs at queue 1 are always available, machine A will keep performing process 1 for new jobs until a job is ready at queue 3. Thus machine A will have to process $(k + 1)$ jobs with process 1 before starting process 3 on the first pallet. Since T3 is greater than T2 and process 3 has higher priority than process 1, then machine A will keep performing process 3 for the $n$ following pallets. When machine A is done performing process 3 for the $k + 1$'th pallet, the system is completely empty and returns to the same starting state. Thus the behavior of the system in this case is periodic with a period of $k + 1$ according to equation 3.

$$\tau n = \begin{cases} (k+1)T1 + T3 \text{ , } n = 1 + i(k+1);\ i = 0,1,2,. \\ T3 \text{ , otherwise} \end{cases} \quad (3)$$

Figure 4 shows the system response for T1=7, T2=55, and T3=150, for which $k$ is equal to 8. It can be seen from the figure that the response is periodic with a period of 9 arrivals. The average cycle time in this case can be calculated as in equation (4) which can be simplified to equation (5).

$$Ct = \frac{(k+1)*T1+T3+k*T3}{k+1} \quad (4)$$

$$Ct = T1 + T3 \quad (5)$$

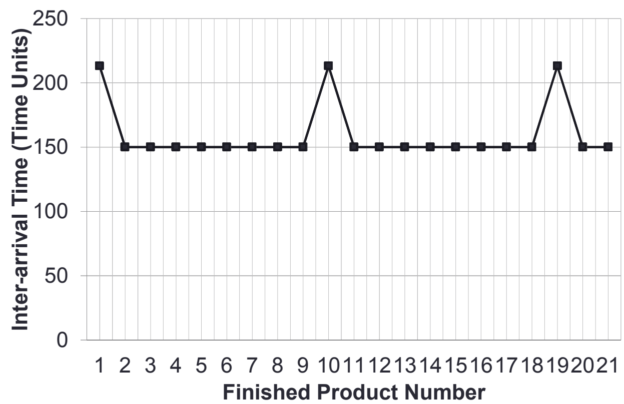



Figure 4: System Response for T1=7, T2=55, and T3=150.

It should be noted that having $k + 1$ pallets yields the optimum throughput. If fewer pallets are used the behavior of the system is different and the throughput is less. Let $p + 1$ be the number of pallets in the system and let $p < k$. The behavior of the system is still periodic but with period $p$ and the behavior of the system is described by equation (6). In that case, the average cycle time is described by equation (7).

$$\tau n = \begin{cases} T1 + T2 + T3 \text{ , } n = 1 + i(p);\ i = 0,1,2, \dots \\ T3 \text{ , otherwise} \end{cases} \quad (6)$$

The average cycle time in this case is equal to:

$$Ct = \frac{T1+T2+T3+(p-1)*T3}{p} = \frac{T1+T2+p*T3}{p} \quad (7)$$

Since $p < k$, $T2$ can be replaced by $(p * T1) + \delta$ where $\delta$ is equal to $T2 - (p * T1)$. Accordingly, average cycle time can be described by equation (8).

$$Ct = \frac{p*(T1+T3)+\delta}{p} = T1 + T3 + \frac{\delta}{p} \quad (8)$$

Therefore, given a fixed T2 and T1, the fewer the number of pallets used the larger the average cycle time and less throughput of the system. Included in this case is the case $T1 < T2 = T3$.

### 4.5 T3 $< T1 < T2$

This case should be subcategorized into two different cases according to whether T2 is greater than the summation of T1 and T3 or not. In the first case, the bottle-neck is machine B, while in the second it is machine A.

#### 4.5.1 $T1 + T3 < T2$

In this case, using only two pallets yields the optimum cycle time which is T2 (excluding the first cycle). The inter-arrival time in this case is according to equation (9).

$$\tau n = \begin{cases} T1 + T2 + T3\,, n = 1 \\ T2\,, n > 1 \end{cases} \tag{9}$$

If more pallets are used, the behavior will again depend on the factor k. If number of pallets (N) is less than or equal to k, the behavior is exactly the same as above and at steady state, queue 2 will always have N-2 pallets waiting.

If N is equal to k+1 then the inter-arrival time is described by equation (10) and queue 2 will keep holding N-2 pallets at steady state. It should be noted that in the previous two cases the average cycle time and throughput are exactly the same, because the extra delay in the first finished product is deducted from the inter-arrival time of the second finished product.

$$\tau n = \begin{cases} (k+1) * T1 + T3\,, n = 1 \\ 2 * T2 - k * T1, n = 2 \\ T2\,, n > 2 \end{cases} \tag{10}$$

#### 4.5.2 $T2 < T1 + T3$

In this case, machine A is the bottle-neck, however; if only two pallets are used, machine A is idle for a period of time equal to T2-T1 in the first cycle of running the system. Also since T2>T1>T3, the variable k will always be equal to two and thus the optimum number of pallets for the system is three. Using more pallets will mean extra pallets waiting at queue 1 at all times.

The behavior of the system in this case can be one of two according to the value of the quantity 3*T2-2*(T1+T3). If this value is less than or equal to zero, the behavior is periodic with period three as in figure 5 according to equation (11).

$$\tau n = \begin{cases} 3 * T1 + T3\,, n = 1 + i * 3, i = 0,1,2, \ldots \\ T3, \ \ otherwise \end{cases} \tag{11}$$

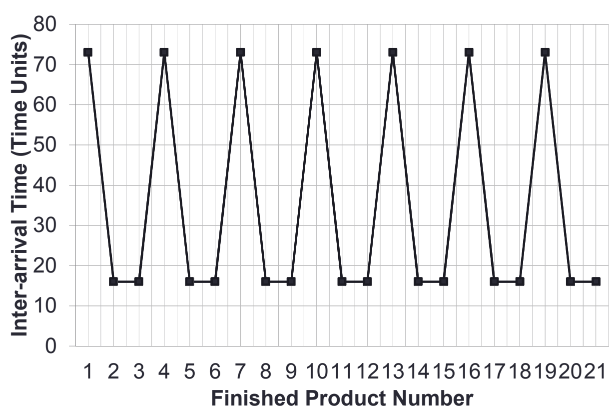



Figure 5: System response for T1= 19, T2= 22, and T3=16.

If the value of the quantity 3*T2-2*(T1+T3) is larger than zero, then the system will go to a steady state with a constant inter-arrival rate equal to T1+T3 after some transients. In this case the inter-arrival time is described by equation (12), where P is a constant that depends on the values of T1, T2 and T3 according to Table 1.

$$\tau n = \begin{cases} 3 * T1 + T3\,, n = 1 \\ T3, n = P, P > 1 \\ T1 + T3, \ \ otherwise \end{cases} \tag{12}$$

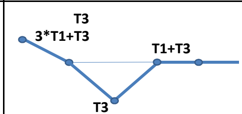
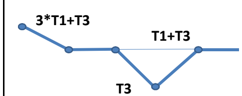
| Condition | P | Inter-arrival behavior |
|---|---|---|
| $T3 \geq 2(T2 - T1)$ | 2 |   |
| $2(T2 - T1) > T3 \geq \frac{3}{2}(T2 - T1)$ | 3 |   |
| $\frac{3}{2}(\mathrm{T2} - \mathrm{T1}) > T3 \geq \frac{4}{3}(\mathrm{T2} - \mathrm{T1})$ | 4 |   |
| ⋮ | ⋮ | ⋮ |

Table 1: Conditions and Inter-arrival behavior for different P values.

#### 4.5.3 $T2 = T1 + T3$

In this case, two pallets would be enough to have the system working at 100% utilization. In this case the system equations are:

$$\tau n = \begin{cases} T1 + T2 + T3\,, n = 1 \\ T1 + T3\,, n > 1 \end{cases} \tag{13}$$

If more than two pallets are used, the equations will differ slightly to become:

$$\tau n = \begin{cases} 3 * T1 + T3\,, n = 1 \\ T1 + T3\,, n > 1 \end{cases} \tag{14}$$

This means that the first finished product is delayed by $3 * T1 - T2$ time units; however an extra pallet is circulating the system, thus increasing its reliability. The case of $T3 = T1 < T2$ is also included in this case.

### 4.6 T1<T3<T2

The behavior in this case is similar to the behavior in case g.

When T2 is greater than T1+T3, the behavior is exactly the same as in case g. However, when T1+T3 is greater than T2, there are some differences.

The main difference is that for optimum throughput, the number of pallets used should be equal to k+1. When k+1 pallets are used, the average cycle time is always equal to T1+T3; however, the steady state inter-arrival time can settle to a constant value (T1+T3) or maintain a periodic behavior.

## 5 CONCLUSIONS

This paper illustrated how the behavior of even a simple re-entrant manufacturing line can change significantly depending on the value of its parameters. Without analysis and understanding of the system dynamics, managing such systems would be very difficult, as small changes to any of the system parameters (number of pallets or processing times of any of the processes) can change the inter-arrival rate from constant to periodic or change the transient period. Experimenting with the physical system or even with simulation would require a long time and might not lead to the optimum performance.

The importance of understanding the behavior of the system increases drastically when the system under investigation is a part of a larger system. In that case, the output of one system is an input to another, thus, any transients, periodicity, or irregularity will propagate through more than one system and its negative effects will increase.

In future work, the analysis presented in this paper will be put into more formal algorithmic methods so that it can be used for different and more complex systems.

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# Role of Reconfigurable Manufacturing Systems in Minimizing Import Dependency in the South African Press Tool Enterprise

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**Abstract**
The global competition in today's manufacturing industry is forcing enterprises to continuously strive for higher operational efficiency and responsiveness to customer demands in an expeditious manner. The press tool industry is facing challenges ranging from inflexible manufacturing systems to ageing technology. Furthermore, having inflexible manufacturing systems and ageing technology allow industries to struggle to compete globally and locally, which leads some of industry retrenching employees and liquidation. South African Press tool industries have a role to play in addressing social challenges such as high unemployment and how to develop ways to create more jobs. For purposes of this study, the reconfigurable manufacturing systems (RMS) principles with the emphasis on reconfigurability are applied in the press tool industry to revamp manufacturing responsiveness towards customer demands. A structured questionnaire, administered by mail was used to collect primary data for the study. The data was analyzed using the Microsoft Excel package. The results of this research indicate that high priority areas that need attention were manufacturing system and business functions that are failing to meet various customer needs and demands. A proposed model has been created to address the high priority areas. Further studies will focus on the RMS performance evaluation within South African Press tool industry.

**Keywords:**
Reconfigurable Manufacturing System; Press tool; Manufacturing Enterprise

## 1 INTRODUCTION

According to Koren and Shpitalni [1], they indicated that manufacturing companies in the 21st century face increasingly frequent and unpredictable market changes driven by global competition, including the rapid introduction of new products and constantly varying product demand. They highlighted the fact that in order for the companies to remain competitive, the companies must design manufacturing systems that not only produce high quality products at low cost, but also allow for rapid response to market changes and consumer needs. The South African Press Tool Manufacturing Industry (PTMI) is not different to those companies that have faced challenges, the industry has experienced a steady decline and lost its global competitiveness in the same sector for the past 10 years. Press tools are widely used across the globe to produce many different kinds of products in various industries. Press technologies have evolved over the years, varying from very big complex machines to simple tools that perform basic press functions. Also, the functions of these machines have diversified, enabling these technologies to also be applied in modern manufacturing.

Press works in many sheet metal industries has been most dominant class of functions in the small medium enterprise involved in the manufacturing. However, comparing PTMI functions in South Africa is no different to other countries in the globe, and governments involvement is needed to promote competitiveness among industries. In his address at the President conference on small business, President Mandela cited the following two reasons for the Small Medium Enterprises (SMEs) in the South African framework: the development of the SMEs is important for the social and economic development of the country ,They increase competiveness and mobilize idle funds to productive aims and the stimulation of the SMEs can reduce the level of unemployment [2]. This crucial sector is central to the creation and retention of skillful jobs and a good standard of living for working families. As a sector, Press tool manufacturing enterprises are especially valuable to the economy because, when they export goods, they bring back to their communities much of the wealth earned from sales around the country and the world.

The PTMI in Gauteng Province, South Africa, which is the economic hub of activity providing thousands of job opportunities, has fallen prey to globalization and international competition. According to the South African Revenue Authority, it was highlighted that South African PTMI are importing machines from Asian which is contributing to low employement [3]. It further showed that from 2005 until 2012, South African users and sellers have imported 24544 machines for Press tool industries.

South Africa PTMI used to be very competitive in the area of manufacturing of some of the technology. Several companies used to manufacture press machines for the domestic and the global market. Due to a fast growing economy of developing BRICS countries (Brazil, Russia, India, China, South Africa) of which South Africa is part, meeting customer demand and product diversity has been the competitive edge for many industries. The industry is exposed to increasing competition from a large number of low labour cost countries, especially from Asia. Historically, the industry has been focused on domestic trading market conditions and is therefore extremely sensitive to globalization and changing business patterns. According to Corbett in his study concluded that in New Zealand, as well as in many other developed countries around the world, the manufacturing sector is under pressure from the rise of low labour-cost manufacturing output in China and other Asian countries, which had led to forecasts saying that half the world manufacturing exports may soon come from the developing world [4].

The changeable characteristics of RMS technology enables the reduction of complexity in the enterprise (due to low changeover times) and increases the ability to customize and individualize products to both customers and consumers. Through the RMS concept, PTMI will be able to reduce lead time, increase capacity, responsiveness and deliver customized demands to customers.

For South African PTMI to handle challenges, they ought to revolutionalize manufacturing systems setup, it is necessary to

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rethink how to innovate their manufacturing systems. Based on the results and literature survey, further studies should be conducted on evaluating RMS performance within South African.

## 2 LITERATURE REVIEW

Masson and Weston [5], stated that understanding the current market position, allows a series of short and medium term milestones to be set in order to realise the long term ambition of manufacturing enterprises. While the authors have identified critical factors for setting short and long term plans for manufacturing enterprises, authors also indicated that planning alone would not make manufacturing competitive. Furthermore, reconfigurable manufacturing process and business environment play a role in making manufacturing enterprise competitive and adaptive to changes. Research was conducted about RMS and its impact towards improving PTMI. Sheng *et al* defined RMS as a “convertible manufacturing system that can respond rapidly to the market demand and according to design plan by the aid of rearrangement, reuse and reengineering of cells and subsystem to realize the system functionality and capacity with low reconfiguration costs” [6]. Nazir [7] conducted a study on RMS as a key to world-class manufacturing status for Indian organizations. In his study he clearly stated that RMS technologies will provide Indian manufactures exactly the production capabilities needed, exactly on time when needed to compete with global players. In the South African context it was found that import inputs from manufacturing rose from 13% of gross profit in 1993 to 15.9% in 2005 [8].

While the South African manufacturing enterprise has showed strength during global economic recession, but much still needs to be done to limit high numbers of imports to South African PTMI. Furthermore, the South African PTMI still needs to be revamped in order for it to compete with the best in the world. However, South African PTMI is using Dedicated Manufacturing System (DMS) which is more beneficial when companies are fabricating specific part at mass production volume over an allocated time. Global competition has become the name of the game in order to survive otherwise this will spell out demise for many Press tool industries. The disadvantages of DMS in South African PTMI are that when demand exceeds supply capability, it becomes a challenge for companies to sustain their capability in the long run.

| Dedicated Manufacturing System | Flexible Manufacturing System |
|---|---|
| Not flexible | Expensive |
| For single part | Machine focus |
| Fixed capacity | Low throughput |
| Not scalable | Single tool machine |
| Fixed variety | Complex |

Table 1: Summary of the weaknesses of DMS and FMS.

Source: Krishna and Jayswal (2012): Reconfiguration of manufacturing system.

One thought about effective manufacturing setup is the ability of enterprises to adapt to variety of customer demands and also According to Mostafa *et al*, they clearly indicated that group technology seeks to identify and group together similar parts to take advantages of their similarities in manufacturing and design [9]. They gave an example of small scale production that is complex, high variety, low volume manufacturing facilities where the changes in production mix, volume, customer base, workforce skills, process technology, etc are significant. In our research we conquer with these researchers in that effectiveness of small scale production when producing for one customer, but it will be expensive when producing for multi customers. Moreover, Mostafa *et al* did not indicate the flexibility and reconfigurability of manufacturing setups that can adapt to changes in demand volume and government regulation.

Leading Manufacturing enterprises are revamping their operations to be ready to act when opportunities or challenges arise. Flexible cost structures and partnering capabilities allow enterprise to rapidly scale up or down. For the Press tool enterprise to be able to adjust its production setup quickly without any major delay to production, enterprises should reconfigure their manufacturing systems and their business environments so as to respond to complexity with operational flexibility.

The concept of a reconfigurable enterprise addresses the rapid adaptation of its processes, operations, and control systems with respect to diverse, customized services or products.

According to Stefanovic *et a*l reconfiguration refers to the redesign of certain elements or components of a system. If an organization is perceived as a system, organizational units can be viewed as elements or components of that system [10]. Thus, business unit reconfiguration is the addition of units to the enterprise, deletion of units from the enterprise, and recombination of units within the enterprise such that resources and activities are still retained by the organization [11].

The roles of manufacturing systems have been critically reviewed and RMS principles have also been identified as necessary for an effective, responsive and relevant manufacturing enterprise. Table 2 highlights strong points about RMS:

| Points | RMS/RMT |
|---|---|
| System Structure | Changeable |
| Machine Structure | Changeable |
| System focus | Part family |
| Scalability | Yes |
| Flexibility | Customized(around a part family) |
| Simultaneously operating tools | Possible |
| Productivity | High |
| Cost per part | Medium(Parts at variable demand) |

Table 2: RMS features for effective manufacturing enterprise.

Source: Design of reconfigurable manufacturing systems: Koren and Shptalni (2010).

The above literature review shows the role of RMS in manufacturing enterprices and its effect in overall performance. This paper highlights the fact that by accomodating product variety in a manufacturing enterprise, it will promote local production to exceed imports. Based on this review, the remainder of this study is organized as follows: the next section discusses the methodology, analyzes the results. Finally it proposes a model to enphasize the benefits of RMS, draws final conclusions and recommendations for further studies are expressed.

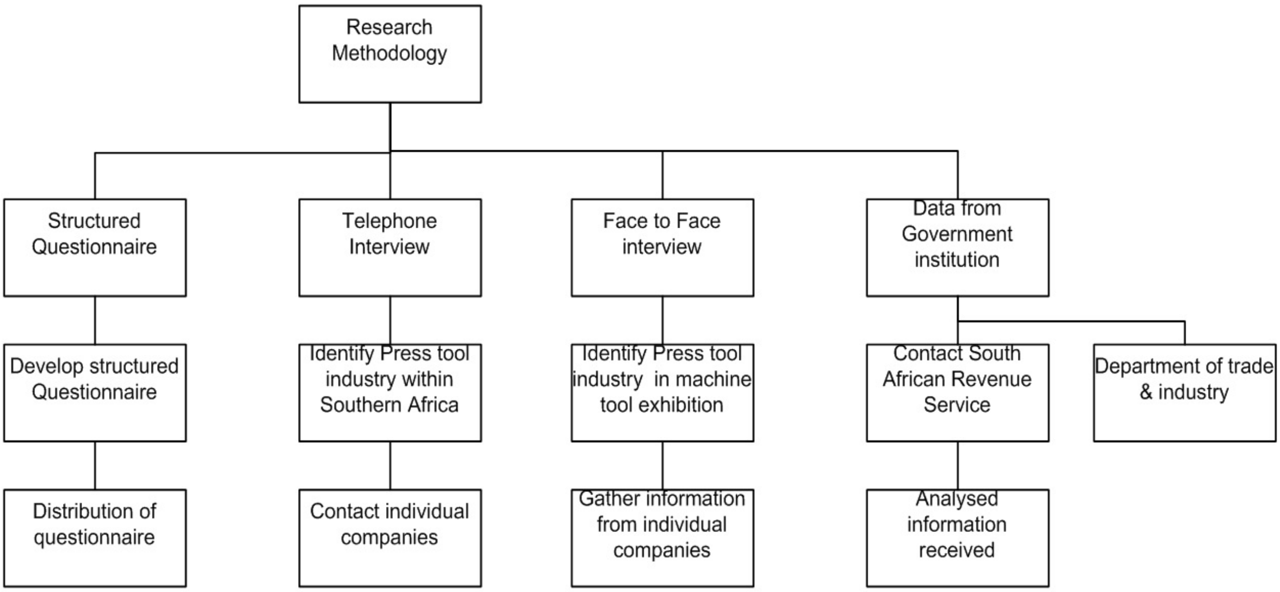


Figure 1: Research breakdown structure.

## 3 METHODOLOGY

For the study to be undertaken, the research questionnaire was developed for the purpose of data gathering. The target population for the research included press tool industries in the machine tool sector. The targeted industries were identified on the basis that they meet the following criteria for inclusion: Press tool industries located in Gauteng Province: and Press tool industries whose employee composition was less than two hundred employees or who has less than 20 press machines. Authors also got a national perspective at the exhibition as all the provinces are represented there.

The researchers contacted 40 PTMI and visited 3 within the area of Gauteng, in South Africa. The questionnaire document was distributed via email to owners/managers of the press tool companies.

The parallel methods used to obtain data were as follows: Telephone interview, face to face interviews through exhibition and onsite visitation, and meeting government structures that deals with statistics.

The breakdown of the questionnaire response is depicted in Fig. 2. The results were received in an interval of 1 week until the end of testing month. Three industries returned their questionnaire completed. Eleven industry's data was gathered through telephonic interviews and six replied during face to face interviews. Twelve industries did not respond at all and nine industries indicated that they were unable due to the fact that they are content with what they have currently.

Bhat [12] stated that research design constitutes the blueprint for the collection, measurement and analysis of data. It is the plan and structure of the investigation to obtain answers to the research questions. The plan is the overall scheme or programme of the research. It includes an outline of what the researcher will do and the operational implications to the final analysis of data.

The questionnaire distributed consisted of three main sections namely; organization details, product design and development, production information and the maintenance management system.

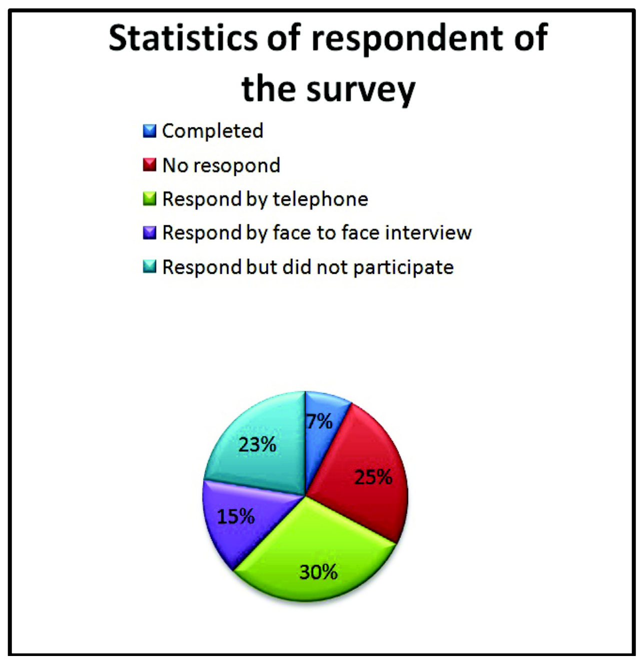


Figure 2: Statistics of respondent of the survey.

## 4 RESULTS

Data was collected through the administration of structured questionnaire, interviews, electronic mails and telephonically

Results gathered from different sources indicated that the areas that need attention were manufacturing systems. The questionnaire indicated that most of these companies still using the old systems such as the dedicated manufacturing systems, furthermore companies indicated that lack of Research and development is the main reason for their poor performance and long term planning.

From the year 2010 to 2011 the export rates decreased from 162 units to 75 units, this statistics provide a clear indication that most PTMI had stopped to produce these machines locally, further more the data collected from questionnaire shows that 0% of the companies contacted indicated that production is currently taking place refer to figure 3 below

Figure 3 shows the response from these companies about the RMS and aspects closely related to RMS implementation.

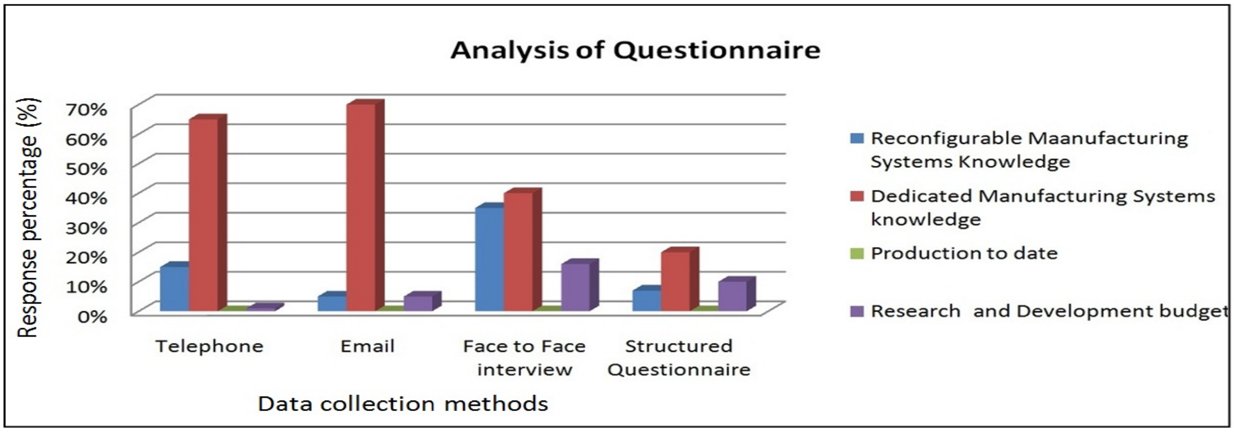


Figure 3: Statistics of respondent press tool manufacturing industry.

### Data Collected from South African Revenue Services (SARS)

The information collected from SARS indicated that there are a high percentage of press machines imports from European and Asian countries in recent years as compared to the past years. According to the graphical analysis in figure 4, the results showed a low decrease of imports in the year 2009 which was caused by the economic recessions and the high exchange rates. The graph figure 4 and table 3 indicate the export rate versus the import rates of the South African press tool industry.

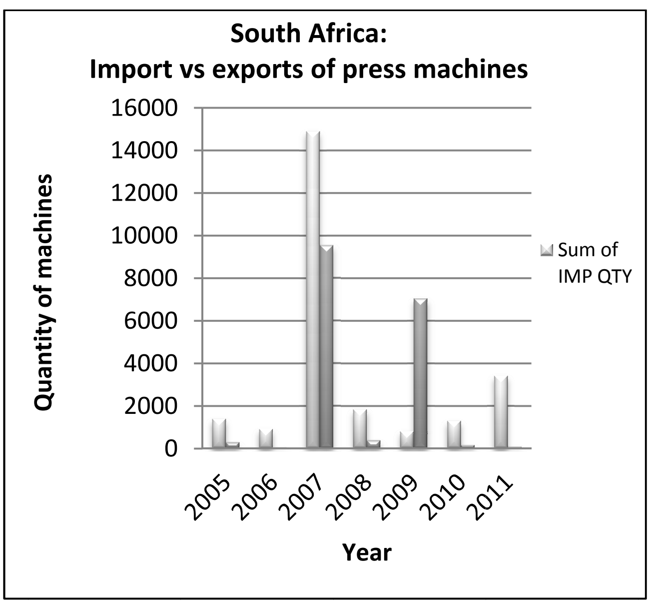


Figure 4: Import and Export rate.

| Row Labels | Sum of IMP QTY | Sum of EXP QTY |
|---|---|---|
| 2005 | 1386 | 288 |
| 2006 | 915 | 54 |
| 2007 | 14909 | 9559 |
| 2008 | 1823 | 375 |
| 2009 | 809 | 7048 |
| 2010 | 1293 | 162 |
| 2011 | 3409 | 75 |
| Grand Total | 24544 | 17561 |

Table 3: Imports Vs Exports.

Source: South African Revenue Services (SARS) data base.

### Data Collected from South African Department of Trade and Industry (DTI)

Data collected from Department of Trade and industry (DTI) indicated that, as of March 2007, there were 107 724 enterprises in the Manufacturing sector in the country, of which 42% enterprises were considered economically inactive. This implies 62 651 active Manufacturing enterprises (i.e. enterprises having some financial activity during the previous five years). Of these, the majority (53%) were very small enterprises, followed by 25% of micro enterprises. Only 4% of enterprises in the Manufacturing sector were large enterprises. Close corporations and private companies almost exclusively represented the Manufacturing SMME sector in the country (43 985and 15 933 of 60 154, which means 73.1% and 26.5%, giving a combined total of 99.6%) [2]. It was observed that currently most press-tool industries are still using the dedicated system, the system is incapable of producing some of the products which results in high importation rates from European and other Asian countries. Countries like China which currently is one of the leading manufactures have adapted these new manufacturing technologies which play an important role to keep their industry more sustainable.

### 4.1 Benefits of RMS

The reconfigurable manufacturing systems (RMS) approach with emphasis on reconfigurability will play an important role in the PTMI to revamp old manufacturing systems to allow responsiveness towards new customer demands. The following are some of the key advantages and benefits of implementing such a system.

- Responsiveness towards customer demands
- Mass-customization
- Reduced lead times
- Reconfigurability

**Mass-customization** – The process of delivering wide-market goods and services that are modified to satisfy a specific customer need. Mass customization is a marketing and manufacturing technique that combines the flexibility and personalization of "custom-made" with the low unit costs associated with mass production. Utilizing mass customization in the press tool industries, will assist the industry to produce diverse products in large quantities at the same time it will be able to meet different customer demands.

**Reduce lead time** – Through shorter lead times to market and to production, Press tool manufacturers would compete effectively among other global competitor.

**Reconfigurability** – In the press tool industry there many regularities that the business needs to adjust to in order to function effectively for example; the environmental issues such as energy savings and pollution, these issues can be overcome by introducing the three main principles of reconfigurability namely; multi-ability, evolution and survivability. These principles will help the press tool enterprise to enhancing their manufacturing systems. In the event of partial failure, reconfigurable systems can potentially configure to a state in which some level of functionality is maintained.

In the next section a detailed discussion is presented to emphasize the benefits of RMS in the PTMI, furthermore a model has been developed to support the discussions.

### 4.2 Proposed RMS Model in a PTMI

By definition, a Reconfigurable Manufacturing System is designed at the outset for rapid change in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in demand by Koren et al [13]. While the definition indicate the important factors that are critical in meeting sudden changes in enterprise current and future plans, however data gathered through different data collection techniques indicate that current press tool industry businesses and manufacturing set up are inflexible towards sudden changes in their business model.

Furthermore, due to the fact that press tool industry business and manufacturing set up are inflexible to meet sudden changes, press tool industry are compel to turn away from their core functions of manufacturing to distribution services. By turning away from their core functions will result in these industries importing more machines from other countries to stay competitive. Due to the cheap machines from Asian countries, some of South African PTMI ends up not having ownership and rights to manufacture the products. By not having right to produce some of these technologies in-house, creates a threat to decline in skills development. These industries will be forced not to invest more in research and development due to the fact that no production or design of product is made. In addition, number of jobs is shared instead of being created to improve social challenges. The South African PTMI has lost its competitive edge among local and globally competitors.

Role of the RMS has been explored to determine theory related to press tool industries and other industries, but much still need to be exposed about the implementation of the RMS. The double lines shown in figure 5, highlights the impacts related to role of RMS in the Press tool industries. In today's world of competitive environment , business such as press tool industry are forced to quickly adjust their manufacturing setup and their business model to meet their sudden changes in demands. The model works in this way, once the model is implemented; it is expected to address the business and manufacturing inflexibility towards meeting sudden changes in demands.

Moreover, the main objective of the RMS model is to help press tool industries in meeting various customer demands and quickly responding to sudden market changes. When South African PTMI meets different customer needs, producing products in mass customisation can be achieved. Once the industry maintains its market base, the industry will increase its profit margin that will sustain the nature of the business. By virtue of business sustainability means that the business will maintain its development and grow into a new level where high import will be reduced due to industry manufacturing capability to meet any market demands. Furthermore, once the manufacturing capability has been achieved by press tool industries, skill transfer and development will be achieved and also exported to other industries locally and globally. In addition, once the manufacturing capability has been achieved , long production lead time will be reduce and effective manufacturing set up will be flexible to meet various demands.

Press tool industries are competing in evolving world, so research and development should be consistently done to be up to date with current challenges and solutions to their business. Overall the role of RMS model will have major impact in meeting government regulations and assisting press tool industries to be adaptable to any changes in the demands.

The competitiveness of a press tool manufacturing industry will give more opportunities and more jobs will be created. Furthermore the model proposed on fig 5 consists of up and down arrows. The upwards arrows on the model indicates the current state of a non-competitive industry, and the downwards indicates a more competitive PTMI. The proposed model will help the industry to consider the factors that will move them from a non-competitive business environment to a more competitive business environment.

The RMS approach will play an important role in the press tool manufacturing system. The changeable characteristics of RMS technology enable the reduction of complexity in the enterprise due to low changeover time and increase the ability to customize and individualize products to customers.

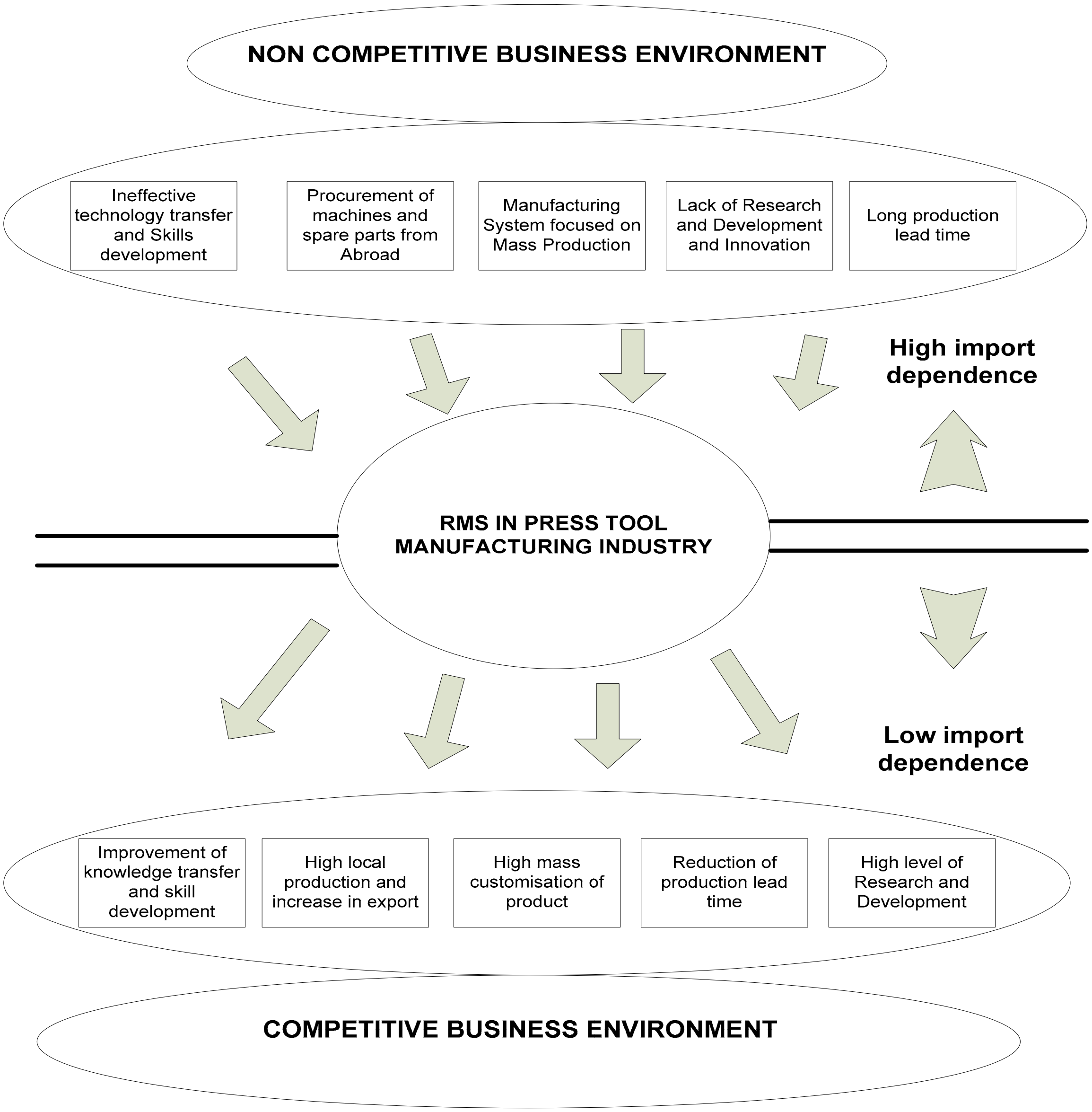


Figure 5: Proposed RMS model in a PTMI

## 5 LIMITATION OF STUDY

In the study only 40 PTMI had been contacted, for further studies a more broad scale of the study population needs to be contacted, since it will provide more detailed statistics of the findings. This paper also identified some factors that influence the import dependency in the PTMI, but there are other key factors which are not included in the context of the study due to lack of evidence, but a survey is currently being carried out to address these aspects.

## 6 CONCLUSIONS

All factors that contribute to the overall goal of improving competitiveness of the PTMI are indicated on the lower-half of the proposed RMS model shown in figure 5. Based on the data collected from the interviews there were some barriers identified that could influence the implementation of the RMS model the barriers consisted of Cost, time, fear and complexity. Before the manufactures accept the new technology, they must be convinced that the new technology will not increase cost, but instead it should integrate into their current workflow. Research work is currently in progress to determine the performance evaluation of implementing RMS model in the industry. The application of RMS was not found anywhere in the South African PMTI. Based on the results from interviews, it was found that RMS was not implemented due to lack of knowledge and lack of understanding of the systems. RMS concept can be implemented in any type of industry starting from SME to SMME and it is also a solution to job creation.

The implementing of RMS system will go a long way in improving the South African press tool industry. Researchers recommend that South African PTMI implements RMS in the current state so that these machines can be produced locally and imports will be reduced. If South Africa could reduce its dependence on imports producing more domestically, then more jobs could be created domestically.

## 7 ACKNOWLEDGEMENT

Authors would like to acknowledge the support from the Department of Trade and Industry (DTI), the South Africa Revenue Services (SARS) for providing us with relevant information and the Technology Innovation Agency (TIA) and the National Research Foundation (NRF) for funding the project.

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# Reconfigurable Production Systems – An Appraisal of Applied Production Breakdown Solution Strategies

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**Abstract**
Due to international competition and frequently changing customer demands, manufacturers production requirements become more complex. Production breakdowns demand for efficient fault solutions. Commonly, this problem is often tried to be tackled by the design of the production systems architecture. An alternative way is the consideration of the system behaviour. The paper proposes an approach based on a behaviour pattern concept for identifying alternate fault and reconfiguration solutions. Further, this work deals with typically applied approaches and strategies for breakdown solution and illustrates appraisements for a use case due to hybrid simulation.

**Keywords:**
Alternate fault solution; Reconfiguration of production systems; Survey

## 1 INTRODUCTION

The pressure of today's global competition enforces an improvement in manufacturers production techniques. The fulfilment of external demands - such as a constant supplement of functional extensibility as well as delivery reliability - require a high degree of flexibility and changeability. Being part of a supply chain, manufacturers have to employ Just-In-Time production strategies. An increase of structural complexity, dynamically changing customer demands and the pressure of cost reduction worsen the influence of errors in the production process. The practical applied strategies for managing production breakdowns are particularly crucial. The manufacturers are enforced to instantly act as well as react. Thus, the success of manufacturers depends on the quick detection of possible sources of errors and the provision of process alternatives for breakdown scenarios. This implies the necessity of embedded reconfiguration approaches and the use of adaptive production principles to maintain their competitiveness.

This paper deals with commonly applied strategies concerning production breakdowns as well as the determination of potentials and tries to emphasise the relevance of neglected alternatives. Therefore, a multi-survey explores commonly employed production breakdown strategies and gives an overview of applied solutions in practice. That means, different types of manufacturers answered questions related on their handling of production disruptions. The responses are evaluated by the means of theoretical concepts for behaviour patterns of changeability. Thus, a classification originates that identifies generalised solution strategies and additional fields of action on the plant floor.

This allows the analyses and comparison of alternate solution strategies by the implementation in a software and hardware based production simulation environment [1]. As, the hybrid simulator offers the utilisation of hardware components like smart sensors, RFID readers and optical cameras, which are important for detecting errors and applying solutions.

One of the results of this paper is a comparison of over and under represented applied production breakdown solution strategies through the analysis and evaluation of suitable optimizing parameters. Furthermore needs for research action and practice will be derived. Additionally, a variety of problem solving approaches for each production breakdown scenario will be illustrated. Moreover an overview in the form of a behaviour pattern-based classification for real case scenarios in production scenarios will be given.

The paper is organised as follows. Section 2 provides background information. Section 3 contains a general overview of the applied approach while Section 4 describes the key facts of the survey; Section 5 describes a use case analysis. The use case evaluation is conducted in Section 6. The conclusions are exemplified in Section 7.

## 2 BACKGROUND

### 2.1 Reconfigurable Production Systems

A production system is a complex socio-technical system of activity-units [2]. It transforms input through value-adding and associates processes to output [3]. Therefore, organisations, resources, humans and methods cooperate and need to be managed [4]. Process steering concerns a sequel of transformations, which are defined by a process-oriented and structural organization [5]. Further, the steering comprises the production as well as the assembling of auxiliary supplies [6]. The potential of production systems is extended by decentral and autonomous production objects [7], [8], which also allow a high degree of reconfigurability [9], [10].

Faults and other non-ordinary events can occur unpredictably during a production process. Reconfigurable production systems are able to handle both, predictable as well as unpredictable environmental changes by its design. Rapid changes in structure, hardware and software components for a quick adjustment of the production system to respond to these changes and faults is its basic capacity

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[11], [12] which facilitates the realisation of breakdown solution strategies. The architecture is determined by its main core characteristics. Those are: Modularity, Integrability, Customized flexibility, Convertibility, as well as Diagnosability [13] and can be considered as indicators. A further way to investigate a production system is to consider its system behaviour by utilized behaviour pattern.

### 2.2 Behaviour Pattern Approach of Changeability

There are various terms that deal with the concept and understanding of changeability - which are synonymously used in this paper - such as adaptability, change capability or evolvability. Changeability characterizes the ability of a system to handle the requirements of the environment in a fast, efficient and autonomous manner [14]. This is facilitated through the application of structures of actions and therefore the achievement of system goals e.g. system preservation, self-protection or growth. Those can be of operational, tactical or strategic nature. Structures of action contain changeability, if further structures of action can be derived without any additional effort for similar environmental situations [15]. The more situations are covered by one structure, the more is the structure capable of change. That means, the more structures of action a system contains, the more the system decrees about changeability. Mobility, Recombinability, Seperability or Automobility are some samples of such structures of action. A system is able to use diverse different paths as pattern for reconfiguration of possible solution strategies.

A further sample for such a structure of action is flexibility. Flexibility in a classical understanding connotes bendability or conformability [16]. In flexibility structures there exists an external force which causes the change. That does not mean that the system is able to adapt actively to the environmental situation, but the flexible object is bended by the environment in the specific situation. Thus, flexibility means that the system is straightened out by external forces and it complies with the environmental conditions. In the case of force disappearance, the system changes its state to the initial condition. However, the capacity of flexibility is not sufficient for the systems' self-adjustment. Flexibility describes only one manner in which a system can behave. It can be considered as a reactive and passive pattern and, therefore, as a part of changeability.

In this work, the behaviour pattern approach is used, firstly, for the classification of in production applied solution strategies in order to enable the comparison of the solution strategies on a generic level and, secondly, for the determination of suitable underrepresented breakdown solution alternatives. The usefulness in real case scenarios is verified by hybrid production simulation.

### 2.3 Hybrid Simulation Environment LUPO

The hybrid simulation environment LUPO [17] (germ. abbr. for performance evaluation of independent production elements) combines the benefits of software and hardware simulation in order to evaluate production concepts and technologies with respect to economic efficiency. The hybrid environment combines the monetary benefits of the "Digital Factory" and enables visual interaction of a "Model Factory" for production simulation [1] Therefore, LUPO consists of a guide rail transportation system and different physical components which e.g. represent customary machines, handwork places and workpieces. The components are operated by self developed software that uses a library of typical production objects. Hence, the environment allows a rapid simulation set up with the integration of hardware technologies like robots, RFID, Barcodes or smart sensors in order to compare operating numbers of prevalent and alternative scenarios [18].

This test bed allows efficient modelling and simulation of different scenarios and helps to evaluate possible breakdown solutions for production processes.

## 3 APPROACH FOR ALTERNATE FAULT SOLUTIONS

The overall goal of the applied approach (Figure 1) is an appraisement of applied production measures and a sensitising for alternative ways of fault solution in production companies. This is realised via the comparison of diverse target processes, which are derived from structures of action and their generic measures. For the achievement of the goal, the in the following described steps were executed.

First, a multi-survey was conducted which consists of a questionnaire, expert interviews and an analysis of handbooks as well as guidelines from various manufactures. All gathered information is transferred into the predefined structure of the multi-survey. Hence, a homogenous evaluation of the data is possible.

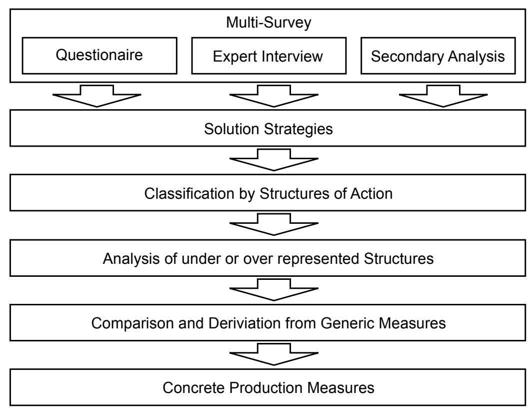


Figure 1: Approach.

The results provide various production breakdown scenarios, plus proactive and reactive solution strategies. Furthermore, subjective appraisals of the strategies were enquired. The surveyed solutions are classified with the aid of the structures of action and their generic solution strategies. This allows an analysis of over and under represented structures of action, which enable a comparison with generic measures and the derivation of alternate manufacturing methods. The simulations of the various processes are conducted within the environment LUPO (sec. 2.3) in order to verify their effectiveness related to commonly applied production measures.

By using this approach, the existing production breakdown scenarios can be classified and an abstract overview of the system can be generated. Second, comparability between inherent characteristics of different systems and their solution strategies can be demonstrated. Third, strategy gaps and in practices unused potentials can be uncovered with the aid of the generic solution strategies and the structures of action. Furthermore, this approach allows the identification of unknown solution strategies and the evaluation of currently applied approaches.

## 4 SURVEY

Forty-three different, mostly international acting SME’s participated in the multi-survey. In detail: thirty-six questionnaire data sets, 4 expert interviews as well as the consideration of 3 different manufacturer handbooks lead to an overall number of sixty-four different production breakdown scenarios. Most participants operate in the automobile industry. An assignment to the industrial sector is given in Figure 2.

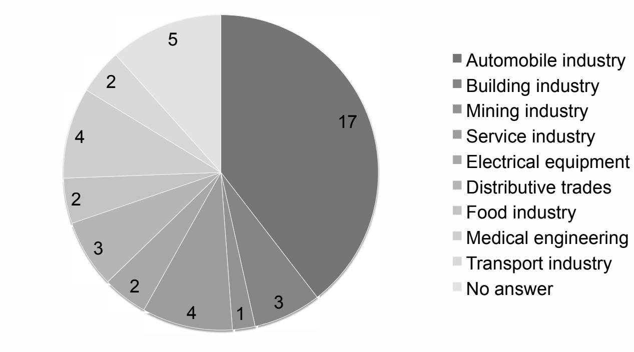


Figure 2: Industrial Sectors of Survey Participants.

The questionnaire and expert interviews were structured into different sub-categories. Firstly the authors collected data about the interviewee’s company, establishing among others, the size, industrial sector, focus of work and types of production.

Secondly interviewees were asked about breakdowns they encountered in their company and solution strategies that were used to counteract. The questionnaire was distributed among the contacts of the LUPO network, including production managers, technical employees and others in the context of breakdown solution scenarios.

The same categories were used in the expert interviews. The secondary analysis complemented the data collection, as it provided deeper insight into the subject.

By combining the three methods of data collection, the authors aimed to identify breakdown scenarios as well as reactive and proactive solution strategies. This allows an integration of solution strategies into the simulation environment.

According to the sixty-four identified scenarios a total amount of sixty-eight solution strategies were identified. The results difference elude from the fact, that both, proactive as well as reactive solution strategies were retrieved. The emerged use case library provides the fundament for the following single use case investigation.

## 5 USE CASE ANALYSIS

The freedom of action of a production system is limited by its system behaviour. Obviously, an inferior degree of action results from a shortcoming in the variation of the structures of action. The survey devotes that solely a few structures of actions are utilized for possible solution strategies. Then, eight in sixteen as relevant considered patterns were applied by the survey participants. As shown in Figure 3 the pattern ‘Mobility' and ‘Variability' are profoundly overrepresented. Against the background that in most cases the solution strategies can be further improved by exhausting the applied patterns, there is a need for further, also adaptive, possible courses of action. Thus, alternative approaches basing on underrepresented structures of action could be promising to overcome the breakdown.

For the evaluation of underutilized pattern application in production scenarios the 43rd use case given by the survey was chosen, which concerns production breakdowns caused by insufficient material drying. In detail, incorrect configuration settings of the material dryer workplace results in shortcomings of drying time which causes inappropriate surface conditions of the synthetically product for succeeding manufacturing steps. For example, the colour applied by following varnishing processes peels of and pollutes in this way valuable production machines. In the case of early quality variation detection by co-workers, the workpiece is lead back to the drying machine and hampers already planned production elements. In order to provide comparable results, the currently implemented process (CP) is also simulated by the LUPO environment. The representation of simulation results for the process and the applied breakdown solutions focuses solely on the processes of the drying machine, to maintain confirmability. Then, the machine by itself comprehends already higher process complexity. For example, the water container of the workplace is required to be replaced when limits are exceeded and needs to be operated for each good by humans, whose unpredictable configuration set up is also concerned by the simulation.

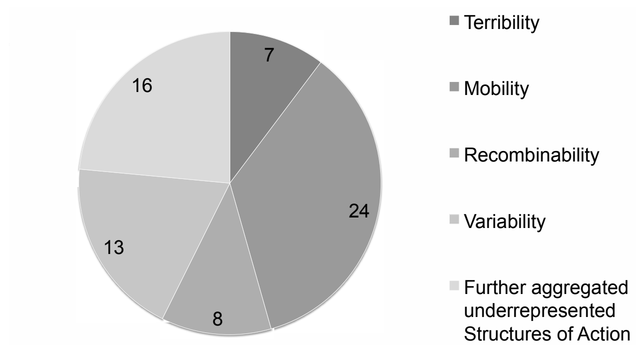


Figure 3: Measure Classification.

Regarding the survey, the company improves the drying process by constantly raising the awareness of the responsible worker for the importance of the rightful adjustments of the material dryer**,** this solution strategy is in the following called target process **(**TP1).

Although, the applied strategy leads to an increase of successfully produced goods, the over usage of drying time is still possible and, therefore, extends the throughput needlessly.

Based on the classification system of [19], the in practice applied solution (TP1) can be related regarding its characteristic values to the structure of action ‘Mobility'. The pattern implies that the system is formed until it is as aligned as possible to the environment. Mobility is considered as an overrepresented structure as it is utilized in twenty-four scenarios.

A suitable solution for CP is Viscosity. Viscosity connotes that the system and its environment are put in relation to each other via lubricant. The in the following demonstrated second target process (TP2) is deducted from this structure of action.

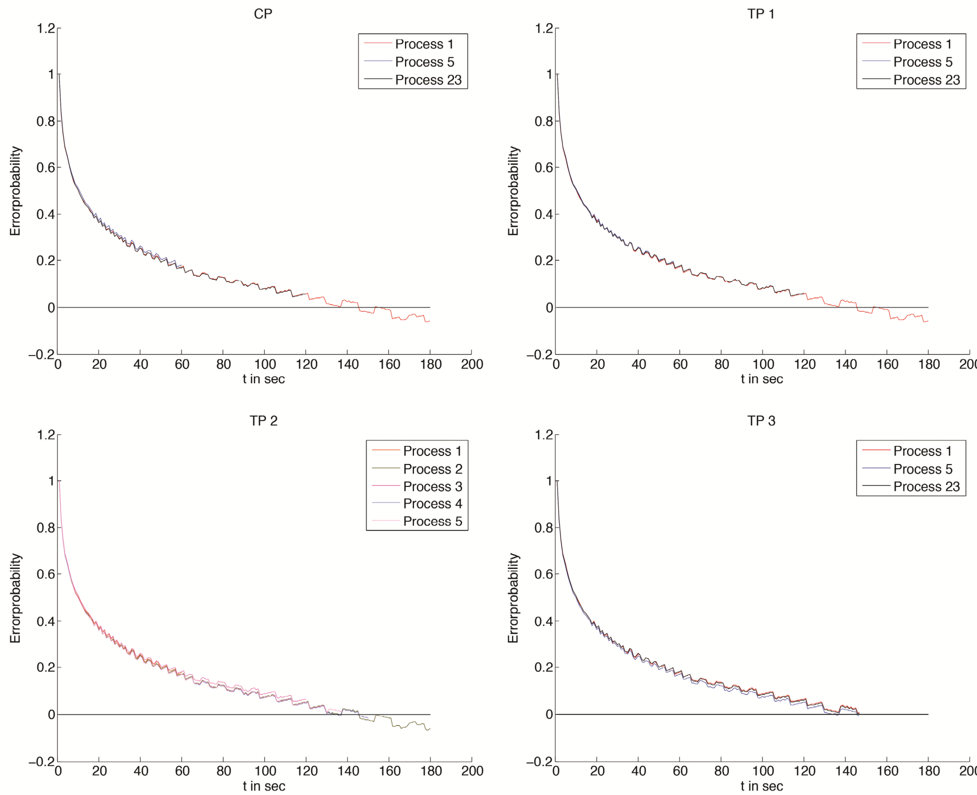


Figure 4: Samples for Process Runs.

A further imaginable pattern is 'Automobility' which means that the system moves automatically into a position so that it is optimally matched to the environment. Target process 3 (TP3) will base on this pattern. The properties for the evaluation of the enhancement of the currently applied solution (TP1) are declared in sec. 6.

The first alternative (TP2), utilizes an external smart sensor [20], [21] which sends a notification about the degree of the over or under usage of applied drying time after the process finishes. Because of the fact, that the optimal drying time is unknown a variation of binary search [22] is applied by the production manager to detect the optimal value. Beneficially, this approach leads to the detection of the optimal drying time after a set of pre evaluation runs. The second alternative (TP3) uses a sensor integrated in the drying machine, which allows the termination of the drying process in the moment of completion. Hence, pre evaluation runs and faulty products are avoided.

## 6 USE CASE EVALUATION

For the evaluation and comparison of the particular scenarios, 50 workpiece iteration runs were applied for each scenario with respect to the Value Stream Design [23] approach to determine the throughput time, the processing time and the assembling time with the help of hybrid simulation in the LUPO production environment (see sec. 2.3). Further, process specific values like the number of water container assemblings and the amount of successfully processed goods are collected.

Therefore, a machine with response curves representing the material drying process and several drying programs that are distinguishable by their processing time, were configured. Additionally, a workpiece representing the good was created with an inversely proportional error model. For the scenarios CP and TP1, the percentages of proper program selection was increased from 50% to 66% and applied as Bernoulli processes. For TP2 and TP3 the LUPO machine model was extended by smart sensor functionality fulfilling the requirements in sec. 5. The results are depicted in Figure 4.

It becomes apparent, that CP and TP1 fail to reach the optimal drying time. The available machine programs process the material for one, two or three minutes. Whereby, the self-learning approach TP2 requires 6 runs to level the optimal configuration by 2.27 minutes. Yet, the quality of four pieces inhibits succeeding manufacturing steps. This shortage is prevented by TP3 that produces valid goods in each process run.

Figure 5 supports the fact that all target processes improve the original approach in terms of successfully produced goods. Although, sensor technologies require monetary expenses, the alternate target processes increases from 56% (TP1) to 92% (TP2) and 100% (TP3). The throughput time rises by each target process, yet about the same degree. Moreover, TP2 and TP3 allow the reduction of assembling time because of the fact that the machine configuration is automatically set up via the computational logic of the applied smart sensor. Overall, the applied changeability pattern of the producer delivers a slight improvement regarding the

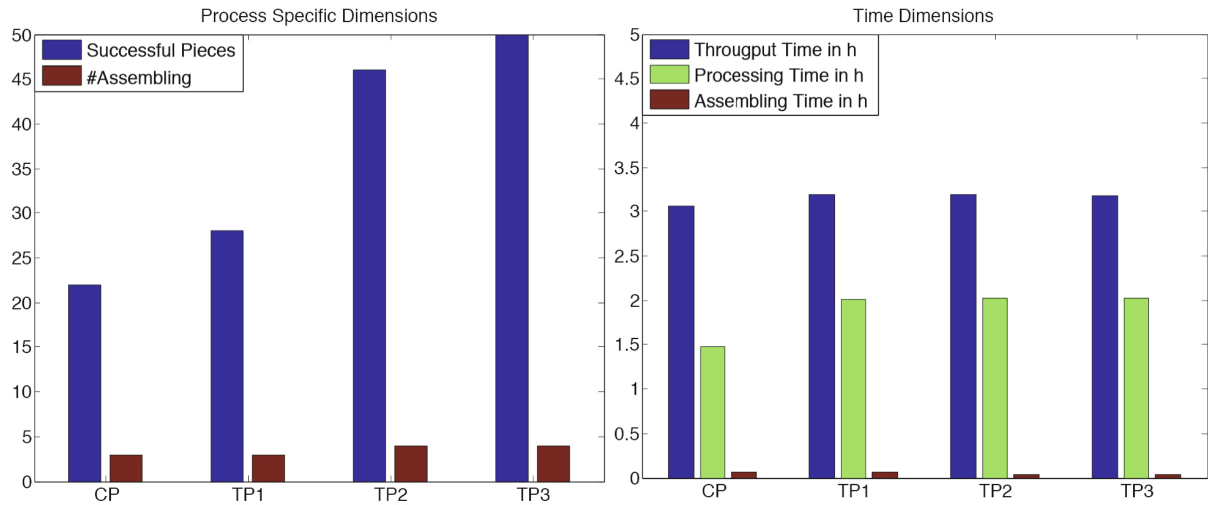


Figure 5: Quality Evaluation.

dimension of successfully manufactured workpieces, yet the processing and assembling time increased by the utilisation of an excessive drying time. Whereby, the patterns of 'Mobilty' and 'Automobility' allow statically and dynamically the detection of an optimal drying by approximately 2.27 minutes. This circumstance enables the process conduction in equal throughput time and additionally provides an increase of the factor 2 regarding the number of successfully produced goods. That means in terms of this use case and in terms of the considered dimensions, the neglected patterns of production breakdowns behave similar or far better than the currently applied solution.

## 7 CONCLUSION

This paper illustrates with the exemplified use case that the currently applied solution strategies for breakdown scenarios are not sufficient for an efficient fault management. The production system inherent characteristics and their solution strategies were demonstrated and concealed strategy gaps as well as unused potentials were uncovered.

An overview about the system behaviour of the production system and its freedom of action was generated at least particular. A completion can be realized by enriching this system investigation with more breakdown scenarios and respectively solution strategies. The potential value of this classification system has to proof its value in further investigations.

An evaluation of the applied approach was consciously not considered in this paper. However, the evaluation of breakdown solution occurs via the comparison of identified solution strategies and derived alternative solution strategies.

The concrete alternatives were generated with the creativity technique PoCCI [24]. This technique represents a kind of inverse approach, which bases on the same theoretical framework described in sec. 2. Based on a problem and the differentiation between system and relevant environment appropriate operational structures of action can be derived. Starting with a concrete breakdown scenario the deduction of alternative solution strategies is possible.

Further research proceedings should concern the implementation of other use cases of this survey in the hybrid simulation environment for enlarging the reconfiguration basis and gaining insights about other practical relevant patterns and, whether further solution strategies are likewise ignored. Additionally, the adaptability of this approach to further application contexts remains to be investigated.

The action capacities of production systems profoundly depend on diverse external and internal factors. Coping with resulting turbulences is mandatory for the sustainable survivability of a production system. Most decisive is the human factor, as it lacks of a coherent view and therefore unpredictably influences the creation, modification and operation in a production system. By the implementation and usage of time and quality efficient alternate fault solutions, potential errors can be reduced, which additionally leads to a high capability of responsiveness.

## 8 ACKNOWLEDGEMENTS

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# Implementing Virtual Assembly and Disassembly into the Product Development Process

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**Abstract**

Virtual assembly and disassembly (VA&D) usage enables knowledge exchange between design department and assembly production and aftermarket in the product development (PD) process. Utilisation of VA&D tools must be connected to the PD process in robust methods to fully employ this potential. A case study was performed at a manufacturing company to identify virtual activities and their position in the PD process. Assembly production and aftermarket departments have common demands on the utilisation of the VA&D tools in the PD process. Milestones that demands VA&D simulations shall be included in both concept phase and development phase in the PD process.

**Keywords:**

Integrated product development; Digital factory; Aftermarket simulations

## 1 INTRODUCTION

Early input from production and aftermarket knowledge is a key factor for a successful product development (PD) process. Through a knowledge exchange of assembly and service characteristics in the development process, better products can be made in a shorter time and at lower cost. Virtual assembly and disassembly (VA&D) is a means to include assembly production and aftermarket awareness in the design process. By accessing virtual models of new products, early feedback can be given on the design. Using the term virtual assembly and disassembly puts equal focus on assembly and aftermarket operations. Their needs and possibility to impact the product are similar and the definition of the term virtual assembly can be applied to both. Jayaram et al.'s [1] definition of virtual assembly is used in this paper:

*"The use of computer tools to make or 'assist with' assembly-related engineering decisions through analysis, predictive models, visualization, and presentation of data without physical realization of the product or supporting processes."* [1]

There is a broad set of tools and methods that can support the decisions in the definition above. Previous studies on virtual assembly have to a large extent focused on development of these computerised tools, concentrating on the techniques behind them, in areas such as virtual reality [2], ergonomic simulations [3], flow simulations of the manufacturing system utilising discrete event simulations [4], path planning simulations [5], assembly training simulations [6] and digital work instructions [7]. Research concerning implementation of these tools into working methods, incorporating users in the industry, is more limited. One example of this is virtual training [8]. A smaller number of studies concern the methods of implementing one of the tools into the product development process [9], [10]. However, there is still a lack of studies with a more operational perspective of VA&D, where the use and implementation of VA&D is analysed from the perspective of the PD process – bottom-up.

This study approaches that gap through a case study at a manufacturing company that does not yet have state-of-the-art tools or methods in all the VA&D areas. It also, to a large extent, lacks connections between the existing VA&D tools and the product development process.

Thus, the purpose of this paper is to analyse potential virtual assembly and disassembly in an industrial setting, based on a process-centred perspective instead of a tool-centred perspective, focusing on the activities in the product development process.

## 2 METHOD

The empirical data in the paper are based on a case study at a global heavy vehicle manufacturer. The manufacturing company works with a limited number of VA&D tools and engages a small number of assembly simulation engineers. The knowledge about all the tools in the area is limited. The departments at the company are relatively independent from each other and put different emphasis on VA&D. The company continuously introduces new products to the market and all manufacturing and aftermarket departments are involved in the PD process.

The case study was designed according to Yin [11], covering the stages: plan, design, prepare, collect and analyse, Figure 1. Each stage is discussed in the following sections.

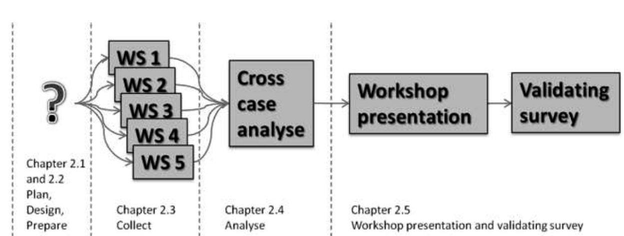


Figure 1: Overview of the research procedure with titles of the corresponding sections in Chapter 2.


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The PD process in the manufacturing company has two major parts, concept development and product development, as shown in Figure 2. All major concept choices are made and potential risks analysed in concept development. Product development is divided into four phases. *Configuration* gives a detailed project definition. *Development* is where the actual design work is done and results in a verified product. *Process verification and market preparation* deals with verification of company processes and marketing activities. *Ramp and close* includes production ramp up and project closure.


Figure 2: The PD process at the company with 19 milestones – 4 in concept development and 15 in product development.

### 2.1 Plan

A plan was drawn up to interview users in manual assembly departments at the heavy vehicle manufacturer. Semi-structured group interviews were chosen as the method for data gathering, since knowledge of the different VA&D tools was limited in the company and individual interviews would most likely result in incomplete descriptions of the total need of the organisation. The workshop format was chosen to give room for discussions in the group, with a moderator leading the discussion but not disturbing it.

### 2.2 Design and Prepare

Five workshops were held in all manual assembly and aftermarket departments separately. The participating departments were engine, chassis, cab and transmission assemblies and aftermarket. White-collar staff in each specific department working in the PD process were invited.

Each of the five workshops identified an individual process of how VA&D could be implemented in the PD process, based on the common workshop question:

*"If you think in a visionary way, how can assembly production and service market, in the next five years, use virtual models (3D CAD data) of the product in the product development process?"*

The result was a mapping of VA&D activities connected with the PD process. The five activity mappings were then summarised into one. The summarised activity mapping was presented to all workshop participants, to validate the suggested result. This validation was done through a survey in which the most important activity areas were identified. To test the procedures and material, a pilot workshop with a smaller group was held, which gave valuable input to the final data collection.

### 2.3 Collect

Each workshop included a number of professions involved in the PD process: production engineers responsible for assembly processes, tools, new products and logistics; process planners; project leaders; and assembly simulation engineers. Managers of all these were asked to engage with their visionary employees who could best answer the workshop question. These five departments consist of totally 25 subdepartments. The response to the invitation was positive, only one out of 25 managers did not let their employees participate in the study. The number and competences of the workshop participants as well as the number of employed assembly simulation engineers is presented in Table 1.

The workshop was divided into three parts: (i) identifying potential use of virtual models as activities, (ii) identifying resources needed and output and input to the activities and (iii) matching the activities with existing milestones in the PD process.

| | Number of participants | | Competences in workshop | | Number of employed assembly simulation engineers |
|---|---|---|---|---|---|
| | Workshop | Validating survey | Use virtual models today | PD process experience > 1 year | |
| Chassis assembly | 6 | 3 | 5 | 5 | 4 |
| Cab assembly | 6 | 1 | 4 | 6 | 2 |
| Transmission assembly | 4 | 2 | 1 | 3 | 1 |
| Engine assembly | 7 | 7 | 7 | 4 | 1 |
| Aftermarket | 6 | 2 | 2 | 6 | 2 |
| Total | 29 | 15 | 19 | | 10 |

Table 1: Number of participants at the workshops and the competences of these participants. Number of employed assembly simulation engineers in the departments.

*Identifying Potential Use of Virtual Models*

The first part of the three-hour-long workshop focused on the workshop question. A brainstorming activity generated a number of activity ideas that were documented on post-its. Unclear definitions and statements that did not concern the workshop question were documented on a flipchart and set aside.

*Identifying Resources Needed and Output and Input to the Activities*

The activities identified from the previous part were closely examined.

*Matching the Activities with Existing Milestones in the Product Development Process*

Each workshop ended with a mapping of the individual activities in the milestones in the PD process. All activities were placed in time relative to existing milestones.

### 2.4 Analyse

The five process maps with activities were summarised into one common map. This synthesis was done by clustering the stated activities into activity areas, resulting in a synthesis matrix of activity areas and PD milestones.

### 2.5 Workshop Presentation and Validation Survey

The synthesis matrix was presented at a meeting where participants from all the workshops were present. The aim of this meeting was to validate the common result. This was done through the validation survey and discussions with the whole group.

The validation survey was done before the actual presentation from the workshops was given and discussions of the results took place because of the risk that the discussion might influence the survey results. It concerned all departments involved and asked them to rank the identified activity areas that were defined based on the input from the initial workshops. This survey was done to validate the findings from the workshops in two steps. The participants from each of the departments were first asked to choose the three most important milestones with regard to VA&D, and then to state how to utilise their fictitious VA&D resource at each of these three milestones with respect to the activity areas and rank them on a scale from one to ten. Ten was their most preferred activity and most important to do at that milestone, one was their lowest priority.

## 3 RESULTS

All five workshops identified a number of VA&D activities and connected them with the general PD process. The activities were summarised according to Section 2.4 into one matrix, presented in Figure 3. Every circle represents a demand of a virtual activity and every workshop/department has its own colour in Figure 3, agreeing with the legend to the right. At the top, 7 of the 19 milestones (MS) are presented together with the corresponding phases, from Figure 2. These MS were the relevant ones mentioned in the workshops. At the left side the activity areas are presented that were identified during the cross case analysis of the data.

The following explanations of the activity areas are based on the development of a new product:

*Assembly preparation system:* Use of virtual models to prepare the product into an existing computerised assembly preparation system. The aim is to use the previous sequence, balance and simulations to automatically do the assembly preparation in the correct system.

*Balance workload at stations:* The identified assembly tasks are assigned to a workstation. The assembly tasks are balanced equally along the complete assembly line considering time and physical load.

*(Dis-)assembly instructions. Training of operators:* The aim is to utilise the simulations already done to create digital instructions. The same simulations can also be used to train the operator virtually to learn new assembly tasks.

*(Dis-)assembly of parts*: Analysis of collisions in the (dis-)assembly paths. The aim is to verify that there is a collision-free path for all parts to be (dis-)assembled.

*Ergonomic simulation:* Analysis of loads on the assembler. In this activity area the worker is in focus. Biomechanical analysis is performed as well as clearance verifications.

*Materials facade in (dis-)assembly:* Analysis of ways to present material in material facades. This is done with regard to distance to assembly positions as well as planned consumption volume compared with other materials at the station.

*Packaging of new parts:* Analysis of packaging are needed in the whole supply chain of the new product. In this task the product geometry is matched to standard pallets or individual packaging solutions.

*Sequence in (dis-)assembly:* Analysis of sequence of both parts and resources.

*Time analysis:* Analysis of assembly time of individual assembly tasks. These times are then used to set an optimum balance.

*Tools/equipment in (dis-)assembly:* Analysis of tools and equipment that handle or affect the products. This includes an analysis of potential collisions in the assembly paths, considering the tools and fixtures used.

A short explanation of the milestones (MS) presented in Figure 3 follows:

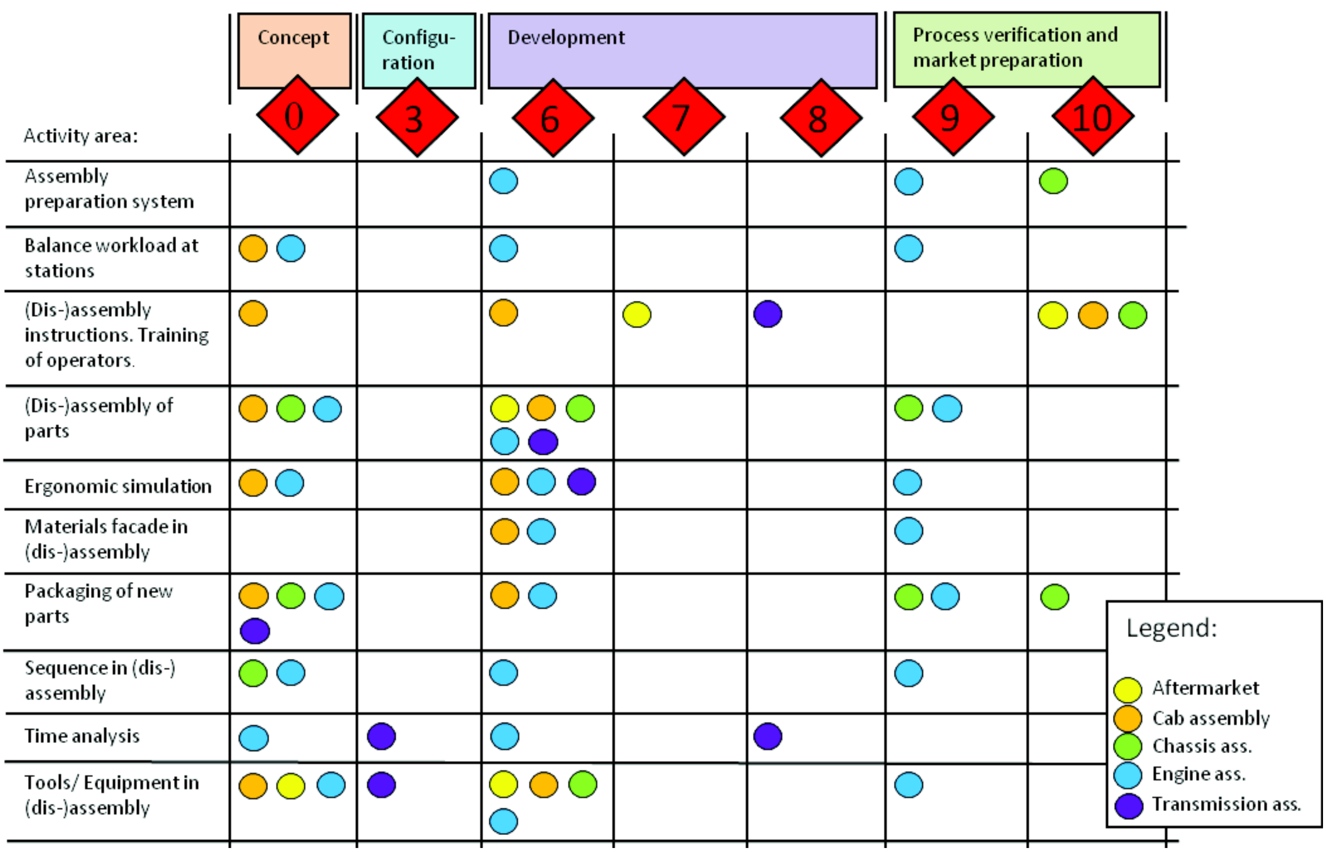


Figure 3: Aggregated results from all five workshops. The circles represent identified activities from different workshops/departments corresponding to the milestones (rhombi) and phases at the top. The activity areas represent a grouping done at the cross case analysis of the data.

*MS0- Concept ready:* At this last milestone in the concept development part the project is either cancelled or continued into product development. One design concept is chosen and all major risks in the future development are identified. This is the only milestone from the concept development part.

*MS3- Establish targets:* Establish detailed targets regarding production and aftermarket key performance indicators (KPIs).

*MS6- Product performance approved*: Follow up that all product targets (from MS3) are reached.

*MS7- Service market products:* Report status of products and services for aftermarket.

*MS8- Project deviation decision:* Inventory of all project deviations.

*MS9- Product verified:* Verify that quality targets are met.

*MS10- Batch closed for SOP decision:* Agreement that the product can be made according to a start-of-production (SOP) time schedule.

At each workshop unclear definitions as well as various demands and questions outside the aim of the workshops were written on a flipchart. This resulted in a list of 15 statements that all concern the usage of VA&D. Five topics were mentioned by more than one department and are presented in Table 2.

| No. of state-ments | Statement |
|---|---|
| 4 | Articles must be possible to find at different appropriate geometric levels by searching for product variants and time. |
| 3 | Clear connections are needed between VA&D processes to inherit results into the following steps. |
| 2 | Assembly path planning shall be done at frozen gates in the product development process. |
| 2 | One common updated database for the product in the whole company is needed. |
| 2 | In the far future there is a wish to do a totally automated verifying assembly simulations of planned production in order to identify potential assembly risks. |

Table 2: Five statements collected from the workshops regarding use of VA&D that did not fit in the general result presentation.

The validation survey preformed together with the workshop presentation answered to which of the milestones that was of most important and how to priorities the VA&D work in those milestones. The first part of the survey indicated which three milestones each organisation found most important in terms of VA&D, as shown in Table 3. The second part of the validating survey concerned giving priority to one fictitious VA&D resource at each of the chosen milestone. Figure 4 presents the mean priority value at each of the milestones relative to the activity areas.

| | 0 | 3 | 6 | 7 | 9 | 10 |
|---|---|---|---|---|---|---|
| Engine ass | √ | | √ | | √ | |
| Chassis ass | √ | | √ | | √ | |
| Cab ass | √ | | √ | | | √ |
| Transmission ass | √ | √ | √ | | | |
| Aftermarket | | | √ | √ | | √ |

Table 3: Participants from each of the five organisations listed their three most important milestones in respect to VA&D.

## 4 DISCUSSION AND CONCLUSIONS

### 4.1 Method Consideration

The assembly production and aftermarket departments are highly interested in the use of the VA&D tools, even though these are not widely spread throughout the manufacturing company. The main reason for this is that the tools offer opportunities to solve one of the main issues from production and aftermarket point of view in product development: the possibility to give early feedback on product design. The interest is reflected in the answers received after inviting managers to send their staff to participate in the workshops. 24 out of 25 managers answered favourably and did see the need to strengthen the virtual tools methods.

The aim of collecting data from workshops was to get synergies from collecting different, and often limited, personal knowledge of the VA&D areas from the participants. Group interviews would through synergies of knowledge lead to a more complete description of needs. [12] The workshops were moderated by one of the researchers, who led the discussions and documented the results. All the results were immediately documented (by the researcher) on sheets of paper, which were the only products from the workshop. This method also helped the researcher not to bias the results since any wrongly understood and stated results were corrected by the group and edited immediately. This was to be done without influencing and interfering with the results. These synergy purposes were fulfilled in four of the five workshops. The discussions there were open and informal. The participants' knowledge of the tools grew through the workshops, and a more complete process became clear. The workshop that did not function so well consisted of a broader group of participants. In addition to the assembly simulation engineers and production technicians it also included managers and senior technicians, which changed the group dynamics. These more experienced (in company terms, not necessarily VA&D terms) employees directed the discussions to their specific area of interest and the group discussion suffered from this. The moderator frequently had to take the discussion back to the question at hand. Different characteristics of a group are important to get the synergies discussed above, but to achieve this effect it is necessary that the group is hierarchically flat so that everybody feels free to speak their mind.

The departments investigated have, as stated in Table 1, varying experience in the VA&D areas. This was reflected in the workshops, where the discussion with the less experienced groups shifted towards the current physical process, trying to "digitalise" it. Those less experienced were uncertain about what the virtual tools could provide. These departments achieved a better understanding of VA&D from the workshops, which enabled them to discuss it further. In Table 1 the number of employed assembly simulation engineers is also presented. These are the ones that currently work most with the VA&D tools. They do assembly path simulations to validate that the new products are possible to assemble in a collision-free way. They cover a number of the activity areas identified in their everyday work, balance, (dis-)assembly of parts, tools and equipment, ergonomics, packaging and sequence. The assembly simulation engineers are, however, only one part of the workshops since the common vision of the complete department is essential if the results from the study are to be implemented in the future. A bit surprisingly they did not lead the discussion in the groups even though they have the most expertise. This shows that the VA&D possibilities are identified and discussed in a broader scope of the assembly production and aftermarket departments. Another interesting column in Table 1 is the PD process experience in the workshops. As a major task was to identify where in the PD process the VA&D tools

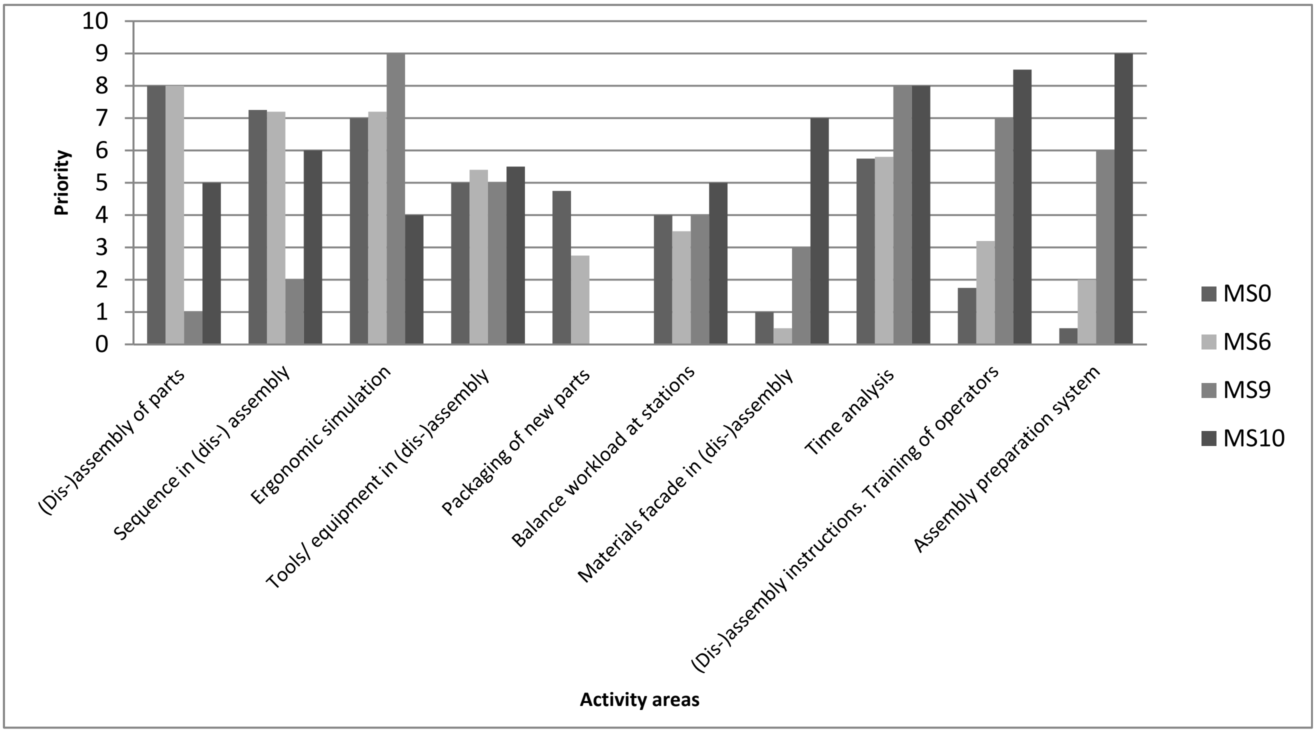


Figure 4: The mean priority value at each of the milestones relative to the activity areas. It is concluded that activity areas to the left are to be focused on in the early phases of the product development process and the activity areas to the right in the later phases.

fit, knowledge of the process was vital. This The number of participants in the validating survey unfortunately was not large enough to give a clear validation of the workshop results. As described in Table 1, only 15 of 29 participants from the workshop also answered the survey. This indicates that the data collected must be critically questioned. However, from table 3, the validation study still concludes that it is milestone 0 (concept ready, product development starts), 6 (product performance approved), 9 and 10 (product verified & batch closed) in the PD process that are of importance.

### 4.2 Activities and Activity Areas

The activities and activity areas identified in the research are compared with current research areas in VA&D that are presented in the introduction chapter of this paper.

*Virtual reality (VR)* was not mentioned in the workshops by the participants. It is an area where currently much research is performed. One reason that none of the workshops mentioned VR can be the limitation in the research question to only look five years into the future. Current issues regarding data transfer and work methods to incorporate desktop path planning simulations could imply that usage of VR tools is possible in the future. In the heavy vehicle manufacturing industry there are still some questions to be answered even when the VR functionality is developed to working methods. It needs to be proved that the results gained from VR outperform the desktop functionality in order to invest in building VR systems. It is more space-consuming and technology-dependent to build virtual studios compared to the desktop solution. One possible way to do this in the future is to have one VR studio where practically difficult and critical moments are investigated but the main analyses are done via desktop solutions.

*Ergonomic simulations* are ranked high in the departments, as seen in Figure 4. The reason for this is not solely care of the assembler working on the production line; the connection between ergonomic problems [13] and quality output is known among assembly and aftermarket engineers.

*Flow simulations of the manufacturing system utilising discrete event simulations (DES)* are not mentioned in the results from the workshops. They were brought up to discussion in some workshops but were never used. The reason for this is that the workshop question specifically mentions "*use virtual models (3D CAD data) of the product*" and it was decided that virtual models of the product are not needed in flow simulations.

*Path planning simulations* are today done in the departments (as discussed in Chapter 4.1). They are also ranked high in Figure 4. Path planning is done in two of the activity areas, (dis-)assembly of parts and tools/equipment.

*Assembly training simulations* have a priority in the later milestones in the PD process, see Figure 4, but only in one department. These virtual training simulations are not implemented in the company, and knowledge of them is limited. Much research in this area is connected with virtual reality, but the company is more interested in a desktop solution. A pilot study of a desktop system where the operator practices the new assembly tasks concerning products, tools and sequence is planned to be carried out in the company in the next few months.

*Digital work instructions* are ranked high in Figure 4. Work instructions are today developed as a separate document without connections with any previous simulations. A link to previous work would give a more effective process.

Table 2 presents the most common statements from the workshops that could not be presented as activities in the general result presentation. These statements generally reveal the current problems that prevent assembly simulation engineers from working more effectively and doing better analyses. The most central statement deals with the problem of structuring the CAD geometry in a way that makes it easy to find a correct version of the articles with corresponding surrounding articles.

### 4.3 Virtual Milestones in the PD Process

In Figure 3 and Table 3 the most interesting milestones can be identified, MS 0, 6, 9 and 10. This clear agreement of positions of activities in the PD process is encouraging and implies that it is possible to find common demands from all assembly production and aftermarket departments regarding how to incorporate the VA&D activities in the PD process. The number of notes in each activity area in Figure 3 is an indicator of importance. In order to validate the degree of importance a validation survey was carried out. This was done in order to meet the risk that departments overlooked some of the activity areas in their workshop discussions and therefore could not make a fair assessment of the whole field.

The validation survey result is presented in Figure 4. This figure gives a more precise presentation of the distribution of all the activities at each milestone than the number of notes in Figure 3. Figure 4 shows that milestones 9 and 10 focus on (dis-)assembly instructions and a production preparation system. These systems have not yet been introduced at the company. Therefore VA&D will first be introduced in milestones 0 and 6.

The following conclusions can be drawn at the manufacturing company level:

- The main focus when implementing milestones for VA&D should be on milestone 0, “concept ready” and 6, “product performance approved”.
- The important activity areas in milestones 0 and 6 are (dis-) assembly of parts, sequence, ergonomic and tools and equipment simulations.
- In later phases in product development (milestones 9 and 10) the following activity areas are of importance: assembly preparation system, (dis-)assembly instructions, training of operators and time analysis.

With important activity areas and milestones identified, the next step is to decide to what degree the activities identified at milestones 0 and 6 in Figure 3 shall be undertaken. These considerations must be taken into account on two levels, the level of virtual simulation analysis and the level of geometry analysed.

*Level of Virtual Simulation*

These considerations cover what level of simulation is included in each of the milestones. Is the demand only to perform a virtual simulation or should all deviations found also be corrected? At milestone 0 our opinion is that it is enough that virtual simulation is used in order to make the correct concept choice. At milestone 6 on the other hand all deviations found must also be corrected.

*Level of Geometry Analysed*

This consideration covers the amount of geometry that is needed at each of the milestones. Shall only articles be analysed or the complete vehicle? At milestone 0 our opinion is that only the articles directly influenced close to the modified ones are to be analysed. At milestone 6 an analysis must be done in a wider geometric area of the vehicle and more importantly of all variants affected.

### 4.4 General Conclusions

A unified view of the use of VA&D is presented in this paper. Managers as well as all of the white-collar staff in assembly and aftermarket departments all contributed to the result presented. They would like to utilise the VA&D tools in concept, development and process verification phases in the PD process. In the early phases the focus is on improving the product, and later the assembly process is improved.

## 5 ACKNOWLEDGMENTS

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# The Contribution of Virtual Production Intelligence to Laser Cutting Planning Processes

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**Abstract**

In order to facilitate the improvement in product quality and production efficiency, many companies use simulation applications. In turn, they face the challenge of making these applications interoperable. Once the interoperability is established, the challenges of understanding and improving the processes arise. They can be overcome by modeling and analyzing the processes in question. This paper presents a use case scenario from laser cutting. A new concept is introduced addressing the challenges aforementioned. It conforms to the principles of the integration and examination of data and combines virtual production with the goal of gaining knowledge through the analysis of simulated processes.

**Keywords:**

Application Integration; Data Analysis; Decision Support; Digital Factory

## 1 INTRODUCTION

Due to the global price competition, an increasing variance in customer requirements and shorter product lifecycles, production companies in wealthy countries face a growing complexity in their production conditions [1]. In order to address this complexity, the integration of computational techniques in the production environment and its simulation have been promoted in the last two decades. Because of this development and the increasing computing performance in speed and storage, the simulation of the complex production processes, including factory, machine and material, has become possible. But to simulate these processes successfully, they need to be understood properly. As a consequence, instead of being confronted with the complexity of the process, the users are confronted with complex simulation applications and processes. To solve this complexity, a process of two steps is executed:

1. Consultancy of available experts for each single manufacturing process.
2. The establishing of communication between these experts to answer specific questions on how to optimize a complete production line.

Additionally, computational techniques and simulation applications are used in the field of production technology [2] to mitigate this complexity. This approach has gained importance in recent years. Due to an increasing computing performance in terms of speed and storage, simulation applications have already changed the execution of research and development (R&D) in an industrial environment.

Although the use and the benefit originating from computational technologies for simulation were demonstrated successfully [3], the implementation of these technologies still seems to be sporadic. It has not become obvious that the simulation can provide a nice overview of a specific manufacturing process and its process domains.

In fact, both the industrial developer for manufacturing machines and the machine operator face essentially the same problem as a navigator in real space that is to find points-of-interest in the configuration space of a single machine or of a complete production line. Crucial differences consist in the fact that the required map (in case of manufacturing a process map) has more than two or three dimensions and that there are few to no “cartographers” who have created maps describing the relevant process domain space.

Exploratory analysis providing the investigation of manufacturing processes resp. its configuration space may be a helpful tool for mastering the variety of dimensions which have to be taken into consideration. With an additional visualization component, it supports developers of manufacturing technologies or even machine operators through the-dimensions of design resp. the configuration space. A prototypic implementation of such an exploratory data analysis tool in combination with selected methods of analysis, such as a multidimensional, multi-objective optimization, is currently in progress.

By now, a digital model of this prototype is drafted containing a description of its essential characteristics instead of engineering a concrete prototype at an early stage of product design. In a further step, this model is passed to a simulation application to predict the prototype's characteristics that may have changed after having passed the manufacturing step. The usage of these digital models is subsumed under the notion of virtual production, which contains “the simulated networked planning and control of production processes with the aid of digital models. It serves to optimize production systems and allows a flexible adaptation of the process design prior to prototype realization” [4] [5].

This paper introduces an integrative concept that applies solutions for the analysis of data within the field of virtual production. This concept provides for the integration, analysis and visualization of data that are aggregated along the simulated process chains of production engineering. The concept’s aim is to support the understanding of considered processes by providing appropriate analyzing methods. Because of its application to integrative virtual production processes, it is called Virtual Production Intelligence (VPI). This paper illustrates the development of the concept of Virtual Production Intelligence and its exemplary application in the field of laser cutting technology. Chapter 2 presents the introduction of VPI into laser cutting R&D. In chapter 3, requirements arising from the analysis of these manufacturing processes are explored. Chapter 4 describes how to meet these requirements. A conclusion and an outlook are given in chapter 5.

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## 2 VIRTUAL PRODUCTION INTELLIGENCE: DEFINITION AND OBJECT

Nowadays, various simulation applications exist within the field of virtual production, which allow for the simulated execution of manufacturing processes like heating and rolling. Herein, different file formats and file structures were independently developed to describe digital models. Through this, the simulation of single aspects of production can be examined more easily. Nevertheless, the integrative simulation of complex production processes cannot be executed without large costs and time efforts as the interoperability between heterogeneous simulation applications is commonly not given.

One approach to overcome this challenge is the creation of a new standardized file format, which supports the representation of all considered digital models. However, regarding the variety of possible processes and application domains, such an approach leads to a highly complex data format. Its potential and expressiveness is not required in most of its use cases. Its comprehension, maintenance and usage, again, require large costs and time efforts. Furthermore, necessary adaptations and extensions take a lot of time until their implementation is finished [6] [7].

Another approach considers the usage of concepts from data and application integration avoiding the definition of a uniform standard. Within this approach, the interoperability between the simulation applications is guaranteed by mapping the aspects of different data formats and structures onto a so called canonical data model [8] [9]. Newer approaches extend these concepts with regard to semantic technologies by implementing intelligent behavior into such an integrative system. This approach is called Adaptive Application and Data Integration [10].

As a consequence, new possibilities concerning the simulation of whole production processes emerge, which allow the examination of different characteristics of the simulated process, e.g. material or machine behavior. With regard to the analysis of the integrated processes, new questions arise as methods for the analysis of the material or machine behavior mentioned above cannot be transferred to the analysis of the corresponding integrated process. A further challenge comes up as soon as suitable user interfaces are added, which are necessary for the handling of the integrated process and its traceability.

Similar questions emerge whilst the analysis of enterprise business data. Applications giving answer to such questions are in many cases subsumed under the notion of Business Intelligence. These applications have in common that they identify, aggregate, extract and analyze data within enterprise business applications [11] [12].

The virtual production aims at an entire mapping of the product as well as of the production processes within a numerical model. Thereby, the mapping should comprise the whole lifecycle of the product and of the production system [13]. Within an enterprise, the virtual production is established by employees, software tools such as Product-Lifecycle-Management applications (PLM applications) and organizational processes [13].

The demanded possibilities for analysis serve the purpose of gaining knowledge by examining already completed planning processes. As already mentioned, the term “intelligence” is commonly used to describe activities that are linked to those analyses. Software tools, which support the analysis and the interpretation of business data, are subsumed under the term “Business Intelligence”.

As this term can be defined in different ways, at this point, the basic idea of “Business Intelligence” will be pointed out [14]: A common feature of the definitions referred to consists in the aggregation of relevant data from different data sources, which are applications within a company, into data storage, which is available whenever needed. The transmission of data taken from the application data bases into this central data storage is realized by the well-known Extracting, Transforming and Loading process (ETL). Though being common, concepts of intelligence solutions like those employed for reporting or customer relationships management (CRM) are not considered in this paper, but the integration and analysis of data. This decision is taken due to the lacking necessity of reporting and customer relationship management within the planning of laser cutting processes.

Requirements for a system that supports the planning process are described in section 3.1. In particular, the idea of Business Intelligence can be subsumed as below:

- Interoperability: Facilitating the interoperability between applications in use.
- Analytical capabilities: Systematic analyses providing the recognition of potentials towards optimization and delivering fundamental facts for decision support.
- Alternative representation models: Taylor made visualization for the addressed target group, which provides an appropriate analysis.

In order to find a solution, which fulfills the requirements mentioned above, a concept formation is needed that addresses the field of application, that is, in this case, the virtual production already mentioned above as well as the aim of gaining knowledge. This aim is also addressed by the term “Intelligence”. The concept formation will take into account approaches, methods and concepts. These will contribute to the gaining of knowledge with regard to/concerning the processes executed within the field of virtual production. Therefore, the concept formation results in the notion of Virtual Production Intelligence.

In [15], an exemplary use case from the field of “factory planning” can be found, in which data integration methods belonging to the idea of Virtual Production Intelligence have been applied.

## 3 VIRTUAL PRODUCTION INTELLIGENCE CONCEPTS APPLIED IN THE FIELD OF LASER CUTTING

### 3.1 The Laser Cutting Process

Laser cutting is a thermal separation process widely used in shaping and contour cutting applications. The industrial most relevant laser cutting process is the fusion metal cutting process, as the cutting of large metal sheets into smaller pieces with specified contours is addressed in many branches of manufacturing industry. Laser cutting has the advantage over conventional cutting techniques that it is a very fast and at the same time very accurate technology with the optical tool laser not being exposed to any wear.

There are, however, gaps in understanding the dynamics of the process, especially with regard to issues related to cut quality (cf. Figure 1). It was found that the modeling and simulation of the laser process can provide that understanding without the need for executing a lot of experiments [16].

The ablation process in fusion metal cutting is mainly based on thermodynamics and hydrodynamics, as the absorbed laser energy is converted to heat, which melts the material. In the end, this melt is driven out of the cut kerf by a gas jet coming out of a cutting nozzle coaxially aligned with the laser beam.

There are some criteria that are of major interest in the context of this manufacturing technology, such as cut quality, adherent dross and maximum cutting speed.

The modeling of a laser cutting process requires the modeling of at least three entities at the same time. The three elements involved in cutting are the gas jet, the laser beam and the material to be cut. Therefore, it is evident that the modeling of the cutting gas flow, the radiation propagation and the ablation of the material (in fusion cutting: removal by melt ejection) have to be accomplished as well as the numerical implementation of these models. This was already put into practice. So, nowadays, there are appropriate models available [16].

### 3.2 Exploration of Parameter Domains in Laser Cutting supported by Virtual Production Intelligence

In modeling and simulation of manufacturing processes, the state of the art incorporates the performance of an individual simulation. The simulation is characterized by a high dimensional input parameter set. Each parameter lies in its own range, and thus forming the parameter domain space. The quality results, which are totally dependent on the numerical model and the parameter set, play an important role in understanding and optimizing the process.

Conversely, gaining knowledge and understanding the process from just having simulation results of discrete points in the parameter space is not enough. These points should be reasonably connected to each other to form a knowledge base system that can be executed by the users.

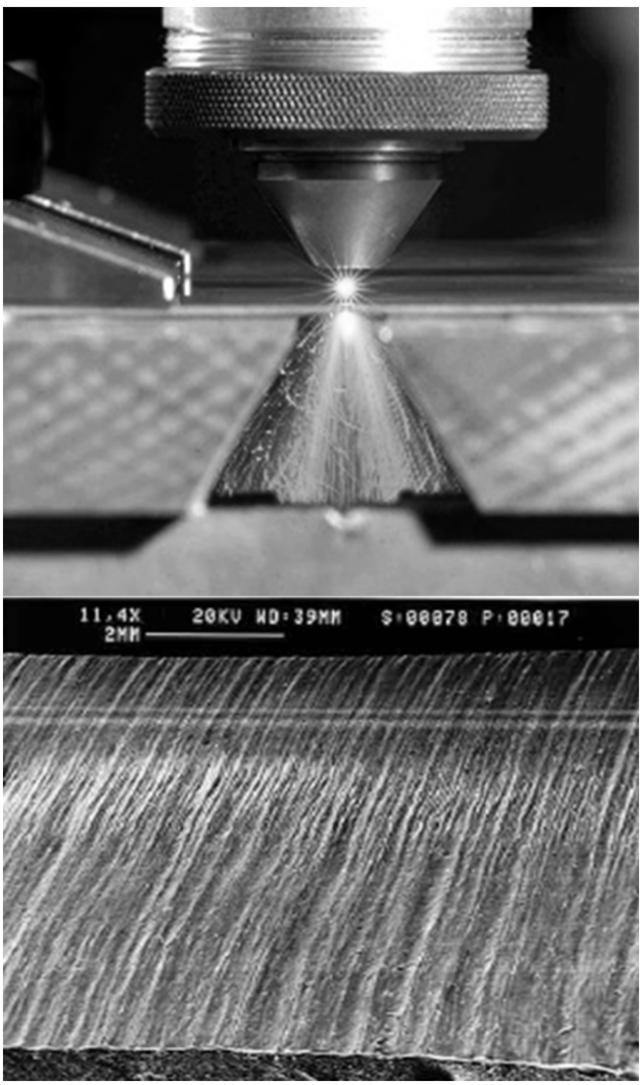


Figure 1: The laser Cutting Process (top) and the resulting cutting kerf (bottom).

The knowledge base system, which is characterized by a simple surrogate of process parameters and process quality, makes it easier and practical for the user to explore any complicated, highly dimensional parameter systems. This is done either by the identification of solution properties that contribute well to any design optimization process or by the visual exploration of certain parameter domains.

The process, in which the discrete points are transformed into a connected continuous map, is called metamodeling. Metamodeling defines a procedure to analyze and to represent complex physical systems using noncomplex, fast mathematical designs to create cheap numeric surrogates that describe cause-effect relationships between setting parameters as input and product quality variables as output.

The metamodeling procedure mainly relies on the training data which has to be collected at different sampling points. In order to choose the best coordinates for the sampling points, techniques called design-of-experiments-method (DOE) [17] are used. However, a growing multidimensional parameter space leads to a rising complexity. In this paper, the initial training set is chosen to be random and sparse. It is initialized using a space filling designs method, e.g. orthogonal array or Latin Hypercube Design (LHD).

As shown in Figure 2, the creation and extraction of simulation data is shown with appropriate physical numerical models : Spatially and time resolved simulations provide whole distributions of physical properties (e.g. temperature distributions), which need to be reduced to criteria significant for the process (i.e. scalar quantities). In laser cutting, these characteristic criteria are extracted from a cutting model such as [18] [19] and are then potentially transferred to a modeling database. The following step consists in mapping the discrete input process parameters and the output process quality through a numerical approximation. The approximation can be executed with the help of various techniques like Radial Basis Function Network (RBFN) [20] [21], Taylor series expansion, Kriging model [22] [23] or artificial neural networks (ANN) [24]. The initial metamodel is considered to have poor quality because of the small number of training data sets. Thus, the metamodel is constructed repeatedly by adding new sampling points to the training data until the quality becomes sufficient. In order to obtain a better quality the most important requirement is instantaneously adding new sampling points, first around the optimum of the metamodel and second around the sparse region in the design variable space [22]. A global optimum for multidimensional parameters can be achieved with the help of Computational-Intelligence (CI)-algorithms, for example genetic algorithms [25], which address complex real-world problems, especially in providing solutions for complicated and/or inverse problems [26]. As a result, the new evolutionary metamodeling uses the concept of evolution control to build up not only the optimal but also the minimal metamodel training data base necessary for the best approximation of the parameter-criteria-relationship possible.

In order to gain insights into the laser cutting process with the aim of optimizing it (e.g. gas savings or energy savings without any quality loss of the cut product), an exploration process is necessary. The exploration process is based on an interactive visualization platform and on optimization algorithms for solving inverse problems. Here, the metamodel is used because of its simplicity and evaluation speed. A further important component of the high dimensional exploration, is the decomposition of the underlying parameter space,

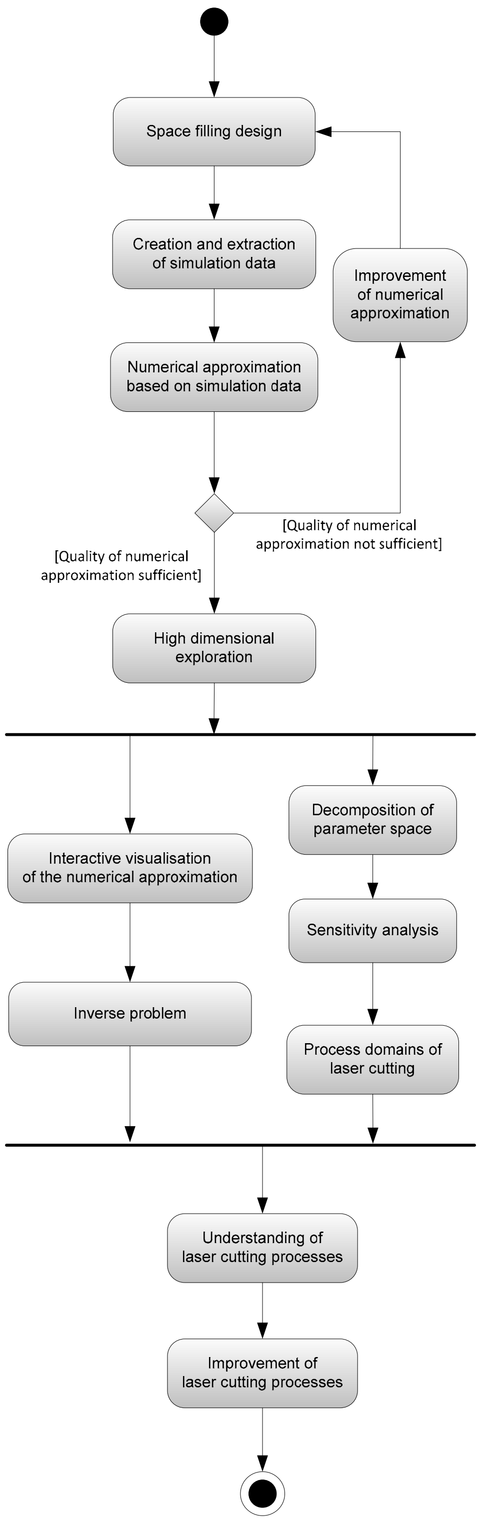


Figure 2: The VPI workflow of laser cutting process.

as it introduces the process domains from which a typical machine configuration is chosen. This could be approached, for example, by the computation of the Morse-Smale complex from unorganized scattered data [27].

The Morse-Smale complex provides a topologically meaningful decomposition of the domain by finding all of the global and local maxima and minima at the beginning of the process. Decomposing and visualizing the domain will help to acquire a qualitative understanding of the laser cutting process. Moreover, it will help to find a feasible configuration space, which is in accordance with potentially pre-defined quality criteria.

The methods introduced above result in an iterative enhancement of the metamodel function which serves as an effective approach of mapping input-output relationships for detecting the influence of input parameters on the output criteria. Besides, they assist in the decomposition of the whole high-dimensional parameter space in so-called process domains. Within these domains, numerous complicated sub-processes (e.g. the evaporation-driven melt-ejection domain should be separated from the gas-jet-driven one in laser cutting) can be better understood and optimized.

Thus, there is the need to propagate output data from simulation applications. These data describe simulated laser cutting processes, which are the multidimensional interaction of input and output quantities.

So the need of multi-dimensional analysis methods to examine the simulated processes arises. The following chapter contains a description of the actions that need to be taken to meet the requirements summarized above.

## 4 INTEGRATION AND ANALYSIS OF PROCESS SIMULATION DATA

### 4.1 Integration Process and the Data Model

Simulation results are written out into output files whose syntax is kept in a table. In doing so, it can be guaranteed that the output data is kept in a human readable form. The columns' names describe both, input and output quantities as well as the unit to measure the corresponding quantity. Table 1 illustrates the first rows of such a file describing an examined cutting process. Four columns have been selected to show exemplary quantities. Their heads describe the quantity's name and its unit.

| | PL.W. | focus.m. | rbd.mm. | wkerf.mum. |
|---|---|---|---|---|
| 1 | 1000.00 | -10.000000 | 0.0150000 | 562.264 |
| 2 | 5655.17 | -10.000000 | 0.0150000 | 769.176 |
| 3 | 5137.93 | -9.310340 | 0.0150000 | 733.526 |
| 4 | 4620.69 | -8.620690 | 0.0150000 | 699.018 |
| 5 | 4103.45 | -7.931030 | 0.0150000 | 664.268 |
| 6 | 3586.21 | -7.241380 | 0.0150000 | 629.733 |

Table 1: Exemplary input quantities of an examined laser cutting process.

To ensure the integrity of data, the user must be aware of the units used within the simulation application. In the case this is not given, appropriate computation steps have to be performed before integrating the data containing the application results into the data storage. This usage can be varied by the application's operator. The selection of a differing unit for the measuring of the laser lens' focus during the examination of one laser cutting process causes the recalculation of the extract data, so that the given quantity fits to the new unit. As a consequence, the computation of adapted values has to be performed before the integration of data is executed. The data for analysis is prepared by making use of five tables, which are depicted in Figure 3.

Each manufacturing process, which was already analyzed, determines a row in the table process. For the later purpose to build up a history of all examined processes, each process is named properly. Naming policies are not considered in the data model and have to be implemented by the use of appropriate ontologies. This approach ensures the separation of content and data. The table also contains an attribute category to guarantee the generality for manufacturing processes, which are examined by making use of the method of metamodeling as defined in section 3.1.

During the examination of a laser cutting process, several discrete simulation data are considered. To ensure this relationship between examined process and corresponding simulation data within the data model, the table metamodel contains a foreign key with the id of the associated process. The table manages the inputs and the outputs for a discrete set of input and output data as already described in section 3.2. To facilitate the versioning within the considered simulation data by examining a single process, each row within the table metamodel has a timestamp, which contains both, information about the point in time at which the simulation data was created as well as a comment for the process analyst.

Rows in the table **metamodel-quantity-value** represent each value involved in an examined process. A row in this table always corresponds to a single row in the table **metamodel**.

Each involved quantity within a numerical simulation generates a row in the table **metamodel-quantity**. It can either serve as an input for the numerical approximation (parameter) or as an output for the numerical approximation (criterion).

To differentiate between these two cases, the descriptor "specification" is used by the following convention: specification=0 means input, specification=1 means output. By following this approach, future specifications such as boundary conditions can also be considered for a numerical approximation and can be mapped into this data model without the need of creating a new attribute for this table.

Each input or output quantity has its abstracted physical quantity, which is managed in the table **physical_quantity**. The following case might serve as a simple example: the diameter of a laser jet corresponds to the physical quantity "length" as well as to the cutting length of the product. The presented approach for the modeling of data within an examined laser cutting process facilitates the implementation of requirements for other manufacturing processes explored by the method of metamodeling.

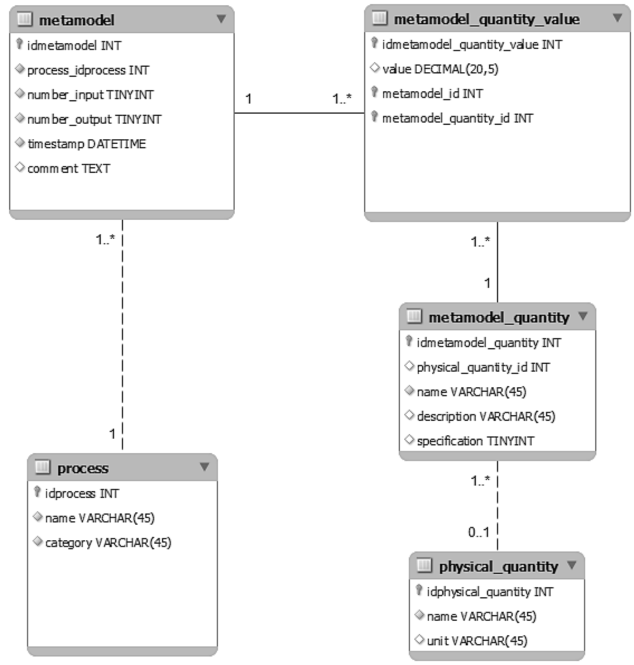


Figure 3: Data model for the integration and analysis of laser cutting data in UML-notation.

### 4.2 Analyzing the Data: Methods and Tools

As already described in section 3.2, the aim of the analysis is to determine the relationships of input variables and measured output values in a high dimensional parameter space. It can be described as follows: Assume a specified target criterion. What are the parameters involved to obtain this criterion? This problem is also known as the inverse modeling problem. Due to the high dimensionality that is characteristic of the examined data sets, dimension reduction is a requirement, which also has to be met.

Since the relationships between input and output cannot be described in a formal way, the interactive exploration of data is the approach most promising to investigate these relationships. To facilitate the exploration, an online tool is under development. The user interface consists of various manipulation and variation tools enabling the user to obtain insights within the data.

Since the philosophy of Virtual Production Intelligence contains, in particular, integration and collaboration, an online tool is build providing the usage of already developed and stable solutions in the field of data analysis. Within the last years, the programming language R [28] was used more frequently; one of the reasons is the fact that this programming language is not proprietary.

The provision of a fast communication with less latency is a crucial requirement. This requirement is met by servers using the web socket protocol [29] enabling the bidirectional communication between client and server.

To build up a prototypical but stable web application as fast as possible, which provides the integration of data analysis methods written in R, the web application framework "shiny" [30] has been used. It is based on the usage of the web socket specification.

The implementation of promising statistical methods like clustering, dimension reduction and singular value decomposition is initiated and first results encourage the implementation of further methods. Most of these are available via packages written in R. One of these packages subsuming many benefits is the Morse-Smale-Package [27], which is also available at the VPI-platform. Figure 4 shows a screenshot of the implementation of the Morse-Smale-Package as a web application with the help of the "shiny" framework mentioned above. In future development steps, further analytical methods will be available for the examination of process data sets. This will be realized by invoking web services with appropriate interfaces to the implementing language, such as C, Python or R.

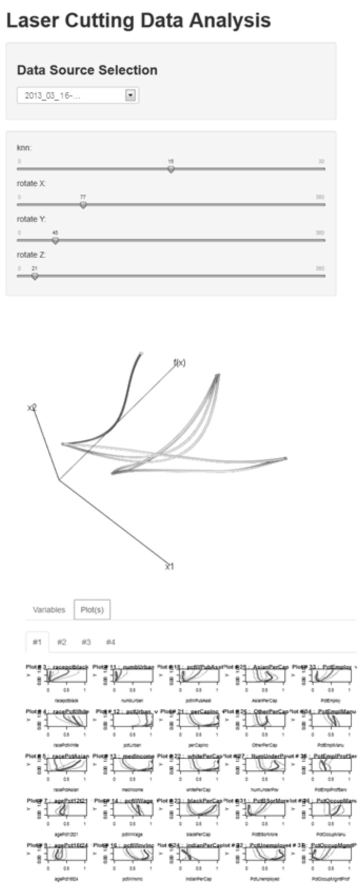


Figure 4: Screenshot of the user Interface for online analysis of simulation data

## 5 SUMMARY AND OUTLOOK

This paper presented the general idea of Virtual Production Intelligence and its application in the planning of laser cutting processes. Generally, its aim is to support processes within the Virtual Production by providing the integration and the analysis of data generated along the planning of production processes. In particular, the analysis requires the usage of appropriate methods and tools.

One concrete application of this idea consists in the use of the computational technologies mentioned above for the R&D of the laser cutting process. During the examination of these processes, numerical methods have a huge impact on the planning. Requirements on data integration and analysis were described and it was pointed out how these requirements can be met. Furthermore, an online analysis tool was described, which is suitable for the analysis of high dimensional data sets.

Further progress will contain the elaboration of additional methods for the refinement of numerical approximation and the identification of suitable stochastic methods. In both cases, an implementation for the validation of the identified methods is intended to show how the additional methods have improved compared to the methods used in the past.

## 6 ACKNOWLEDGEMENTS

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# Immersive Presentations: Enabling Engaging Virtual Reality Based Training and Teaching by Merging Slide-Based and VR-Based Elements

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**Abstract**

Training of the staff is a time consuming task. Today a lot of explanations are done at the built machine. Using Virtual Reality (VR) the staff could be trained at a virtual model. Presenting additional information like texts or diagrams besides the virtual model is essential for education purposes, but a time consuming process feasible only by experts. We are addressing this issue by presenting a concept to create Immersive Presentations and an App suite that enables the trainers to create VR based education scenarios augmented with additional information in an easy and comprehensible way on their own.

**Keywords:**

Virtual Reality; Training; Authoring

## 1 INTRODUCTION

In the globalized manufacturing market, the pressure to reduce time and costs is rising constantly. Development cycles are getting tighter and demand parallelisation of work. One time consuming step in this cycle is the training and teaching of the staff that is responsible for installation, maintenance and operation of new machines. It is often necessary to spend a lot of time for explanations at the built machine, although the design of the machine is completed a long time before and the virtual model could also be used for training purposes.

This is the point where Virtual Reality (VR) steps in. By utilizing the 3D CAD data the staff can be trained and taught at a virtual model of the machine in parallel to its construction. The benefits from a VR based education, using a true to scale virtual model that one can interact with in real time, are high. This has been seen by others and there are already a few pilot projects that have implemented such training scenarios[1-4]. But the key aspect for the quality of VR based training and teaching is the level of immersion of the trainees [5, 6]. Besides the virtual model, presenting additional information like texts, diagrams, 2D plans or data sheets is essential for educational purpose. Commonly such information is shown in form of slides. Separating the presentation of the VR model and the presentation of the additional information, that would actually be presented best together, leads to a huge quality drop of the training and teaching [7]. But embedding the additional information in a VR model is a time consuming process feasible only by experts. Creating different VR based education scenarios with different scopes for different audiences concerning the same machine model would be way to expensive. This is important especially for small and medium size enterprises, where a very slim, effective and flexible workflow is the main prerequisite for VR-applications.

We are addressing this issue by presenting an App suite that enables the trainers to create VR based education scenarios augmented with additional information in an easy and comprehensible way by their own. For handling and presenting this additional information we will introduce an element called 'Information Carrier'. This is a 2D plane always rendered on top of the virtual 3D scene that can contain textual and image information. Further we will describe how our developed flexible presentation structure allows the teacher to create comprehensive, agile and immersive VR presentations through the seamless combination of very few basic visualisation components. The description of the Apps that are using this as a common data base will point out that our uttermost concern lies in a high reusability of the created Immersive Presentations as well as an easy usage. Further we will show that the created Immersive Presentations are in principle independent from a specific VR software. We will achieve this by defining a very simple and lightweight independent interface that has to be adapted to the specific target VR Software. We will also outline how our flexible interaction concept allows the integration of existing and novel interaction devices by separating the actual interaction method from the interaction trigger.

## 2 VR BASED TEACHING AND TRAINING

The first applications of VR in training were established in the military sector, e.g. as flight simulator [8, 9]. A second main application area of VR based training is medical sciences were VR is used e.g. for surgical or diagnose training [10-12]. In addition, VR is frequently used as training environment for dangerous emergency situations, like firefighting on a ship [13] or sensitizing children to the dangers of fire [14]. Especially the last application mentioned uses the motivating and explorative character of the VR technology. Therefore, regarding education in schools and at universities, VR can be used in many different ways [15]. In schools it is used to betters describe e.g mathematical [16] or physics related problems. In terms of engineering education at universities VR can be used as visualization tools for lectures or as hands on training environment for exercises and practical training [15].

Over the last view years, some VR based training applications have been developed in the area of production engineering [17]. Some of those training applications have been developed for operator trainings at machine tools [18, 19]. Others target the simulation and training of assembly processes [20, 21] or the operation of heavy equipment [22].

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DOI: 10.1007/978-3-319-02054-9_21, 

All of those VR based training applications have one thing in common – a VR expert is needed to create them. That is one of the most critical barriers that prevents VR from being used for training applications more frequently. The first step to create such a training application are the VR objects (e.g. the VR model of the machine tool). If 3D CAD data is available, it can be used as a basis for the VR model. Depending on the type of training, the CAD data has to be processed – e.g. adding photorealistic textures and process animation. If for some parts CAD data are not available they have to be created using other software tools. All these steps need expert knowledge and are time consuming but are not within the focus of this paper.

Starting from mentioned VR models, the next important step is to integrate additional information material into the sequence of the training session. Therefore it has to be defined which objects (models, images, etc.) are visible at a certain point. Furthermore the way of interaction has to be realized, e.g. how the switching of images will be done and with which interaction device this will be realized. Taking all that into account, creating a VR based training session is very complex and usually requires expert knowledge in VR and information technology. But those experts are not the experts for creating training applications based on didactical concepts or for maintenance processes.

To solve this problem, a method for an easy to use authoring tool has to be developed. Using this tool, the “non VR-expert” teachers should be able to use the VR-scene and create Immersive Presentations. The result is a VR training presentation created without the help and support of VR-experts.

## 3 CONCEPT FOR IMMERSIVE PRESENTATIONS

Our approach for creating Immersive Presentations lays uttermost concern on the seamless integration of prepared VR-ready 3D-Models, VR interaction and 2D content by defining a small and easy to use but mighty set of elements. By analysing the basic elements from VR presentations and common slide-based presentations we found out that these elements can be separated in two general categories: content elements and structuring elements. Fig. 1 gives an overview of the elements of the method and how they are connected. A content element can be ‘Text’, an ‘Image’, an ‘Animation’ in the VR model and the ‘Highlighting’ or ‘Visibility’ changing of parts of the 3D model (see Figure 1).

But to actual build Immersive Presentations out of these five basic content elements they have to be combined through structuring elements. We adapted four structuring elements that are well known from common slide based presentations to the VR context. The first is ‘Presentation’, which represents a comprehensive and consistent VR presentation. A ‘Presentation’ element is composed of one optional ‘Master’ element and multiple ‘Slide’ elements. The ‘Master’ element contains content elements that are active through the whole presentation, like a company logo that appears in the lower right corner of the VR scene throughout the whole presentation. A ‘Slide’ is just a simple container for ‘Click’ elements which contains the actual content elements. As this may appear as an unnecessary boxing of containers we think it is an important construct to assure a good usability. When thinking of common slide based presentations there are in general two ways of how to present the content of one slide. The first is that the whole content is shown when the slide appears first. The second way is to show only a part of the content when a new slide appears first and displaying the rest of the content by consecutive clicks. Our ‘Slide’–‘Click’ boxing construct just enables the user to apply both patterns based on the slides content or personal preferences. Furthermore there is a difference between ‘Slides’ and ‘Clicks’ in the way the content is handled. While after the start of a new ‘Slide’ all afore displayed content is removed, a ‘Click’ only defines the change of content. Content shown on previous ‘Clicks’ of the same ‘Slide’ are untouched. This mirrors precisely the behaviours of common slide based presentations (see Fig. 1).

There exists one other element that represents a hybrid of content and structure element, called ‘Sequence’. The ‘Sequence’ is a content element in the way that it can only be added as content to a ‘Click’ or ‘Master’ and therefore is handled like all other content elements. Nonetheless a ‘Sequence’ itself only consists of other content elements that are activated or deactivated sequentially after a defined time which is clearly structure element behaviour (see Fig. 1). A vivid example for a useful utilization of a ‘Sequence’ would be the display of measure values in accordance to a measuring process animation of a work piece.

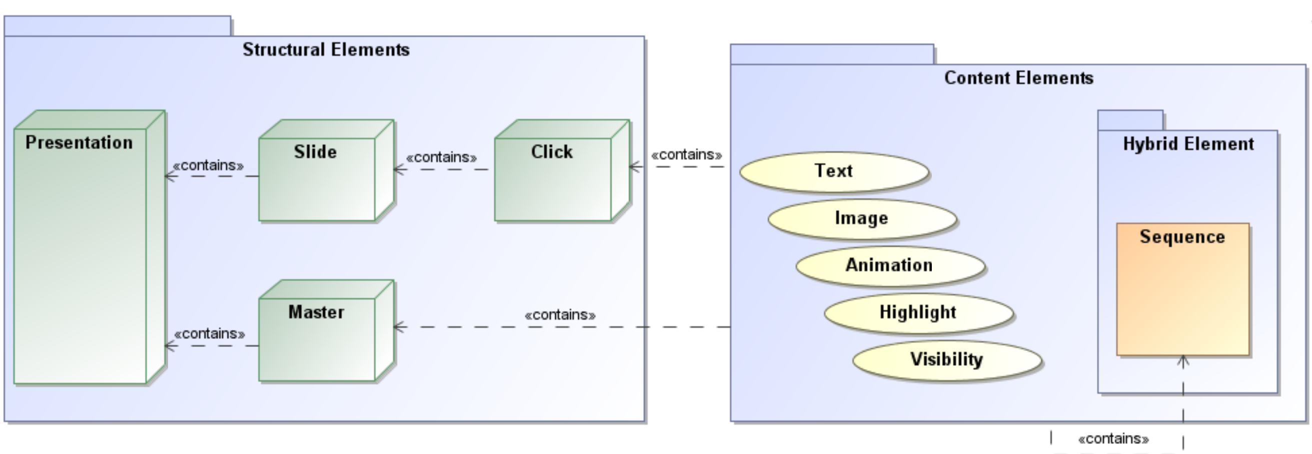


Figure 1: Elements of an Immersive Presentation and their connections.

With this small set of elements the trainer is able to create Immersive Presentations that are combing the advantages of VR with common slide based training methods. For embedding the 2D Information we define an 'Information Carrier' that works as a container for images and texts. This 'Information Carrier' is always rendered on top of the VR scene and therefore always visible. Embedding 2D information like diagrams or sketches next to an animated VR model and tailoring it together in a common presentation like structure, leads to a very engaging training experience for the trainees. In Figure 2 shows an example of an Immersive Presentation training application for maintenance staff.


Figure 2: Example of an Immersive Presentation for measuring the concentricity of a spindle in a VR training application in the field of maintenance.

## 4 APP SUITE

Essential for the practical usage is that the trainer can define and play such a presentation in an as easy as possible way with various interaction devices. This section will outline an App suite that tries to solve this issue.

### 4.1 Overview

The first version of Immersive Presentations was designed as one all-embracing program. The extended use of mobile devices changed the way, users are interacting with software as well as the way programs are being used. We decided to go away from the classical design to a small set of easy to use and task specific apps. These apps do currently not exist in their desired functioning state but rather have to be seen as a work in progress.

When analysing the tasks of the trainer, we concluded that they can be split in to three main groups:

1. Creating the Immersive Presentations and editing existing ones
2. Playing the Immersive Presentations
3. Adapting the usable interaction devices and techniques to the trainers preferences

Based on this we deemed that four apps would be sufficient to fulfil all tasks:

1. An 'Authoring' app containing all created Immersive Presentations to ensure an easy managing of the Immersive Presentations and a high reusability of the created content.
2. An 'Editing' app that allows the manipulation of one existing Immersive Presentation.
3. A 'Playing' app that is used to control the Immersive Presentation and to show it to the trainees.
4. An 'Interaction' configuration app that allows the trainer to specifically set an interaction method to an interaction trigger.

All four apps are built on the same data model of the Immersive Presentations. The Immersive Presentations are made persistent in two XML files so that changes could easily be done even without the help of an app. One XML file contains the actual 'Presentation' (*.prs) and the other one is storing the information of the 'Master' (*.mst). This separation was made because a 'Master' can be used in multiple 'Presentation' and changes to it should not lead to inconsistences in all dependent 'Presentation'. Resources like images are not stored inside the XML files but only their reference to their location in the file system.

### 4.2 Authoring and Editing

The idea behind the 'Authoring' app is that of a workspace, were all the Immersive Presentations are stored. Three folders are located under the workspaces root folder:

- The Presentations folder containing all *.prs files
- The Masters folder containing all *.mst files
- The Resources folder containing all resources like images

In the workspace the trainer can create, edit and delete the Immersive Presentations via the 'Authoring' app. By using this concept the trainer can easily reuse parts of other Immersive Presentations and has a complete overview. If the trainer wants to play a immersive presentation it isn't convenient for him/her to copy the whole workspace on a flash drive for demonstration on a VR system. Besides this inconvenient data handling, there is also the security aspect that has to be taken into account. If the trainer conducts the training on a computer from a different company it could be dangerous to store the whole workspace with every Immersive Presentation on this computer.

To account for this, every Immersive Presentation can be exported out of the 'Authoring' app to a *.ply file containing all data. This allows the trainer to only take the relevant Immersive Presentation(s) to the training place. In a lot of cases the need for slight changes of the Immersive Presentation will occur. With the 'Editing' app the trainer can open an Immersive Presentation file and carry out the changes. The *.ply file is an encrypted ZIP file storing the same structure but only with relevant data of the exported Immersive Presentation. This use case is the reason why it is very reasonable to have two apps for manipulating the Immersive Presentations although this might seem redundant at first glance.

Figure 3 (left) shows an example of the user interface (UI) for an 'Image element in the 'Authoring' app. This UI could have been used to define the image in the right picture of Figure 3, which shows a part out of an maintance worker training created with the first version of the Immersive Presentation. On the left side of the UI mock up, the workspace with all present Immersive Presentations can be browsed. We decided to separate the visualisation of the 'Presentation' and the 'Master' in two different tabs to clearly

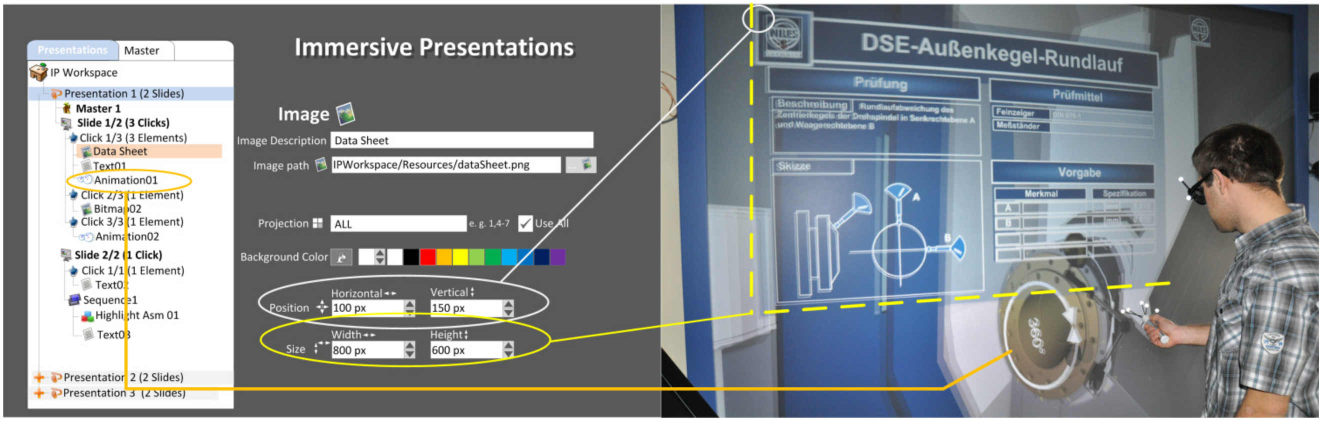


Figure 3: Example of an UI mock up for an 'Image content element (left) and the correspondence of the parameters in the immersive einvironment (right).

highlight the conceptual differences. This left side for navigating through the Immersive Presentations always stays the same, no matter what element in the tree is currently marked. The right side of the UI always shows the editable properties of the currently marked element in the tree. Most of the properties for the 'Image' element in Figure 3 are well known and do not need further explanation, so we concentrate on the not obvious ones. Both 'Position' properties simply tells how far away the upper left corner of the 'Image' should be away from the upper left corner of the projection screen. The 'Projection' property indicates on which projection screens the 'Image should be displayed. This is only of interest in a multi-projection virtual environment like a Cave Automatic Virtual Environment (CAVE).

For the 'Editing' app the only difference in the UI is that on the left side only one 'Presentation' and 'Master' is shown and accessible.

### 4.3 Playing and Interaction

The 'Playing' app is a program used to show one Immersive Presentation and responsible to carry out the interaction. Starting the app can be done independently from launching the VR software and loading the model of interest. Just when the Immersive Presentation should be started it is necessary to have already loaded the model. Only the exported *.ply files can be shown with the 'Play' app.

Various interaction devices are currently available whilst there is also a steady increase of new available devices. We have decided to go with the principal of separating the interaction method from the interaction trigger to avoid a binding of the software to a specific interaction device. This principal was shown by Olwal and Feiner [23] as part of their presented UNITY framework and was adapted by others like Wittstock et al. for their VR interaction framework using Android devices [24].

In the case of Immersive Presentations a further separation between the interaction in the VR environment and the presentation interaction has to be made. VR software systems can usually be configured for the usage with different interaction devices, so it is possible to adapt the VR interaction. But setting up the interaction device in the VR software is a task that has to be done by an expert once. Afterwards the interaction device can be used by the trainer without the experts help.

For the Immersive Presentation interaction we have defined a small set of possible interaction methods:

- Moving a 'Slide' forward/backward
- Moving a 'Click' forward/backward
- Hiding the 'Information Carrier' that displays 'Text' and 'Image' elements
- Starting/Stopping the whole Immersive Presentation
- Starting/Pausing an currently running animation
- Making a 2D screenshot of the current viewpoint of the VR scene

These interaction methods can now be mapped to any kind of trigger, which can be a button on a device, a button on a graphical UI, a gesture or even a spoken command. The integration of the trigger has to be done by an expert, but once it is integrated, the trainer can easily configure the mapping between the interaction methods and triggers to his/her own preferences. This mapping is exactly what the 'Interaction' app is there for. In Figure 4, the UI for a Wiimote is shown which we have integrated. The UI is very simple and quite self-explaining. The trainer can choose for a button on the Wiimote which Immersive Presentation interaction method should be triggered by pressing it. The trainer is even able to trigger the same method with different buttons, like in Figure 4 where the 'Click Forward' method is triggered by the '+' button and the right arrow of the control cross. A detailed look on the UI leads to question why the 'A' button and the button on the backside of the Wiimote are not configurable. We use these buttons to control the VR software which in our case is ESIs VDP [25].

To use the Wiimote as a full-fledged VR interaction device we had to solve the tracking issue. We decided to use optical tracking with passive markers. The first approach to attach the target tree to the Wiimote can be seen on the left side in Figure 5. We used a shell to put the markers on and the Wiimote could be attached. Although the Wiimote was now absolutely usable we were not satisfied with the design as it is pretty chunky. After another design iteration we came up with the version shown on the right side in Figure 5. We replaced the infrared communication part at the front of the Wiimote with a little block of hard plastic where the target tree could be built into.

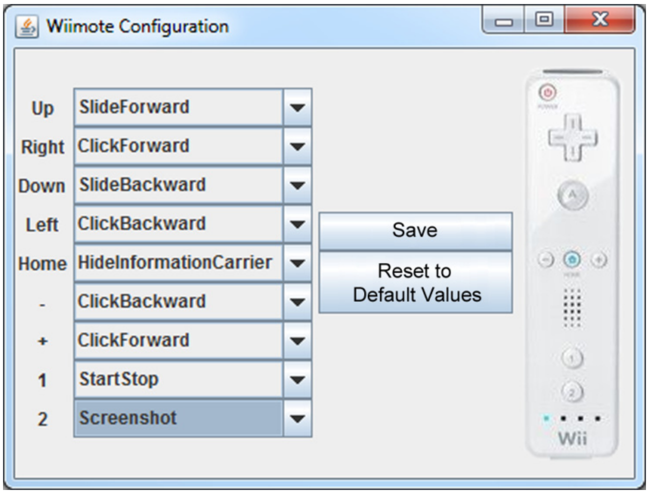


Figure 4: UI for mapping the Immersive Presentation interaction methods to their triggering buttons of the Wiimote.

## 5 VR INTERFACE

As important as the flexibility regarding the usage of interaction devices is the independency from the VR software system. Binding the Immersive Presentations strictly to a specific VR software system would drastically decrease its usability. In the previous section we have implied that in the current implementation of the Immersive Presentations VDP [25] is used as the host VR software. But in the software design, we made sure to use it over an abstract interface. This interface defines the set of methods which are necessary to execute the described functionality of the Immersive Presentations; Methods such like positioning the 'Information Carrier' for 'Text' and 'Image' elements on the screens or starting an animation that was defined in the VR model. Right now only a full implementation for the VDP VR software exists but to really proof validity of this concept we are currently implementing the Interface for a second VR software which is instantreality developed by the Fraunhofer IGD [26].

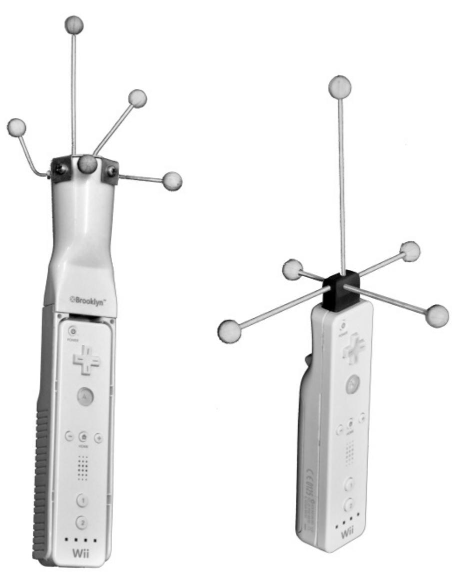

Figure 5: Wiimote enabled for passive optical tracking in a VR environment. Click-in version (left) and built-in version (right).

## 6 IMMERSIVE PRESENTATION LINK TO VR MODEL

The usage of the VR content elements 'Animation', 'Highlight' and 'Visibility' are depending on the used VR model. Any animation that the trainer wants to use as a part of the Immersive Presentation has to be defined in the VR model. The granularity of the objects of the VR model, that the trainer wants to highlight or change the visibility, is limited by its structure. Only the objects that are a part or an assembly (like in CAD) can be used for this. This may seem as a big hindrance for definig an Immersive Presentation at first glance but actually it is not that grave of a constraint. The VR models used for training are generated by using the CAD data of the machine. The CAD source garantuees a high granularity of assemblys and parts. The definition of the animation is an extensive task depending on how much animation is needed, but once the VR model with the animations exists, it can be a source for multiple Immersive Presentations.

## 7 CONCLUSION

In this paper we have presented the concept of Immersive Presentations which can improve VR based training. This concept combines the structuring elements of common slide based presentations and 2D information with VR functionality. We have further outlined that the App suit for creating, editing, playing and interacting with these Immersive Presentation is easy to use and would enable trainers for the first time to create VR training without expert knowledge. We showcased this with the example of a mock up UI. Our presented data handling concept also shows our concern for an easy usage of the Immersive Presentations by the trainer.

As the easy creation of VR training content is one of the big hindrances currently preventing VR based training to become state of the art we think that our user centric development approach tackles this issue in a comprehensive way. By presenting our flexible interaction approach that separates the interaction method from the interaction trigger, which we have adapted from Olwal and Feiner [1], we made sure that our Immersive Presentations can be interacted with through a variety of devices, assumedly even currently non-exiting ones. We outlined this with the example of a slightly modified Wiimote controller. To ensure an as wide as possible usage of the Immersive Presentations we have defined an universal interface that consist of all functions necessary to execute the Immersive Presentations concept. We have done an implementation of this interface for the VR software VDP and are currently developing one for the VR software instantreality.

Although we require a VR model with prepared animations, which stays a complex time consuming task, it is possible to build different Immersive Presentation basing on the same model but focusing on a different audience. Taking the model form the maintenance worker training that we have mentioned, it would be easy to create an Immersive Presentation for sales training based on this exact same model.

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# A Vagueness Measure for Concurrent Engineering of Manual Assembly Lines

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**Abstract**

In concurrent engineering, uncertainty in process planning arises because product design remains unfinished. Common solutions involve staying vague or creating concrete but speculative plans. In this work, a vagueness measure for process descriptions is proposed. The proposed method employs a controlled natural language for process descriptions. The measure is applied to an automotive end assembly project. Results show that the vagueness measure in initial planning is correlated with the number of changes in both work task attributes and work task descriptions. Future applications could address optimisation of planning detail throughout concurrent process planning.

**Keywords:**

Concurrent engineering; process planning; controlled natural language

## 1 INTRODUCTION

In order to address issues such as high product variety and shorter product development time, concurrent engineering has been proposed for an early integration of product design and production planning [1]. Today, concurrent engineering is common business practice for automotive producers. It introduces the challenge of planning assembly processes against changing product designs. In such environments, planners regularly have incomplete knowledge of design. One approach to process planning is to employ abstract and vague words in alpha-numerical assembly plans until product details are concretised. Another approach is to create concrete but speculative assembly plans, assuming the risk to re-plan as product details are concretised (s. Figure 1). In the last few years, the latter approach has been introduced to multiple large scale assembly planning projects. It is referred to as “front loading”.

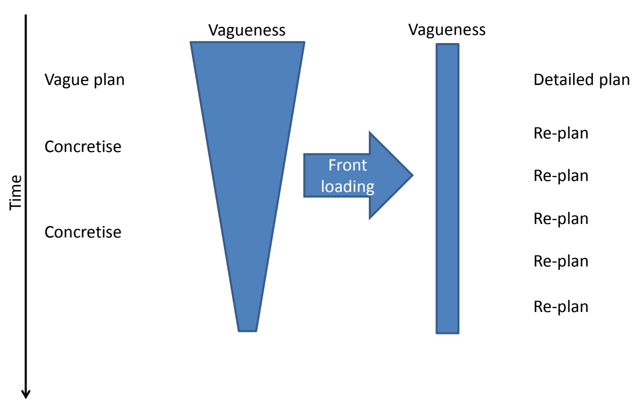


Figure 1: Vague versus speculative concurrent process planning.

In practice, process descriptions within one planning project employ different levels of vagueness. However, process description texts that are written individually by each planner are normally not objectively analysed and aggregated even though management has a general idea about which level of vagueness is desirable. Therefore, the exact effect of varying the level of vagueness stays unclear. If varying the vagueness has an effect, for example on planning effort, then the vagueness level might be optimised. Such an optimisation would require an objectively quantifiable measure of the process description text vagueness. Ideally, such a measure should be automatically generated so that it does not introduce additional cost.

## 2 PROCESS MEASURES FOR CONCURRENT ENGINEERING AND PROCESS MODELLING

### 2.1 Measures for Concurrent Engineering

Concurrent engineering projects have been subject to numerous studies that define quantitative measures. These measures aim at performance measurement and optimisation. Subjects of performance quantification include:

- Measurement of concurrent engineering practices affecting on product innovation, price and quality [2],
- Estimation of project progress to minimise project duration and redistribute remaining work [3],
- Measuring the degree of concurrency and understanding its effect on product cost and quality [4] and
- Quantification of complexity and emergence aiming at more reliable effort estimations [5].

Many approaches integrate measures – often from multiple domains. In [4], the degree of concurrency involves aspects such as information flow and overlap in problem solving.

Koufteros et. al. use questionnaires in order to derive a set of scales for concurrent engineering practices. These scales concentrate on concurrent engineering practices such as work-flow, number of teams and early involvement [2]. However, the impact of early release of information is measured on a general basis, i. e. the questionnaires address usage of “techniques such as QFD” (Quality Function Deployment) or “process design is done concurrently with product design”. While this information is clearly quantifiable, it tells little about how detailed manufacturing planning – including the aforementioned methodologies – should be. In order to derive such information, process based measures are required. While such analysis has been discussed for production process complexity (c. [6]), there is no established measure for the level of detail of work task descriptions in manual assembly processes.

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DOI: 10.1007/978-3-319-02054-9_22, 

### 2.2 Process Modelling

Manufacturing process content can be modelled systematically using e. g. graphical methods [7]. These methods map on data structures that can be employed to define measures about different process aspects such as complexity or standardisation.

One drawback of this approach is that production planners normally use natural language as a planning tool, e.g. by writing work task descriptions inside assembly plans in free text form. In order to standardise natural language work task descriptions, controlled natural languages (CNL) have been introduced [8][9]. These CNLs allow planners to write work task descriptions using a limited set of terms and a predefined grammar.

Since work task descriptions that are written in a CNL are readable for both humans and computers, alpha-numerical assembly plans can continue to be employed in a way familiar for planners and workers. At the same time, CNL based descriptions open a wide range of possibilities for different automated analysis and applications. For instance, in [9] digital human model manual assembly simulations are automatically created using CNL written assembly plans.

## 3 A MEASURE FOR PROCESS DESCRIPTION VAGUENESS

This work presents a vagueness measure for single sentence work task descriptions in automotive end assembly. The measure is employed in an analysis of a production planning process. The goal of this study is to understand whether the vagueness of work task descriptions at the beginning of process planning has an effect on the subsequent planning effort.

### 3.1 Standardisation of Work Task Descriptions in a Controlled Natural Language

In order to make process descriptions readable for both planners and computers, a CNL has been set up. The objective of this CNL is to change work task descriptions as little as possible. Therefore, a frequency analysis of grammatical components of 1824 existing process descriptions has been conducted. This analysis reveals single sentence structures without subordinate or conditional clauses. Sentence structure is found to mainly depend on the activity. Thus, an activity based grammar has been set up, which constructs sentences from the following semantic roles:

- ACTIVITY Main process activity
- THEME Part that is manipulated
- GOAL Part that the THEME is joint to
- SOURCE Part that the THEME is separated from
- FASTENER Part that secures a fastening
- TOOL Part that is used to conduct the ACTIVITY
- INSPECTION Objective of an inspection ACTIVITY
- NUM Number of times an ACTIVITY is conducted
- LOC One to three locational attributes of a part

The grammar of the CNL consists of one fixed role sequence per activity, which allows simple parsing. In order to reduce migration of legacy process descriptions, an input mask for easy validation of planning input has been developed. In close collaboration with planners, role contents have been optimised. This has led to a CNL that is able to cover between 70% and 90% of the process descriptions depending on the planning domain.

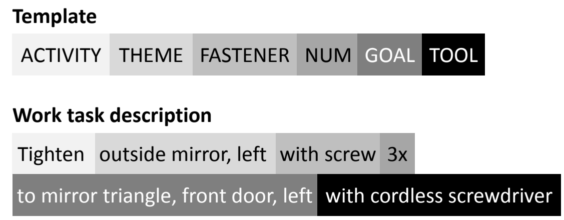


Figure 2: Example of a work task description in the controlled natural language.

### 3.2 Measuring Vagueness of Semantic Roles

Activities and role content are mapped to hierarchies, which have different levels of abstraction. For value adding activities, DIN 8580 ff [10]. is used. Activities levels are determined from the layer of the mapped manufacturing process definition in the standard's tree. The closer a term's node is to the tree root, the vaguer and more abstract a term is considered (s. Figure 3).

The activity "tightening", for example, is mapped to the tree node 4.3.1 of DIN 8593-3 [10] (German term "schrauben"). Its distance to the root node is 3. Its vagueness level $A$ is calculated by subtracting the ratio of the node distance to the tree root to the maximum tree depth of the sub tree from 1. For node 4.3.1, $A = 1 - \frac{3}{3} = 0$. For the parent tree node 4.3 "pressing on/force fitting" $A = 1 - \frac{2}{3} = \frac{1}{3}$ etc.

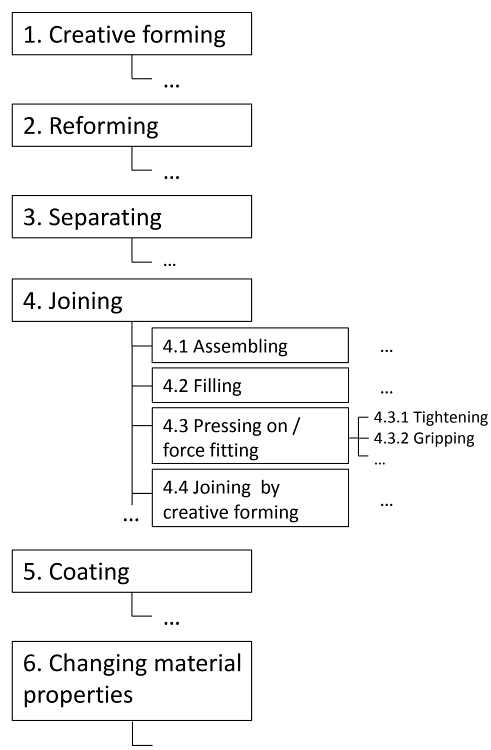


Figure 3: Scheme of arrangement for the six main groups of the manufacturing methods (excerpt from [10]).

There are non-value adding assembly activities such as conveying, storage and handling, which are not covered by DIN 8580 pp. [10].

For these activities, the tree hierarchy of VDI 2860 [11] (fig. 7 of the standard) is employed. The abstraction level is again determined from the tree level. In order to gain levels of abstraction that are comparable to DIN 8580 pp., the nodes “conveying”, “storage” and “handling” are considered having a distance of one to the root node.

Role content comprises multiple types of terms such as product parts, handling resources, building features, locational and feature describing attributes, prepositions, number information, inspection types and abstract terms such as product precedence, e. g. “next car”, or test feature. These term types do not coincide with semantic roles because a part or a resource could for example be in the role of being handled by a worker.

The most comprehensive role content type is product parts. Product parts are described in a term hierarchy, which is dependent on part functionality but independent from model type and variant. This term hierarchy enables reuse of work task descriptions as well as comparison of products that follow different design concepts. An example for a path through product part hierarchy is (K/Z* stands for cable/tube):

1. Interior equipment
2. Center console
3. Center console/storage tray
4. Center armrest/stowage compartment, front
5. Lid, center armrest/stowage compartment, front
6. Lock storage tray
7. Ambiance illumination, center console
8. K/Z*, ambiance illumination, center console
9. K/Z*, ambiance illumination, center console, left
10. K/Z* 2, ambiance illumination, center console, left

For product parts, which are normally used in THEME and GOAL roles, a term hierarchy is employed that comprises about 80,000 terms. For resource and abstract terms, no multi-level hierarchy is employed. Therefore, these terms are ignored.

### 3.3 Aggregation to One Vagueness Measure

Role content can be assigned a vagueness level using the above described methodology. This approach yields a component for part vagueness levels $P$ (THEME, GOAL, SOURCE, FASTENER and TOOL), and an ACTIVITY vagueness component $A$. Each measure ranges from 0 to 1 and therefore is normalised.

However, there is information such as location that can be described by adding an additional role as well as by choosing a more detailed term from the database. Therefore, the vagueness level of each semantic role has to be accompanied by the number of roles $R$ that are present. An intuitive approach would be to interpret a large number of roles as decreasing vagueness. However, in the depicted use case, a large number of roles resulted from wordy yet vague work task descriptions. Therefore, the proposed vagueness measure includes a component for $R$, which is also normalised between 0 and 1, where 0 means the lowest possible number of roles and 1 means the maximum number of roles.

Thus, an aggregated vagueness measure $v$, between 0 for least vague and 1 for most vague, with the different component values equally weighted is derived as follows:

$$v = \frac{1}{3}(\bar{P} + A + R) \quad (1)$$

where,

$A$ is the activity level,

$\bar{P}$ is the average part level and

$R$ is the normalised number of roles.

The aggregated vagueness measure can be further aggregated across multiple work tasks and stations up to whole assembly lines. Such an analysis would allow a quick overview of the latest state of a large scale planning project.

## 4 APPLICATION TO AUTOMOTIVE ASSEMBLY PLANNING

The presented vagueness measure is applied to a planning project for a model change in an automotive end assembly. In the initial planning phase, work tasks are organised in modules. From 8 randomly selected modules, work tasks that later are employed in the end assembly line are identified. The measure is derived for the resulting set of 49 work task descriptions. In order to gain information about the measure’s relevance to the concurrent engineering process, the change history of these work tasks until start of production is analysed.

The analysis comprises the following end assembly modules:

- Front door (left and right)
- Front door hinge (left and right)
- Rear door (left and right)
- Rear door hinge (left and right)
- Instrument panel cross member
- Rear side window
- Interior illumination lamps
- Seat belt

For each work task the total number of changes from initial creation until start of production, as well as the number of changes of the work task description is counted. This approach allows differentiating between work description related and total planning effort. For example, when design replaces a part that is related to a work task then the new part is linked to the work task and the old part is unlinked. If this does not affect the task description then only the total number of changes is increased.

In this analysis, work task changes without manual involvement are not counted. Furthermore, a range of work tasks had been split during the planning process. These tasks are analysed from their initial version, i. e. all changes of all split work task components are added together.

## 5 RESULTS

### 5.1 Total Number of Work Task Changes

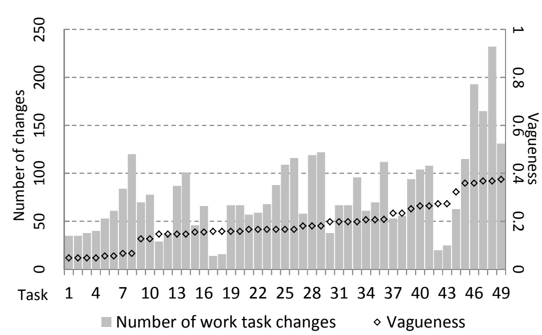


Figure 4: Total number of work task changes and vagueness measure for each one of the 49 analysed work tasks.

In the analysed work task descriptions, the activity vagueness level has an average of 0.10 and the normalised part vagueness level has an average of 0.19. The number of filled-in roles varies from 3 to 8 with an average of 5.16. The aggregated vagueness measure shows a minimum of 0.05 and a maximum of 0.38 with an average of 0.19.

Figure 4 shows that for the analysed data the maximum number of work task changes is 232 and the minimum number of changes is 14. The average number of changes is 77.8.

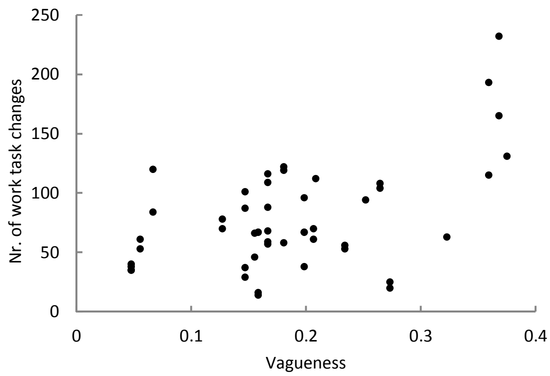


Figure 5: Total number of work task changes to task description vagueness.

Figure 5 displays that the average re-planning effort increases with increasing work task description vagueness. A cluster of five work tasks with high vagueness level and high number of work task changes can be distinguished. These tasks show both high number of roles and a high degree of abstraction in each role.

### 5.2 Total Number of Work Task Description Changes

If the same analysis is applied to the number of work task description changes then a similar pattern is derived. For the analysed data the maximum number of work task description changes is 21 for a vagueness measure of 0.37 and the minimum number of description changes is 0 for a vagueness of 0.16. The average number of description changes is 5.9.

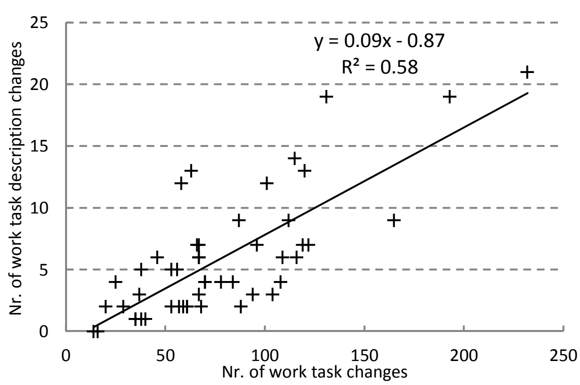


Figure 6: Number of work task description changes and total number of work task changes for the 49 analysed work tasks.

Figure 6 displays the distribution of the work task and the work task description changes for the analysed work tasks. As expected, the more changes made to a work task, the more its description changes. A linear regression analysis of the data shows that the number of work task description changes is roughly 9% of the number of total work task changes.

A strong correlation of work task description vagueness with changes that are not related to work task descriptions could result from anticipation of part changes. This hypothesis seems to be invalid because work task changes and work task description changes are closely correlated (0.76, c. Figure 6). Therefore, the strong correlation of planning texts may result from an impact of planning vagueness on re-planning effort.

### 5.3 Correlation of the Vagueness Measure and Its Components

In order to better understand the effect of the proposed vagueness measure on planning effort, correlation values for total number of work task changes and work task description with respect to the vagueness measure and each one of its components have been calculated (s. Table 1).

A dependence of the re-planning effort on the vagueness measure is observed. This dependence is greater for the total number of work task description changes, with a correlation of 0.61, than for the number of work task changes, with a correlation of 0.54. It is also clear that the activity level is not a good predictor for the re-planning effort, with a correlation of -0.16 for the total number of changes.

| | $\boldsymbol{A}$ | $\boldsymbol{\bar{P}}$ | $\boldsymbol{R}$ | $\boldsymbol{v}$ |
|---|---|---|---|---|
| Total changes | -0.16 | 0.51 | 0.46 | 0.54 |
| Description changes | 0.10 | 0.47 | 0.39 | 0.61 |

Table 1: Correlation of $v$ and its components to the total number of work task changes and work task description changes.

## 6 DISCUSSION

The idea of front loading is to plan in a standardised way so that once planned, a detailed work task description never has to be changed during the planning project. In the evaluated case, this was the case for only 4 % of the work tasks. However for the large majority of work tasks, between 1 and 21 description changes were made. The required total number of changes ranges from 14 to 232. This result shows that front loading has not reached its goal of reducing re-planning effort.

Since each change requires the planner to access the system and update the values, finding a way to predict the number of changes would help find an optimum vagueness level for preliminary work task descriptions, which will minimize the time required for changes, thus allocating planning time for other more important tasks. The time for a work task change can be measured well for the actual change process, i.e. for finding the right work task and for changing the database content. However, this approach does not take into account preliminary work such as discussions with designers or quality experts. Therefore, the measurable time impact is likely to be underestimated.

The proposed methodology of vagueness aggregation has been compared with alternatives such as using the minimum or the maximum operator instead of averaging the normalised components. Both approaches yield lower correlations to the number of work task description changes (max: 0.49, min: 0.19).

The analysis does not take into account that standardisation of work task descriptions took place after start of planning activities. In order to get results, initial work task descriptions have been translated into the controlled natural language. Even though great care has been taken not to include or leave out information, the translation has led to an increase in role content detail for all analysed work task descriptions because the planners rejected all more abstract part descriptions. Therefore, work tasks that had vague content at the start of the project (when the controlled natural language had not been introduced) became more detailed during the process of approving the new task descriptions. Before it is possible to conclude if the term vagueness is relevant an analysis of a project that employs a CNL from the start has to be conducted.

The analysis measures only the initial task descriptions' vagueness. A detailed analysis of the vagueness evolution may reveal optimum project milestones at which vagueness should be decreased.

Since work task changes and work task description changes are highly correlated, work task description changes seem to be an indicator for change effort. Such an indicator could simplify project progress analysis and communication.

## 7 CONCLUSION AND OUTLOOK

The practical benefit of the proposed vagueness measure lies in optimising the level of vagueness during concurrent engineering because planning cost is an important factor in large scale projects. However, more data is required for such an optimisation so that statistical analysis of different levels of vagueness is possible.

Even though vagueness correlates to re-planning effort, it cannot be deduced that changing initial vagueness affects the number of changes in a certain way. In order to prove dependency, comparing projects with different initial vagueness is necessary.

Vagueness can be viewed as a measure for uncertainty. Since complexity is also such a measure, vagueness could be compared to existing production system complexity measures such as Shannon entropy [6] or manufacturing systems complexity [12]. Such an analysis could reveal potential dependencies of optimum planning vagueness on the structural and time-dependent complexity of production systems.

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# A Multi-Period Changeable Modular Product Assembly Model

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**Abstract**

Corporations are adopting different strategies and enablers to cope with changing market demands and customers' requirements. Customer demands are often unpredictable. Different product demand in different periods increases the need to integrate product platform design with product inventory models. A Multi-Period Changeable Modular Product Assembly model is introduced to design optimal product platforms by determining the best product family formation and modular product platform composition. The new model customizes product platforms by either assembly and/or dis-assembly, to produce different products and families. The optimal product platforms are defined based on product demand in each investigated period. The developed model incorporates the cost of assembly/disassembly in forming product platforms and families. A four product family of modular products is used to illustrate the application and advantages of the proposed multi-period changeable product platform design model. Results show the ability of the model to identify optimal sub-product families from the initial large family. Different inventory, mass assembly, and customization assembly and disassembly costs have been optimized in reasonable computing time.

**Keywords:**

Modular product families; changeable platforms; multi-period assembly

## 1 INTRODUCTION

Products variety is becoming a necessity to respond to market and customers' different requirements and challenging technological issues. Customers increasingly ask for more new products with very changing demands and needs. Novel concepts to enhance the application of Mass Customization should be explored. The competition to acquire new markets, and even to preserve existing ones, requires efficient production methods to decrease costs, while ensuring quality and maintaining product functionality. One of the prime strategies to cope with these challenges is the use of effective Product Platforms and Architectures. The use of the product architecture concept by industrial corporations were discussed and researchers differentiated clearly between modular and integral architectures and further divided the modularity to slot, bus, and sectional types [1]. The product architecture concept was later referred to as product platforms, and it was suggested that there are three models which govern the product realization: function, technology, and physical appearance [2]. Many researchers devised models for forming product platforms which assume that modules are assembled to a common core of components (platform). Very few researchers considered both assembly and disassembly of components to platforms to realize derivative products [3]. Inventory cushions are needed in such cases to safeguard against un-predictable changes in market demands. The only model devised to combine product platform design with inventory cushions has limitations [4]. It is highly non-linear and can only form one product platform. In this paper, a new multi-period multi-platform formulation for the assembly/disassembly product platforms design which also incorporates inventory considerations is proposed.

## 2 LITERATURE REVIEW

Product Platform research is a large and diverse field. It considers many elements such as commonality measures and indices, and different optimization criteria (e.g. maximum commonality, minimum functionality loss). Platforms have been categorized depending upon: modularity, scalability and functionality [5] [6] [7]. A Product Platform is defined as a: set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently produced and developed [8].

Platform assessment metrics were developed to evaluate the generational variety of a platform defined as an estimate of the amount of effort needed to convert a platform to another as products change [10]. A coupling index which determines the degree of coupling between different products components was suggested. A top-down approach is used by obtaining "Minimum Spanning Network" to form a platform that can be used as a customizable baseline product to serve different customers' needs [11]. A thorough literature review of product architecture, modular design methods and platform formation techniques can be found in [12]. Similarity and sensitivity indices were used to form a suitable product platform for a multi-stage gear box [13]. The best platform components were those having highest similarity (physically or functionally) and the smallest sensitivity to changes in customers' requirements. A utility-based compromise decision support method was devised to determine a platform map (two dimensional graph of two platforms variables) of a cantilever beam that serve different requirements and demands [14]. A similar approach to select and decide the number and types of machines to be used in the production of those beams was also proposed. A simulation model was also proposed to determine suitable product family to maximize market share [15].

Researchers used Design Structure Matrix (DSM), Functional Structure Matrix (FSM) and Genetic Algorithm and proposed an Impact Metric (IM) to obtain the optimal set of shared components among a group of products [16]. A mathematical formulation was proposed to configure single and multiple platforms by both adding or removing components to the platform to form the final product [3]. This model requires defining the number of platforms to be formed a

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priori, which is considered a drawback. The model resulted in negative costs when increasing the maximum number of platforms to be formed which is a serious flaw. The model's objective function is nonlinear which increases the solution time. A number of plane cuts were included in the model which does not affect the solution time, and does not guarantee optimality. Another novel model used Cladistics, which is a classification technique used in biology, to form a tree-like layout of products components. It identifies common platforms and defines the best delayed product differentiation assembly point and subsequent variants assembly steps [17].

## 3 PROBLEM STATEMENT

Companies and corporations are always trying to increase their competitiveness. This competitiveness can be increased by adopting new assembly techniques and product platforms and safeguard them against changeable customer demands. Using product platforms, new assembly/disassembly technique with an inventory model can boost companies' responsiveness and competitiveness across global markets. It is required to design a mathematical model to define the optimal numbers and members of products families and platforms, taking into consideration the proper inventories amount to guard against markets fluctuations. This is illustrated in Figure 1. The multi-period concept considers the demand of each product variant in each production period (e.g. variants demand each month). The multi-platform means that in each period different modular product platforms may be best to produce, customize, and/or store as inventory. The product platform, in this model, is a mass produced subassembly of different components which can serve a number of products down to one product per platform. The model may determine that only one product per platform is optimal to mass produce due to high demand for that product in different production periods.

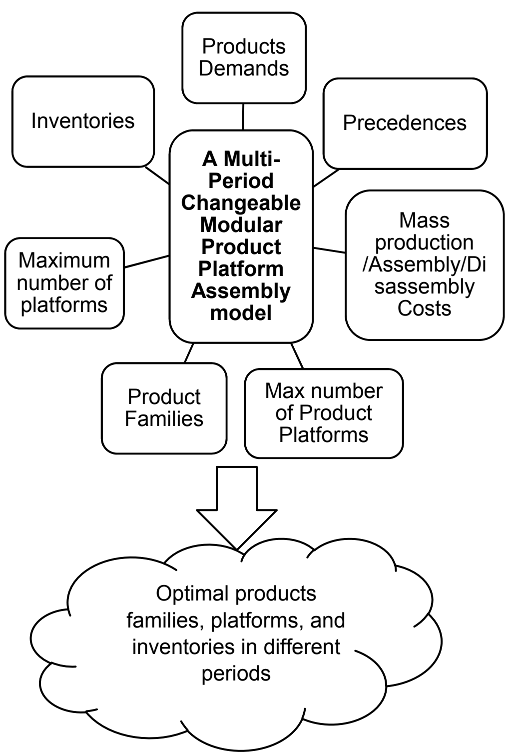


Figure 1: Multi-period changeable modular product assembly model.

## 4 MATHEMATICAL MODEL

In this section, the entire model is developed and discussed. First, all of the variables and parameters are enumerated as follows:

### 4.1 Model Parameters

p: Maximum number of production periods

l: Maximum number of platforms

m: Maximum number of components

n: Maximum number of products

$\mathrm{CP_j}$ : Mass production assembly of a component j to a certain platform

$\mathrm{C_j}$ : Cost of component j

$\mathrm{d_{kt}}$: Demand of product k in period t

$\mathrm{AC_j}$ : Customization assembly cost of component j

$\mathrm{DC_j}$ : Customization disassembly cost of component j

c : Labor training cost of each platform

$\mathrm{H_{prod}}$ : Unit holding cost of product inventory

$\mathrm{H_{plat}}$ : Unit holding cost of platform inventory

$$\mathrm{v_{jk}} = \begin{cases} 1, & \text{if product k contains component j} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{f_{kjd}} = \begin{cases} 1, & \text{if component j precedes component d in product k} \\ 0, & \text{otherwise} \end{cases}$$

$\mathrm{s_{io}}$ : Amount of starting platforms inventories

$\mathrm{e_{io}}$ : Amount of ending platforms inventories

$\mathrm{s_{ko}}$ : Amount of starting products inventories

$\mathrm{e_{ko}}$ : Amount of ending products inventories

### 4.2 Model Decision Variables

$$y_{ik} = \begin{cases} 1, & \text{if product k is assigned to platform i} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ij} = \begin{cases} 1, & \text{if component j is assembled to platform i} \\ 0, & \text{otherwise} \end{cases}$$

$$a_{ijk} = \begin{cases} 1, & \text{if component j is assembled to platform i to form product k} \\ 0, & \text{otherwise} \end{cases}$$

$$r_{ijk} = \begin{cases} 1, & \text{if component j is disassembled from platform i to form product k} \\ 0, & \text{otherwise} \end{cases}$$

$$P_i = \begin{cases} 1, & \text{if platform i exists} \\ 0, & \text{otherwise} \end{cases}$$

$p_{it} =$ Quantity produced of platform i in period t

$p_{kt} =$ Quantity produced of product k in period t

$I_{kt} =$ Amount of inventory of product k in period t

$I_{it} =$ Amount of inventory of platform i in period t

### 4.3 Mathematical Model Formulation

The mathematical model is formulated first as a nonlinear mixed integer model as follows:

**Minimize Z (Total Cost) =**

$$\sum_{t=1}^{p}\sum_{\mathrm{i}=1}^{\mathrm{l}}\sum_{\mathrm{j}=1}^{\mathrm{m}}\sum_{\mathrm{k}=1}^{\mathrm{n}}(\mathrm{CP_j}+\mathrm{C_j})\; x_{ij}y_{ik}p_{it} + \sum_{t=1}^{p}\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n}(\mathrm{AC_j}+\mathrm{C_j})\; a_{ijk}\, y_{ik}p_{kt} + \sum_{t=1}^{p}\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n}\mathrm{DC_j}\, r_{ijk}\, y_{ik}p_{kt} + \sum_{t=1}^{p}\sum_{k=1}^{n}\mathrm{H_{prod}}I_{kt} + \sum_{t=1}^{p}\sum_{k=1}^{n}\mathrm{H_{plat}}I_{it} + \sum_{i=1}^{l}P_i\mathrm{c} \quad (1)$$

**Subject to:**

$\sum_{i=1}^{l} y_{ik} = 1 \;,\; k = 1, \dots, n$ (2)

$a_{ijk} - v_{jk} + x_{ij} + 1 \geq y_{ik} \;,\; i = 1, \dots, l;\; j = 1, \dots, m;$

$k = 1, \dots, n$ (3)

$a_{ijk} \leq y_{ik} \;,\; i = 1, \dots, l;\; j = 1, \dots, m;\; k = 1, \dots, n$ (4)

$r_{ijk} - x_{ij} + v_{jk} + 1 \geq y_{ik} \;, i = 1, \dots, l;\; j = 1, \dots, m;\; k = 1, \dots, n$ (5)

$r_{ijk} \leq y_{ik} \;,\; i = 1, \dots, l;\; j = 1, \dots, m;\; k = 1, \dots, n$ (6)

$1 + x_{ij} \geq f_{kjl} y_{ik} + x_{il},\; i = 1, \dots, l;\; j = 1, \dots, m;\; k = 1, \dots, n$ (7)

$\mathrm{M}_1 \sum_{k=1}^{n} y_{ik} \geq x_{ij},\; i = 1, \dots, l;\; j = 1, \dots, m$ (8)

$\sum_{k=1}^{n} y_{ik} \geq P_i,\; i = 1, \dots, l$ (9)

$\sum_{k=1}^{n} y_{ik} \leq P_i \mathrm{M}_1,\; i = 1, \dots, l$ (10)

$I_{i(t-1)} + p_{it} = I_{it} + \sum_{k=1}^{n} y_{ik} p_{kt}$ (11)

$I_{k(t-1)} + p_{kt} = d_{kt} + I_{k(t-1)}$ (12)

$I_{io} = \mathrm{s_{io}}$ (13)

$I_{ip} = \mathrm{e_{io}}$ (14)

$I_{ko} = \mathrm{s_{ko}}$ (15)

$I_{kp} = \mathrm{e_{ko}}$ (16)

The objective function is composed of six terms. First term calculates the cost of forming products platforms (i.e. mass production assembly costs and components costs) across all periods. Second term calculates the cost of individually customizing different platforms formed by assembly to form different products across different periods. The customization by individual components/modules disassembly costs across periods are calculated by the third term. Fourth and fifth terms are concerned with inventory costs of finished products and unfinished platforms respectively. Labor training costs to assemble a certain platform is determined by the sixth term.

Constraint set (2) assigns each product to one platform. Constraint set (3) assembles component j to platform i to obtain product k if the platform does not contain this component. Constraint set (4) prevents assembling any component j to a certain platform i if there is no product is in that platform. Constraint set (5) disassembles component j from platform i to get product k if product k does not contain that component. Constraint set (6) prevents the disassembly of any component j from a certain platform i if there is no product in that platform. Constraint set (7) forces the obtained platforms to have component j if product k in platform i has component l, and component j precedes component l. Constraint set (8) forces platform I to have zero components if no product is assigned to that platform. Constraint (9) and (10) remove any platforms that are not used to produce any products. Constraint (11) ensures sufficiency of platforms inventories and production with the products needs in each period. Constraint set (12) preserves the initial and beginning products inventories. Constraint sets (13-16) assigns the initial and the end inventories of products and platforms to the model. In most cases, all of the initial and ending inventories are set to zeroes, to minimize holding costs and decrease quantities of obsolete products and platforms.

### 4.4 Model Linearization

The proposed model is highly nonlinear. Hence, a linearization scheme is adopted from [18], to linearize both of the objective function and the constraints to make it possible to find optimal products platforms and families in less computing time compared to the initial nonlinear model. The method depends on replacing each two nonlinear variables with one variable and two constraints. The linearization of the objective function is as follows:

**Minimize Z (Total Cost) =** $\sum_{t=1}^{p} \sum_{i=1}^{l} \sum_{j=1}^{m} \sum_{k=1}^{n} (\mathrm{CP_j} + \mathrm{C_j})\; g_{tijk} + \sum_{t=1}^{p} \sum_{i=1}^{l} \sum_{j=1}^{m} \sum_{k=1}^{n} (\mathrm{AC_j} + \mathrm{C_j})\; q_{tijk} + \sum_{t=1}^{p} \sum_{i=1}^{l} \sum_{j=1}^{m} \sum_{k=1}^{n} \mathrm{DC_j}\, s_{tijk} + \sum_{i=1}^{l} P_i \mathrm{c} + \sum_{t=1}^{p} \sum_{k=1}^{n} \mathrm{H_{prod}} I_{kt} + \sum_{t=1}^{p} \sum_{k=1}^{n} \mathrm{H_{plat}} I_{it}$ (17)

**Subject to:**

$\mathrm{M}_2 u_{ijk} \geq g_{tijk}$ (18)

$g_{tijk} \geq p_{it} + \mathrm{M}_2 (u_{ijk} - 1)$ (19)

$x_{ij} \geq u_{ijk}$ (20)

$u_{ijk} \geq y_{ik} + x_{ij} - 1$ (21)

$\mathrm{M}_3 w_{ijk} \geq q_{tijk}$ (22)

$q_{tijk} \geq p_{kt} + \mathrm{M}_3 (w_{ijk} - 1)$ (23)

$a_{ijk} \geq w_{ijk}$ (24)

$w_{ijk} \geq y_{ik} + a_{ijk} - 1$ (25)

$\mathrm{M}_3 z_{ijk} \geq s_{tijk}$ (26)

$s_{tijk} \geq p_{kt} + \mathrm{M}_3 (z_{ijk} - 1)$ (27)

$r_{ijk} \geq z_{ijk}$ (28)

$z_{ijk} \geq y_{ik} + r_{ijk} - 1$ (29)

$u_{ijk}, g_{tijk}, w_{ijk}, q_{tijk}, z_{ijk}, s_{tijk} = \{0,1\}$ (30)

To linearize constraint 11, the same former procedure is used here again:

$I_{i(t-1)} + p_{it} = I_{it} + \sum_{k=1}^{n} y_{ik} p_{kt}$ (31)

$\mathrm{M}_3 y_{ik} \geq y1_{ikt}$ (32)

$y1_{ikt} \geq p_{kt} + \mathrm{M}_3 (y_{ik} - 1)$ (33)

## 5 ILLUSTRATIVE EXAMPLE

It is required to obtain the optimal products families and platforms formation, using the proposed model, for the hypothetical four-product example where each has different assembly precedence constraints and different demands in each period. The used fictitious modular products example, shown in Figure 2, is adopted from [3] as follows:

| NUMBER OF PLATFORMS | PRODUCT FAMILIES | PRODUCT PLATFORMS COMPONENTS | PRODUCT PRODUCTION Volume (Variant Unit/period) | PRODUCTS INVENTORIE (Variant Unit/period) | COST ($) |
|---|---|---|---|---|---|
| 1 | All products are produced individually without families (i.e. fully customized assembly) | No Platform components (i.e. no mass production). | ((25 100 300 400)<br>(25 500 500 200)<br>(25 500 200 100)<br>(325 500 100 200)) | ((0 0 0 0)<br>(0 0 0 0)<br>(0 200 0 0)<br>(0 300 0 0)<br>(0 0 0 0)) | 294900 |
| 2 | - Product 2 in one family ( i.e. one platform and can be mass produced )<br>- Other products are custom assembled. | - Product 2 platform components (A, B, D, E, and F). | ((25 100 300 400)<br>(25 500 500 200)<br>(25 500 200 100)<br>(325 500 100 200)) | ((0 0 0 0)<br>(0 0 0 0)<br>(0 200 0 0)<br>(0 300 0 0)<br>(0 0 0 0)) | 284900 |
| 3 | - Product 2 in one family ( i.e. one platform and can be mass produced )<br>- Product 3 in one family (i.e. one platform and can be mass produced)<br>- Other products are custom assembled. | - Product 2 platform components (A, B, D, E, and F).<br>- Product 3 platform components (A, B, C, E, and F). | ((25 100 300 400)<br>(25 500 500 200)<br>(25 500 200 100)<br>(325 500 100 200)) | ((0 0 0 0)<br>(0 0 0 0)<br>(0 200 0 0)<br>(0 300 0 0)<br>(0 0 0 0)) | 278650 |
| 4 | All products are mass produced | Each product is its own platform. | ((25 100 300 400)<br>(25 500 500 200)<br>(25 500 200 100)<br>(325 500 100 200)) | ((0 0 0 0)<br>(0 0 0 0)<br>(0 200 0 0)<br>(0 300 0 0)<br>(0 0 0 0)) | 270900 |

Table 1: Results of the multi-period changeable model.

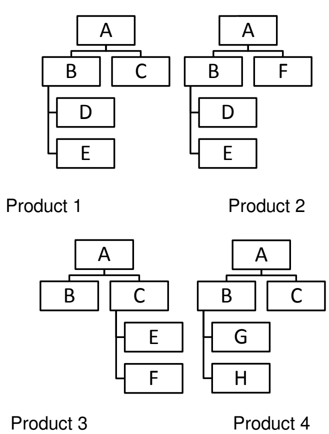


Figure 2: Product Variants architectures.

The data used in solving the multi-platform multi-period problem is enumerated as follows:

p = 4, l = 4, n = 4, $CP_j$ = \$0.5, $C_j$ = 10, 11, 12, 13, 14, 15, 16, and 17 for Components: A, B, C, D, E, F, G, and H respectively. $AC_j$ = \$2, $DC_j$ = \$0.8, $c$ = \$2000, $H_{prod}$ = \$1, $H_{plat}$ = \$2, $(s_{io}, e_{io}, s_{ko}, e_{ko}) = 0$ , $M_1 = 10$, $M_2$ = 2000, $M_3 = 500$ $d_{kt}$ = ((25 100 300 400) (25 300 500 200) (25 400 200 100) (325 800 100 200))

## 6 RESULTS AND DISCUSSION

The multi-period changeable assembly model is programmed using the Optimization Programming Language (OPL) and IBM ILOG CPLEX Studio 12.4 as a solver. The model is solved by varying the number of platforms, starting with one platform (Table 1). The fourth column shown in table 1 is the product variant demands per period (i.e. 25 is product 1 demand, 100 is product 2 demand, 300 is product 3 demand and so on). The model determines that products one, two, three, and four cannot be grouped into one common platform.

Hence, each product variant should be assembled separately as an individual product with cost of assembly: $AC_j$ = $2 per component. Due to linearization, two constants $M_1$ and $M_1$ control the maximum number of platforms and products that can be produced. Therefore, these two constants act as capacity constraints. As a result, the model recommends assembling extra products as a buffer (e.g. product two at the end of period two has 200 extra units as inventory, and has 300 extra units in period three) and store them for future period 4. In second instance, the number of platforms is set to two. In this case, product two is contained in a separate platform and produced as in a mass production (i.e. by using $CP_j$ = $0.5 to assemble each component) by allocating it to platform two. Each other product is produced separately like the first instance. Third case is allowing the three platforms to contain the four products. In this case, the model allocates product two to platform one and product three to platform two. Each of these two products is mass assembled.

| M2 | M3 | TIME (seconds) | COST($) |
|---|---|---|---|
| 400 | 400 | 12 | 271600 |
| 400 | 500 | 73 | 271600 |
| 2000 | 400 | 270 | 271600 |
| 2000 | 500 | 540 | 270900 |
| 7000 | 400 | 600 | 271600 |
| 7000 | 500 | 1525 | 270900 |

Table 2: Sensitivity analysis.

In the last case (i.e. platforms = 4), it is the optimal solution. All products are produced in separate platform each. It is worth noting that the cost decreases by allowing more platforms. Platform inventories are zero, due to their relatively large holding costs. In this model, platform inventories are considered a work-in-process which are stored and brought upon request. The maximum number of platforms (i.e. number of products) is not always the optimal solution for different costs and product demands. The proposed model solution time ranges from two seconds for one platform and five minutes for four platforms. Customization by disassembly in this example was found to be suboptimal using this data set. Hence, the model chose either mass production assembly for all products or customized individual product assembly when differentiation is required.

A sensitivity analysis is done on M1 and M2 constants (Table 2). These constants represent the maximum capacity of platform production and product production respectively. The total assembly cost is equal to the last cost in table 1. Two important notes: solution time increases with any increase in M1 and M2 value. First, this remark emphasizes the importance of properly assigning reasonable values for these factors, given product demands and requirements, that match or even less than the available capacities. Second, increasing or decreasing companies' capacities for platform and product production does not lower total costs beyond a certain point (principle of diminishing returns).

## 7 CONCLUSIONS

A new mathematical model is proposed to decrease costs of assembly of modular products. This model obtains optimal products platforms using the concept of both assembly and disassembly of components to/from platforms to derive new products. In the literature, the only available model can obtain one platform for each group of products for one demand period using nonlinear mathematical model. The proposed Multi-period Multi-platform Changeable Modular Products Assembly model overcomes these drawbacks by developing a linear multi-period and multi-platform assembly model. The model is able to form optimal families and platforms and determine best inventory levels. Results showed – for the discussed example – that it is better to allow more platforms (i.e. mass production lines) to decrease assembly costs. Products inventories are kept to minimal, while platforms inventories are zero, because of large holding costs of work-in-process platforms. Companies' capacities for platform and product production must be chosen carefully. Increasing capacities for platform production does not always guarantee lower production and assembly costs. Many factors and costs are included in the model. Therefore as a future work, these factors could be investigated to determine their relative importance to the assembly costs.

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# Reducing the Development Time of Flexible Metal Forming Tools Using Hardware-in-the-Loop Simulation

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**Abstract**
The sheet metal forming industry is one of the most important suppliers in the automotive sector. However, the industry sector is struggling with a steadily increasing number of different parts, coupled with decreasing batch numbers. As a result, new flexible tool concepts must be developed. However, because of the high cost and consequently high risk of development of such tools, manufacturers have been careful. This paper presents a new design process based on hardware-in-the-loop simulation. This new process allows development of mechanical and controller design in parallel. In addition, programming of the controller can be tested against the mechanical design of the tool, before the machine is built. The method was applied to a new tool and proved to be effective in reducing development risks and optimizing the process sequence.

**Keywords:**
Metal forming; Hardware-in-the-loop simulation; Servopress

## 1 INTRODUCTION

The sheet metal forming industry is an industry defined by its high output of parts with low production costs. The manufactured parts can range from small punching parts, like washers, to complex free-form parts, like the front lid of a car. The capability to manufacture free-form parts at low costs is what makes the sheet metal forming industry one of the main suppliers in the automotive sector.

However, the commonly employed classical mechanical presses with fly wheel limit the flexibility of metal forming systems, due to their fixed sinusoidal motion. In contrast to this, servo presses are no longer limited to this. Due to their direct drive, the servo press is combining the free motion capability of hydraulic presses with the speed of classical mechanical presses. This new freedom of the press motion allows the integration of peripheral processes into the forming tool, thus reducing costs and increasing productivity [1]. However, many tool manufacturers have yet to embrace the new capabilities of the servo press. Until now, the main effort of improving the tool design for servo presses has been to increase the speed during non-contact times. The goal is to increase the overall production speed and thus the productivity of the press.

In recent years the markets have become more volatile. Especially in the automotive sector shorter development cycles and an increased number of different vehicle types have led to decreasing order quantities. This is especially problematic for sheet metal forming companies. The tools and machines for part manufacturing are expensive. In addition to the high cost, sheet metal forming tools are single-purpose tools. Even though tool manufacturers try to modularize the tools as much as possible, the capability to manufacture free-form shapes at relatively low cost comes at the price of inflexible tools. The result being that if the manufacturer cannot sell enough parts, the tool is uneconomic. Therefore, manufacturers have sought new tool design directions, in order to improve the flexibility of their tools. For the development of new flexible tools, a research cooperation with industrial partners named *Formäleon* was funded by the Federal Ministry of Education & Research of Germany. An overview of the project was given in a previous paper [2].

In *Formäleon* a new tool was designed. The new tool shortens the current production process significantly. Figure 1 a) shows the currently employed process, manufacturing a clamp for holding pipes. To manufacture the clamp, two presses are used to form holder and ring of the clamp. The two parts, ring and holder, are sorted by hand and inserted into a welding machine. The current manufacturing layout takes a great amount of resources, both in man power and machine time. Therefore, it must be carefully considered if it is economic to manufacture the clamp and for which quantities it is still economic.

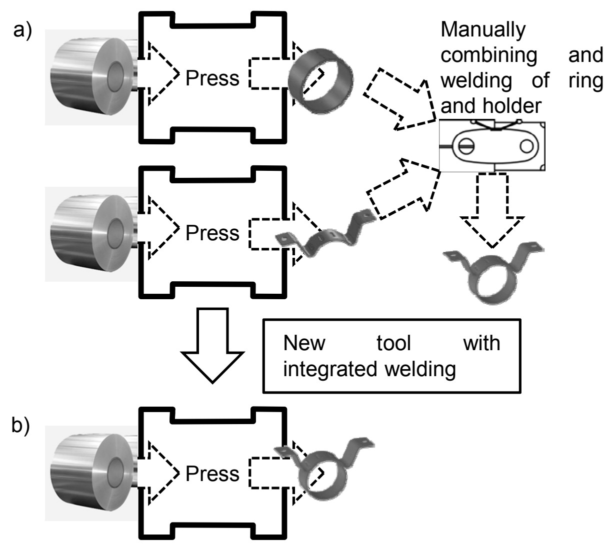


Figure 1: Current (a) and new (b) process layout.

In contrast, the new tool, shown in Figure 1 b), can manufacture the clamp in one press, without the need for sorting and inserting the clamp manually into the welding station. This greatly streamlines the production process and allows cheap manufacturing of the clamp. In addition, the tool is designed to scale with respect to production demand, further improving the competitiveness of the parts manufacturer.

This paper will present a new approach to controller programming parallel to tool design, by usage of hardware-in-the-loop (HiL)

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simulation. In the following sections, the risk involved with the new tool design, the limitation of the currently employed simulation support and the results of the newly employed approach of using HiL simulation for parallel controller programming will be discussed.

## 2 INCREASED COMPLEXITY – INCREASED RISK

Classic tool designs focus exclusively on the die forming the parts. There is usually no additional need for dedicated actuators in the tool. The formed parts are either interconnected and moved by the feed motion of the sheet metal coil or moved by additional transfer systems with dedicated handling systems. In case of interconnected parts, the part is formed but not clear-cut until the very end of the process. Therefore, the feed motion of the coil can be used to transport the part to each sequential forming step, essentially forming a chain of unfinished parts. Consequently, the motion direction is in line with tool and press. The designer of the tool only needs to make sure that the parts can move freely during non-contact times. This is usually done by lifting the complete chain of partially formed parts with pneumatic actuators.

Where this transfer method cannot be employed, a dedicated transfer system is used. Dedicated transfer systems are usually placed at the sides of the press in line with the tool. During non-contact times the transfer system moves inside the tool area and moves the part to the next forming step. With a dedicated transfer system, parts are moved which are either too big to move in a chain of parts or might be damaged during the movement process.

However, in the new tool design, none of the transfer options employed by classic tool designs are viable. The parts cannot stay interconnected until the forming is completed. Therefore, the feed motion of the sheet metal coil cannot be used as a transfer option for the whole process. The reason for this constraint is twofold. Firstly, the ring cannot be finished while interconnected with the sheet metal. Clear-cutting of a finished interconnected ring would result in deformation of the ring. Secondly, ring and holder need to be combined for welding, this is only possible if both parts are clear-cut and can be handled independently. The standard transfer system cannot be used because the motion direction is not only in line with tool and press, but also across the press. In the usual setup, the transfer system has to move only slightly into the tool for grabbing and moving the part. It is therefore feasible to place the transfer system at the sides of the tool. Because ring and holder must be combined in the welding station, the transfer system must also move across the tool. This makes it necessary to move very far into the tool. Placement of transfer axis at the sides is therefore infeasible because the transfer system would take very long to move in and out of the tool and, in addition, the handling system of the transfer might become instable due to vibrations.

The new tool, therefore, incorporates the transfer system into the tool. Thus, the distance from the actuator to the moved part is shorter and it is possible to add a cross axis to the tool. This cross axis moves the ring to the welding station, in which ring and holder are joined and welded. The cross axis' actuator path is as long as the path of the other handling systems. Therefore, placement precision can be guaranteed. However, this new tool layout with an integrated transfer system poses the problem that now the tool manufacturer has to consider, in addition to the die form, the transfer placement and programming of the transfer axis. The result is a longer design process, as depicted in Figure 2. Moreover, the necessity to program the transfer is a new field for tool manufacturers. Previously, the tool manufacturer had to make sure that iterative forming steps result in the demanded shape of the part and that there are clearances where the transfer actuators can grab the part.

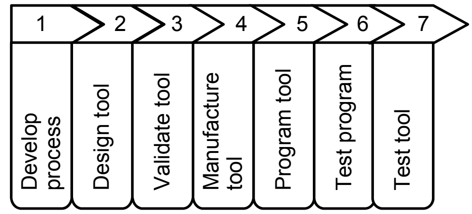


Figure 2: Current design process.

In case of tools with the new tool design, manufacturers have to make sure that the parts are moved and combined correctly. With these additional development steps the complexity of tool design and development process is increased. Consequently, the risk of failure during development is increased. The previously employed methods of evaluation in CAD tools for reducing the development risks are not applicable for the new tool design. The functions of the tool are too complex to be modeled in CAD tools. For example, the evaluation of complex interactions, such as the synchronization of the cross axis with the holder and ring axis, are difficult to implement in CAD tools.

## 3 CURRENTLY EMPLOYED SIMULATION SUPPORT

For more complex die designs and for preemptive testing there are a number of simulation tools to support the tool manufacturer. These systems are mostly supplied by press manufacturers. The simulation allows testing of the die performance on a given press of the corresponding manufacturer. These simulations cover the evaluation of each forming step and the collision detection between die and transfer system. The tools use CAD data of die, press and transfer system. The simulation is performed offline, without need of specialized hardware. In most cases, the simulation allows to change and optimize the stamp motion, which can be exported and used as parameter set for actual manufacturing. Using this simulation support, tool manufacturers are able to evaluate and optimize the process at very early stages. However, the simulation is limited to the manufacturer of the press. Also this type of simulation does not support testing of the programming of the tool. Considering the design of the new tool, automation is going to be a major part in future tool development, therefore testing of the automation is necessary.

Abourida et al. describe a methodology called hardware-in-the-loop (HiL) simulation, in which a simulation is used to test the control program, using actual controller hardware [3]. The merit of the design process associated with HiL simulation is the possibility of testing and detecting errors before deployment or production of the system, therefore reducing impact of said errors. However the overall design process is still mostly linear. The main difference is when the physical system is deployed. In case of the Abourida step four in Figure 2 would be exchanged for the development of a HiL model of the hardware and postponed until the automation program has been validated against the simulation. This reduces risk of malfunction but offers no advantage in development time.

For the new tool design, however, parallel development of both tool form and control is essential in order to reduce time to market and therefore increase competitiveness. Dwivedi et al. describe a method by which parallel development is supported through simulation support [4]. The proposed method uses CAD data as communication basis for parallel development and evaluation in a complex project. The result is a streamlined development process with continuous evaluation of the project status. The development process is parallelized by leveraging a growing simulation environment. This is especially important for the control development, because in standard development processes control development can only start after the machine is completed. In the method proposed by Dwivedi et al., the control development can start after the initial system design process. Missing components or specifications are simulated or emulated, depending on hardware availability. As the model and development becomes more refined and hardware interfaces specified, the previous emulations can be used as stimuli in the more detailed simulation.

## 4 HARDWARE-IN-THE-LOOP SIMULATION SUPPORTED DEVELOPMENT

The design process based on development methodology by Dwivedi et al. generates a large overhead. Considering the new tool design, development based on this methodology would mean that several simulations must be adjusted with each change in tool design. Therefore, this paper proposes a revised design process. The CAD data are still used as means of communication. Instead of using several simulations for each sub-project, a single HiL simulation is used for the controller development. In the revised version, the design process allows for parallel simulation, although only two development chains are used. In addition, the usage of the HiL simulation reduces the necessity of emulating hardware; instead, real control hardware can be used. The revised development process is depicted in Figure 3.

The previously sequential development steps 5 and 6 in Figure 2 are performed in parallel to the mechanical design of the tool. The development of a HiL simulation starts with the development of the process, as seen in step 1 of Figure 3. The necessary parameters for the simulation, e.g. an estimate of the number of axes, inputs and outputs, can be derived from the specification of the process. Based on this data, an initial model is developed. Step 1 of the design process thus requires more coordination than the previous approach.

However, this higher initial coordination effort makes it possible to perform the development steps 2 and 2’ as well as steps 3 and 3’ in parallel. The initial cost is remedied by the shorter development cycle and an immediate feedback between controller development and hardware design.

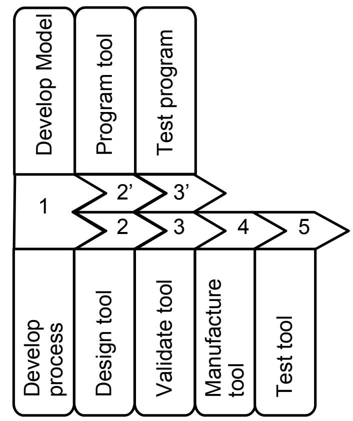


Figure 3: Proposed parallel design using HiL simulation.

### 4.1 Simulation Topology

Figure 4 shows the topology and interconnections of the simulation. There are three interconnected systems: press controller, simulation model and tool controller. All systems can either reside each on their own hardware or together on a single hardware. In case of this paper, all three systems were run on a single hardware. Prerequisite for this setup are PC-based control systems. Fortunately, the press controller as well as the tool controller uses a PC-based control system. It is therefore feasible to run all three parts on the same hardware, thus reducing the setup cost. The central element of the topology is the simulation model of the tool. The simulation model is interconnected with the press controller and tool controller. From the press controller the master cam is connected via a field-bus connection. The value of the master cam is used to simulate the stamp motion of the press. Via another field-bus interface, the simulation is connected to the tool controller. Instead of directly interpreting the value, as is the case with the master cam, the simulation emulates the field-bus behavior of the decentralized I/Os and drives. It is later possible to exchange the simulation of the tool with the cabinet of the tool, without the need to make additional changes to the programming of the tool controller.

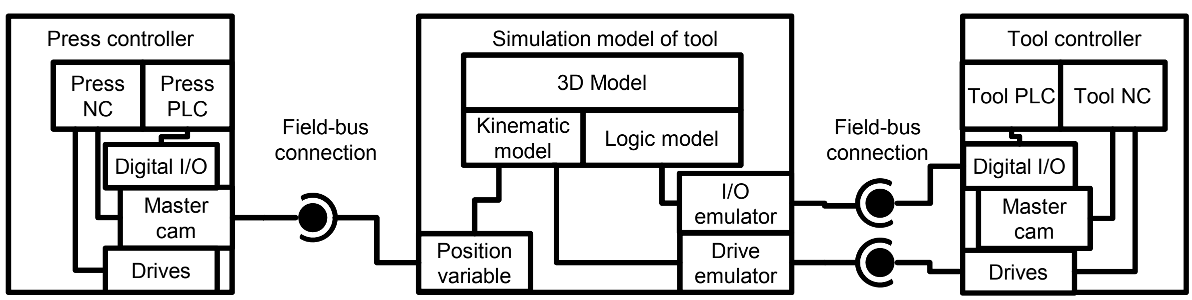


Figure 4: Simulation topology.

### 4.2 Simulation Model

The structure of the model is displayed in Figure 5 by the example of a pneumatic cylinder. The pneumatics are controlled via digital I/Os. Therefore, the input to the model is the emulation of the digital I/Os. The control system is configured as if there would be a real field I/O, however, the simulation is just emulating the actual field device behavior. Subsequently, the I/O data from the field-bus connection is interpreted by a logic model. This logic model is the logical reaction of the pneumatic system, e.g. the switching behavior of the valves of a pneumatic cylinder.

The logic model is interconnected with the kinematic model. This model describes the kinematic behavior of the cylinder. The kinematic behavior encompasses the mechanical behavior, e.g. reaction time, movement behavior and stop positions of the cylinder. The kinematic behavior is fed into a 3D model of the system. This 3D model is based on the CAD data of the tool. With the 3D model, the collisions of the system can be detected. The data of the kinematic model is fed back into the logic model.

The logic model checks the current position of the kinematics with the stop positions. If a stop position is reached, a logical feedback is given to the digital I/O to be transmitted via the field-bus to the tool

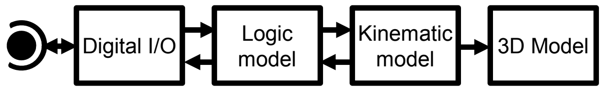


Figure 5: Interconnection in the model.

controller. As a result, the tool controller can be programmed as if there is a real machine available. The servo axes are simulated in the same way, with the exception that there is no need for a dedicated logic model.

## 5 RESULTS

As a result of the new methodology the development time of the tool was significantly reduced. An absolute value of the time reduction cannot be given, because the method has been employed for the first time to the development of a sheet metal forming tool of this complexity. However comparing the development time to projects of similar scope showed that about three months of time could be saved, which was about a quarter of the overall programming and testing time, required for a project of this scope. The controller program was developed in parallel to the mechanical design of the tool. In addition, the 3D simulation of the tool based the actual CAD data allowed the evaluation of the effectiveness of the movement sequence and the identification of design and programming errors. The evaluation showed that changing the process sequence resulted in more simultaneous motion of the axes, consequently reducing the length of each transfer step and thus increasing the throughput of the tool.

The evaluation also showed some mechanical design issues, which were subsequently corrected. A picture of the 3D simulation is shown in Figure 6. The area marked with the circle shows an additional cavity inserted after it was found that during pressing the mount of the camera collides with the upper die.

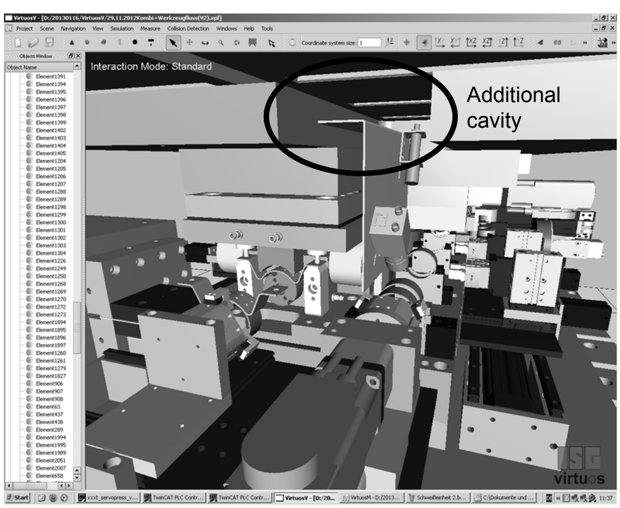


Figure 6: Picture of the 3D simulation.

Because the system is interconnected with the real press controller, it was also possible to perform a virtual tryout measuring the tool performance. During the tryout, the speed of the press was slowly increased. The press speed was increased until the tool mechanics could no longer keep up with the stamp motion, resulting in a collision between transfer and die. It was found that the tool easily handles up to 15 strokes per minute, with a sinusoidal motion curve. Adjusting the curve showed that it might be possible to approach up to 30 or more strokes per minute. However, this is a rough estimate. The simulation is currently not considering the material flow of the system. It might be possible that, at high speed, the transfer system introduces vibrations into the moved parts, which in turn reduces the placement accuracy.

## 6 SUMMARY

The paper showed the current development in the area of flexible sheet metal forming tools. Current tool designs focus on the production output only. However, flexibility becomes more and more important, due to increasingly volatile markets. The development of flexible tools, however, introduces risks, because of an increased complexity of the tool. To reduce these risks, manufacturers use simulations. However, currently available simulation support focuses on tool design only. The presented new tool design, however, incorporates additional motion axes into the tool. Consequently, the design process must also consider the programming of these additional axes. This is impossible with the currently employed design methodology. As a way to parallelize the design process and decrease the risk due to the additional programming of the motion axes, a revised tool design process was proposed, based on hardware-in-the-loop simulation. The new design process was discussed using the example of a new flexible tool design. It was shown how the simulation is structured and by the example of a pneumatic cylinder the setup of the model is explained in detail. The development based on the proposed design process resulted in a shortened development process and in an early detection and correction of mechanical errors. In addition, the capability of the new tool could be tested to the point, where the transfer axes cannot keep up with the stamp motion.

The HiL simulation is currently only considering the kinematics of the tool. Therefore, testing can only provide the validation of tool mechanics, without considering parts mechanics. However, the behavior of the parts is important for the success of the process. Vibrations introduced by the transfer might lead to inaccurate placement of parts. Inaccurate placement in turn might result in malformed parts or damage of the tool. In future research, the material flow and forming of the parts should be considered.

Another open topic, which should be addressed in future works, is the reduction of CAD data. Generally, the CAD data include more information than necessary for the simulation or the CAD data include information, which is not directly accessible in the simulation. In future works automatic reduction, partitioning and kinematic coupling might increase the ease of use of HiL simulation.

## 7 ACKNOWLEDGMENTS

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# Assessment and Configuration of a Product Production System

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**Abstract**
The insight that manufacturing companies nowadays have to compete in an increasingly dynamic and differentiated market environment with increased competition is not new. Nevertheless, it is still difficult for many companies, particularly in high wage countries, to cope with the dilemma of simultaneously increasing cost pressure and differentiation. The following paper introduces a model to address this challenge. The model attempts to give support in finding the right fit between the production system set up and the product portfolio offered to the market. The core element is a navigator for an integrative assessment and configuration of product production systems in the domains "Customer Value Management", "Product Architecture and Technology Design", "Integrated Product and Production Design" and "Production Process Design".

**Keywords:**
Integrated product and production design; Manufacturing system; Production planning; Product development

## 1 INTRODUCTION

### 1.1 The Dilemma of Scale and Scope

Companies that produce are confronted with the challenge to persist in an increasingly competitive market environment. Unique customer requirements demand for individualized products and services. The complexity of products is increasing. More functionalities and individual customer requirements lead to diversified product structures and a higher number of product and process variants within a company. Meanwhile, the international competition and the shift towards a buyers' market in many industry branches increase the cost pressure on enterprises. Therefore, a key strategy for manufacturing success and economic sustainability is to simultaneously leverage economies of scale and scope [1][2].

Until now, the main lever to combine a manifold product program with efficient manufacturing has been the intelligent adaption of product architectures to realize product and process commonality via modular product platforms. Beyond this mechanism, matching the solution spaces of product architecture and production structure adds to resolving the dilemma of scale and scope. To realize this, an integrative assessment and configuration approach for the product production system is required to adequately structure the complex problem [3][4][5].

### 1.2 Industrializing the Production of Electric Vehicles as an Example for the Dilemma

Current efforts to promote electric mobility illustrate the challenges to offer individual products while competing in established markets. An initially low market volume and the direct competition with conventional cars lead to an extreme cost pressure on the development of electric vehicles. Although costs of key components, such as battery and electric powertrain, are predicted to decline, the price of electric cars will exceed customers' willingness to pay [6]. Even when considering governmental subsidiaries and savings of electric vehicles in energy consumption over the life time, the price of an electric vehicle must not exceed the price of a comparable gas-fuelled car by more than 25% [7].

In order to compete with the regular power train technology, especially the product and production costs of the vehicle have to be reduced drastically [8]. Therefore, solutions to reduce production costs are to be developed. The optimisation of production costs purely by economies of scale is not sufficient for new technologies (see Figure 1). Electric vehicles must be competitive to gas-fuelled cars even in small production volumes and the variety required by the market. Yet, low production volumes in combination with product variety imply high production costs that are transferred to the customer. Accordingly, the low economical attractiveness complements the vicious circle. A successful market penetration demands for realizing cost innovations [9].

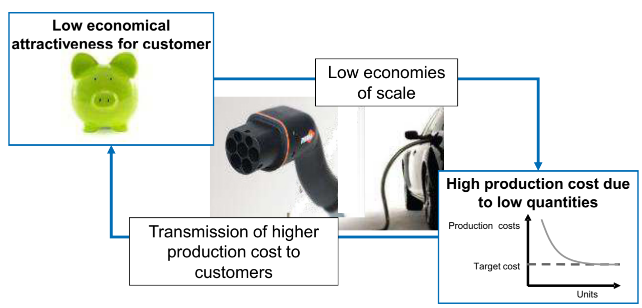


Figure 1: The Vicious Circle of Low Quantities.

To accomplish real cost innovations, it is necessary to break with classical design and development procedures. Significant cost reductions demand a radical rethinking of existing structures addressing product and process design simultaneously [6]. In the design of the electric vehicle "StreetScooter" and the corresponding production technologies at the RWTH Aachen University, a production-oriented development approach has been employed to fully exploit the solution spaces of product architecture and production structure within an increasingly dynamic, market-driven and therefore complex environment.

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## 2 COMBINING PRODUCTION EFFICIENCY AND PRODUCT VARIETY

### 2.1 Existing Approaches

Science and industry have been trying to overcome the dilemma of scale and scope for some decades now. However, many companies still face the problem to combine a manifold product portfolio and an efficient production. In 1980 Michael E. Porter already described the risks to combine a cost leadership and differentiation strategy in his "Stuck in the Middle" scenario [10].

Most state of the art product development procedures comprise an integrated planning of product and production processes. Mainly in order to decrease the time to market, a shift from strictly sequential product and production planning approaches took place towards a simultaneous development of product and production processes. For that purpose, the integrated product and production planning has become common practice in most industrial branches [11]. In contrast to simultaneous or concurrent engineering, the integrated product and process development already promotes the consideration of manufacturability in product development at an early stage of the development process [11].

Solving the dilemma of offering a broad product variety while realizing an efficient production has been the centre of various research efforts in different disciplines. The lean production philosophy, including a vast number of methods and tools, focuses on optimizing and adapting production structures for a given product variety and range [12]. Other methods address the concurrent design of products and production systems (e.g. [13]) or the assessment of interrelations between product architecture and production structure (e.g. [14][15]). The design approaches aim at systemizing the engineering of products and production systems with the intention of increasing economies of scale or scope. The assessment-focused approaches focus on evaluating the degree to which economies of either scale or scope are achieved [1].

### 2.2 Fitting the Solution Space of a Product Production System

Fitting production structure and product architecture demands for matching the solution spaces of product and production design. Although the above mentioned approaches or a combination of them contribute to solving the dilemma of scale and scope, they fail to comprehensively address all structure-forming elements of a product production system and their interrelations (i.e. product program, supply chain, product architecture and product structure) [16].

Schuh et al. developed a systematic assessment framework to integrate both the view on the product and processes of a production system as well as an external (customer and market view) and internal perspective on a production system [16]. Based on Schuh's model to assess product production systems Kampker et al. developed a configuration model simultaneously employing different perspectives on the design of a product architecture. The model can help to identify the best fit for the configuration of a product production system. It was shown that it is possible to engage the scale-scope dilemma by assessment and configuration models that integratively consider interrelations within a product production system [1].

Both models help to identify the best fit of a product architecture from both scale and scope point of view. However, the challenge to systematically identify and elaborate specific improvement measures for all domains of a product production system still remains. An orientation guide to cluster and align product and production design measures to fully exploit the solution space of an integrated product and production design is yet to be developed. Thus the integrative and complexity-focused assessment model by Schuh et al. can be effectively supported by a model structuring the product and production design measures within a product production system.

## 3 ASSESSMENT AND CONFIGURATION OF THE INTEGRATIVE PRODUCT AN PRODUCTION DEVELOPMENT

### 3.1 Methodology and Approach

The development of the presented model results from an explorative research process according to Tomczak [17]. It is based on the finding, that a consequent and sustainable design of a complex product production system requires an integrative framework that covers all areas of activity (domains) within the design process. Further, it has to show interrelations between these areas and provide an understanding of how these domains affect both benefit of variety and resulting complexity costs within the system. To close this deficit, interrelations of existing assessment and configuration approaches for product production systems (see 2.1/2.2) have been studied and, in an explorative process, an integrated assessment and configuration model has been deduced.

Existing approaches show a wide range of activity areas within the product production system design and underline the challenge of finding the best fit in any one of them, i.e. product architecture design or production organisation. Consequently, it is not the goal to present another competing approach to solve the individual activity-area-based problem of complexity. But it is the goal to deliver a structuring framework to integrate existing approaches, assess their interrelations, and derive a configuration approach for a product production system by understanding the consequences for all activity areas as well as monetary costs and benefit.

The approach proposed in this paper attempts to give support in finding the right fit between the set up of a product production system and the product portfolio offered to the market. It is based on an integrative assessment and configuration model which contrasts the benefit of variety for the market with the variety-induced complexity costs in production. Consequently, the model aims at significantly reducing production costs while simultaneously offering a broad product variety, thus addressing the scale-scope dilemma. Furthermore, the underlying framework proposes fields of activity to systematically influence the benefit-cost ratio within the integrative planning of product and production process.

### 3.2 Definition of a Constitutive Framework

Following the assessment model of Schuh et al. [16], the consideration of integrative product and process development requires the differentiation of external variety which results from external influences such as market behaviour, and internal variety as a consequence of self-induced conditions within a company. Furthermore, variety can be generally subdivided into a product variety and the resulting process variety, leading into four variety categories:

- External Product Variety (e.g. induced by the market).
- External Process Variety (e.g. induced by the external supply chain).

- Internal Product Variety (e.g. induced by product structure).
- Internal Process Variety (e.g. induced by product structure and production process design).

As both External Process Variety and Internal Process Variety are direct or indirect consequences of the market, product structure and production system design, this specific differentiation will not be considered in the development of the model; however, both are addressed by the term *Process Variety* (Figure 2).

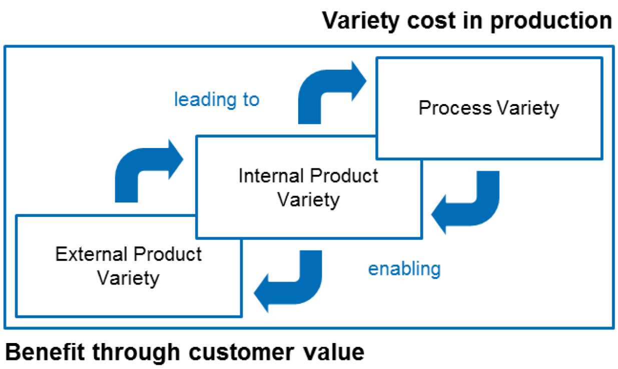


Figure 2: Interdependencies between variety categories.

The three resulting variety categories can be clearly distinguished, however, they interact in fundamental ways: Product design translates an External Product Variety into an Internal Product Variety by use of technical differences of parts (geometry, material, technology) and product structure [18]. Vice versa, Internal Product Variety allows for a defined External Product Variety, depending on product design, i.e. degree of modularity. Further, the Internal Product Variety has a significant impact on Process Variety, as an increasing variety of components tends to require an increasing variety of processes [19]. But also, Process Variety can be an enabler for an Internal Product Variety, thus leading to a better fit of variety on the market. Consequently, these three variety measures are not independent from each other. Their interrelations, however, are not necessarily constant or deterministic, but rather a result of approaches within corresponding activity areas of the complex product production system. At last, while the fit of External Product Variety determines the variety-induced benefit for a company, Process Variety has multiple ways of generating variety-induced cost, i.e. resource utilisation and capital costs [16]. Variety-induced benefit and costs result in a single-dimensional measure which brings together the areas External Product Variety and Process Variety on one common scale. Four framework-forming aspects result:

- Three variety categories (External Product Variety, Internal Product Variety, Process Variety).
- The resulting, so far not discussed interrelations of the variety measures.
- Their corresponding areas of product production system design.
- One variety-induced benefit and cost scale of external product variety and process variety.

These aspects fulfil the above stated requirements (3.1) and form the constitutive framework for an integrated product and production design (Figure 3). With the given structure, the framework categorises the following relations:

- External Product Variety as a determination for the variety-induced benefit under consideration of the domain “Customer value management” (I).
- Internal Product Variety being transformed by “Product Architecture and Technology Design” (II) from the External Product Variety.
- Process Variety as a result from Internal Product Variety and the influence of “Production Process Design” (III).
- Variety-induced costs as a consequence of Process Variety and the influence of “Production Organisation” (IV).

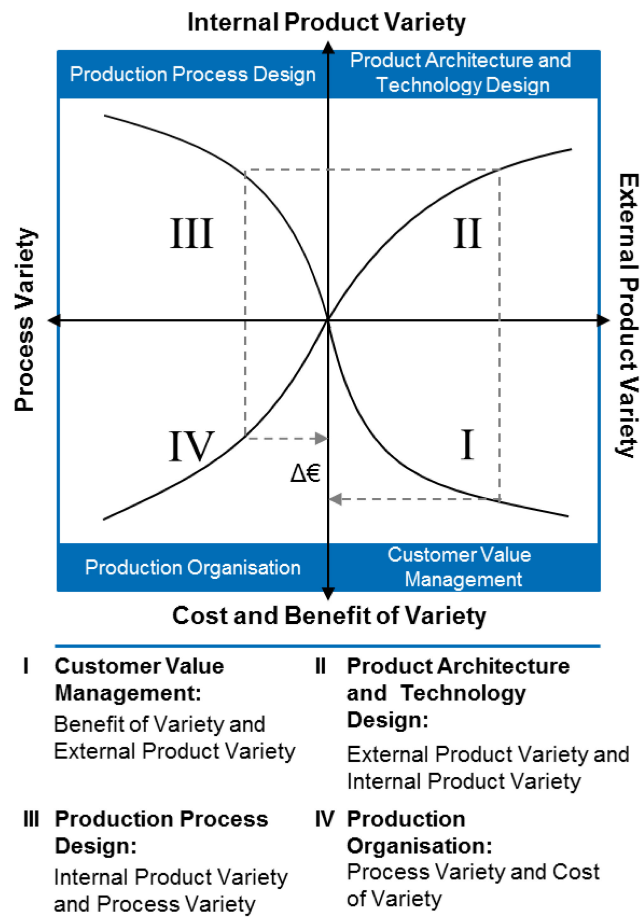


Figure 3: Model framework.

Cost and benefit of variety form two directly comparable monetary assessment criteria and consequently represent the same dimension. This assessment dimension forms a crucial link between the two opposite and causally connected ends of variety, enabling a stringent and integrative approach of product production system design. The configuration process itself requires the integration of suitable approaches into the four introduced domains (I-IV), which are introduced in the following section.

### 3.3 Explanation of the Model

To enable the application of the presented model, it is necessary to discuss its domains that are the central levers to generate a benefit for production companies. Furthermore, it is required to point out the importance of these domains for the relation between both influenced variables. If these relations can be described and the levers to influence these relations are known, the model theoretically will quantify the value of variety in each category. However, each of the three variety categories has to be understood as a multi-dimensional amount of variety elements which cannot necessarily be superposed. This will be explained in the following sections and is topic to further research at the Laboratory for Machine Tools and Production Engineering (WZL).

*Customer Value Management*

Considering only the product, customer value is determined by the match of offered and required product characteristics which creates a benefit for the customer larger than the suppliers demanded price [20]. The domain of Customer Value Management accordingly determines the potential turnover of a company in relation to the offered product range or product variety. Often, only a small number of variants generate a large amount of revenues. Therefore, Customer Value Management must identify the largest fit between customers' demand and potential External Product Variety of the company. However, External Product Variety can have multiple elements which individually or in combination have a specific value and generate a monetary benefit. For example, External Product Variety can be described by the number of products offered to the market an the differences in particular characteristics. It also contains the distribution of individual variant amounts offered to the market. Consequently, the domain of Customer Value Management has to make decisions that affect a multi-dimensional product variety with elements which cannot necessarily be superponed. At the same time, the interrelations between the benefit of variety and the different dimensions of External Product Variety are not necessarily constantly the same, but rather subjects to continuous changes. The description of relations between variety and benefit as well as the identification of approaches to influence these relations are the main levers of Customer Value Management. This domain is an important interface towards the market and translates the markets requirements that it is willing to pay for into the corresponding External Product Variety which the company is able to offer for an acceptable price.

*Product Architecture and Technology Design*

Product architecture and technology determine the ratio between the variety externally offered to the market and internally produced [18]. Accordingly, the corresponding domain has a major impact on all production-related activities. With intelligent design approaches, such as modular architectures, a large external product variety can be achieved by a comparably small internal variety of parts and components. Existing design approaches aim at creating synergies within product architectures and components of different external variants. This way, complexity can be dramatically reduced, e.g. in form of a lower Internal Product Variety. Yet, also the transformation of External into Internal Product Variety is a multi-dimensional and thus often complex task. Internal Product Variety can be explained by various aspects, e.g. the number of different parts, possible configurations, shapes and technologies. This results in a variety of different approaches within the focused domain. Design for assembly, variety management and technology management are three of them.

*Production Process Design*

Production Process Design enables the realisation of optimal production processes for a given Internal Product Variety with its range of different components, shapes, surfaces and technologies and structures. It is a main objective to maximize production efficiency, minimize time and assure required quality. Regarding the reduction of complexity costs, process communalities have to be effected to enable economies of scale [16]. The result of Production Process Design can be a physical production system with defined capacities and material flows. These define the main restrictions for an operative process realisation. Also, Production Process Design has to face several aspects of both Internal Product Variety and Process Variety. Process Variety, for example, can be subdivided into the amount of different process times, the time differences themselves, the amount of different kinematics, etc. Approaches are e.g. production segmentation (horizontal or vertical), qualitative and quantitative capacity planning, definition of technology and logistical chains, production resource design, paced production lines, etc.

*Production Organisation*

The realisation of production processes inevitably determines productivity and consequently the resulting manufacturing costs to a high extend. Costs which result from the given Process Variety are projected on the variety-induced cost scale. Given a defined process design, Production Organisation is the last lever to influence these costs. This can be done e.g. by production control measures (operative capacity and personnel planning, order creation, order release and order sequencing) which results among others in a certain capacity requirement and utilisation and an inventory level. Thus, Production Organisation lastly decides about the management of variety within the production system.

*Consequences for the Assessment and Configuration of a Product Production System*

It has been shown, that each domain of the model has to be understood as an area of complex interrelations which are only partly understood today. The integrative consideration of all relevant aspects of a product production system cannot be managed with conventional approaches. Hence, the suggested model supports the adequate and feasible structuring of a highly relevant problem of product production system design in a highly dynamic and complex environment. The model delivers a framework that enables the categorisation of measures to identify an optimal fit for a product production system. The model proposes tree tasks for producing companies. Firstly, companies are to identify their individual challenges within the four domains. They can do this by assessing their approaches of variety transformation among the domains, and by systematically assessing the results. Secondly, companies should manipulate the ratios in all four domains to improve their fit of product portfolio and production processes. As a last and continuous task, companies have to assess and potentially rearrange the match between their positions in all four domains. Short-term improvements can be obtained in quadrant IV, mid-term achievements in quadrant III, and long-term in quadrant II and I.

## 4 APPLICATION OF THE MODEL ON THE STREETSCOOTER CASE STUDY

In a consortium of industry and research, the RWTH Aachen University develops the electric vehicle "StreetScooter" under the lead of StreetScooter GmbH, aiming for competitive manufacturing costs compared to a conventional vehicle. Besides the development of the vehicle the production technologies and processes are designed simultaneously. Consistently, both product architecture and production processes are designed as modular and standardized as possible. Thus, different derivatives can be developed on the basis of one platform concept and, moreover, identical production and assembly stations can be used for future production to a large extent. An example of the coordinated product and process design is the variant-wide standardisation of joining interfaces and tools. This allows for all exterior parts to be mounted in the same way.

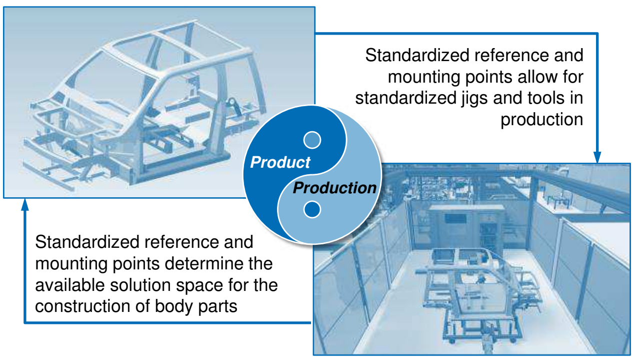


Figure 4: The integrative design principle of StreetScooter.

In the development of the "StreetScooter" the presented approach has been employed to reduce complexity for production:

- **Customer Value Management:** As a starting point for the configuration of the StreetScooter, the customer value of possible specifications along the bill of materials has been assessed for all components. As a result, the solution space of potential combinations could be reduced to a manageable number of combinations and unnecessary specifications were eliminated.
- **Product Architecture and Technology Design** In a next step, the affinities of the technically feasible configurations of the “StreetScooter” were assessed according to the perspectives product architecture commonality, process commonality and resource utilisation following the approach of Schuh et al [16]. As a result, a generic platform concept was developed that is the basis for four different derivatives Without compromising the external variety the internal product and production variety was reduced noticeably.
- **Production Process Design:** Due to the early consideration of production process improvements within the phase of product design, process commonalities were realised. It has been simulated that the product and production design can enhance the resource utilisation and decrease the lot sizes in production without negatively affecting the external product variety. The results are summarised in [1].
- **Production Organisation:** The benefits of fitting product architecture and production structure for the “StreetScooter” are to be realized with the start of a small series production in 2014. Feasible results are subject to several activities at the Laboratory for Machine Tools and Production Engineering (WZL). Further publications will follow.

Given the initially low volume expectations, the alignment of the product and production structure for the StreetScooter is crucial to achieve competiveness to comparable vehicle concepts. Until now two derivatives of the StreetScooter have been developed (Figure 5).


Figure 5: The StreetScooter platform concept.

Employing different improvement measures along the domains of the configuration model, a concept for the StreetScooter platform and production processes has been developed that can reduce the production costs by 11,8% compared to the initial design concept. The presented assessment and configuration model supports activities and decision-making processes within the StreetScooter project.

## 5 SUMMARY

An optimal fit of the product production system can add to solving the challenge of simultaneously realizing economies of scale and scope. Consequently, the integrated product and process development including the exploitation of the degrees of freedom in the solution space of product and process design must be enhanced. In order to consider manufacturability as a core product function, the dependencies of product and production design have to be systematically mapped. Furthermore, the challenge of complexity requires an adequate and feasible structuring of the problem to enable improvement.

Fitting the solution space of product and process design allows for realizing cost savings in product and production design.To provide methodological support at this point, an assessment and configuration model was presented. The model comprises the four domains “Customer Value Management”, “Product Architecture and Technology Design”, “Production Process Design” and “Production Organisation”.

The operability and potential of the model have been verified by experimental application in the production-oriented development of the low-cost electric vehicle “StreetScoter”. The consistently production-oriented design approach in the development of the “StreetScooter” prototype and its variants allows for significantly reducing the production cost while simultaneously offering a broad product variety. The presented model is subject to further development in recent projects at the Laboratory for Machine Tools and Production Engineering (WZL).

## 6 ACKNOWLEDGMENTS

The presented results have been developed in cooperation with the “Graduiertenkolleg Anlaufmanagement – Entwicklung von Entscheidungsmodellen im Produktionsanlauf“ (GRK 149/2) founded by the Deutsche Forschungsgemeinschaft (DFG). The author's sincere thanks also go to the StreetScooter GmbH for supporting the verification of the model.

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# Optimized Factory Planning and Process Chain Formation Using Virtual Production Intelligence

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**Abstract**

The increasing complexity of products creates new challenges in production planning. Hence, the methodology of process development has to be designed valuable. An innovative approach to reach efficient planning consists in the virtualization of planning processes. The concept of the "Digital Factory" enables a preliminary evaluation of the planning success. In the present work, a framework is presented, which allows for the integration of dedicated applications into an integrative data model to gain a holistic mapping of the production. Using Intelligence approaches, data can be analyzed to provide decision support and optimization potentials. The advantages involved are demonstrated by a production structure planning approach in connection with a process chain optimization.

**Keywords:**

Digital Factory; Virtual Production; Business Intelligence; Virtual Production Intelligence; Cyber Physical Systems

## 1 INTRODUCTION

In order to stay competitive within an economic environment, which is characterized by globalization and networking, so-called key competencies are indispensable in the process of modern factory planning scenarios. These competencies comprise of leading positions in cost minimization, quality and an individual compliance of the consumer's interests [1]. In the modern factory planning process, the formation and application of these core competencies contribute to the "concurrent strategy" of modern enterprises [2]. According to Frese, the concept of competitive strategy hereby constitutes how the involved institutions will determine their corporate strategic product-market-combinations in order to reach a competitive advantage against the concurrence.

In contradiction to the classical procedures of the factory planning process, which are described by [3], modern planning projects have to take into account cost and resource reducing procedures that enable an individual and modular design of planning processes. This demand requires both a quantitatively established support of decisions during the planning process provided by Intelligence solutions [4] as well as an integrative mapping of the production process within an overall context of the factory [5] [6].

In practice of factory planning, the specific knowledge of experts plays a decisive role. Based on special experience values, existing planning solutions are evaluated qualitatively in order to adapt the results into tailor made solutions of new planning projects [7]. According to this procedure, ancient planning results and specific knowledge are taken into account to decide, which planning steps have to be taken next. However, this does not lead to sustainable systematics in solving problems of the process design [8] [9]. The gained knowledge cannot be generalized to provide common solutions for similarly natured problems as, during the planning process, concrete decisions are made using specific knowledge that is based on rather qualitative evaluations.

This leads to a central problem in the systematisation of production planning. There are only a few approaches which provide a quantitatively based evaluation of the planning success during the dedicated steps of the planning process. These dedicated steps of planning were introduced by [10] within the Condition Based Factory Planning (CBFP). CBFP hereby serves encapsulated functions to perform the essential steps of factory planning independently. However, the interconnections between these planning modules are mostly based on qualitative models and on a subjective assessment made by the factory planner. Under these circumstances, neither a quantitatively based evaluation of the planning success nor a systematic decision support during planning is realisable.

A promising approach, which supports the realisation of an active decision support tool, is based on so-called Intelligence concepts. These concepts are designed to process information in order to gain a deeper understanding of the underlying processes within a manufacturing enterprise [11]. According to Kemper, there is no clear definition of the Intelligence term, but there are a few approaches to define the term using other technologies. Thus, the Intelligence concept can help filtering information from huge data amounts, can allow fast and flexible data evaluation, can serve as an early warning system or is capable of saving information and knowledge. In terms of production planning, Intelligence concepts are in charge of collecting historical production data to treat the information in a structured way. Consequently, the factory planner is able to access the information in an appropriate form [12].

To enable the transformation of big data into a structured data model, information has to be gathered from different applications. On the one hand, data can be generated by tools, which provide the simulation of single production entities within the factory. These pieces of information often differ significantly. On the other hand, big data pools can be self-generated using modern monitoring systems like the *Cyber Physical Systems* within a connected infrastructure in terms of the *Internet of Things*.

If this information is aggregated and combined with simulation and historical data, they can e.g. be utilized to map the layout planning of the factory in detail. Various models of segments generated in a similar way can be assessed against each other in order to gain quantitative measures regarding the planning success of each solution. This leads to resilient results and generates data, which can be utilized to build up substantiated decision support systems.

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In this context, the central challenge in planning consists in guaranteeing interoperability between all IT systems which are in use to collect, to generate or to aggregate production data. Furthermore, interoperability is needed not only between different simulation processes, but also between different planning modules of the planning scenario to enable an aggregation of different planning modules into one holistic model of the production site. Using this model, an evaluation of different optimization procedures can be performed considering their overall impact on the holistic production planning. If interoperability is not ensured throughout different planning modules, the algorithms and procedures of the optimization cannot be evaluated properly as their impact on other planning modules is not determined. In this case, an assessment of each planning module causes a comparatively high planning effort because all further planning modules have to be fulfilled in a certain order even if changes are performed in only one of them.

An integrative solution for the interoperability issue between heterogeneous, distributed simulations was presented with the concept of adaptive information integration. A framework based on this concept enables the aggregation of input and output data of different simulations so that the data can be stored within one integrated data basis [13]. Upon this data basis, Intelligence solutions can be established, which are based on Business Intelligence approaches and which were introduced as the "Virtual Production Intelligence (VPI)". Hereby, the VPI concept takes into account basic concepts of Intelligence solutions to transfer them into the domain of "Virtual Production". An according web interface provides not only access to the integrated information, but also treatment, manipulation and analysis of process data using various algorithms and heuristics of information technology like Data or Text Mining.

Based on this web interface, cross-functional interconnections as well as interdependencies between different planning modules can be identified and integrated within the evaluation of the holistic factory planning project. In this connection, *Integration* is defined as the functionality and power to interconnect and to harmonize data from various operational data sources [14].

The functionalities provided by these integration methods are used within so-called Data Warehouse (DW) systems, which are able to manage big data from various heterogeneous or even incompatible systems into a consistent structure. Through the integration process into the DW system, dependencies between the different planning modules can be identified. These dependencies can be developed further into general, quantitative *impact relationships* between the evaluations of each planning module within the holistic context of the factory planning project. These results enable the development of methodical, well-founded Intelligence Systems that are able to provide active decision support through the production planning process of the factory.

Within the present work, existing approaches concerning production structure planning are presented in section 2. Section 3 shows the added value of an integrated information basis founded on the VPI Framework. To enable a connection of the VPI Platform into operational levels of producing enterprises through a suitable interface, a web interface will be described in a further step. Finally, the added value of the VPI Platform in terms of factory planning is demonstrated by means of a process chain optimization algorithm within a factory planning use-case. The publication closes with a short conclusion and an outlook to future work.

## 2 STATE OF THE ART

### 2.1 Production Structure Planning in Factory Planning

Production structure planning constitutes a central component of the layout planning. In terms of factory planning, "layout" is defined as the arrangement of operational functional units [3]. In this context, the production structure planning has evolved to one of the core elements of factory planning.

Within factory planning, the term "optimal arrangement" stands for the optimal arrangement in terms of an optimized material flow. The material flow thus serves as the determining optimization criterion of the manufacturing flow [3]. A main reason for this specification consists in the high relevance of material flow costs in production. Due to investigations, the costs of the material flow within metal processing enterprises aggregate up to 10–12 % of the turnover and about 20 % of the manufacturing costs [15] [16]. Structure planning can be performed by using different approaches and levels of detail, e.g. ideal/real layout [3].

Within the present work, the layout planning is restricted to the ideal layout of the arrangement of production entities, particularly on the formation of process chains in terms of the production structure planning. These process chains represent the manufacturing stations that products have to pass until their completion. Due to the fact that the initial segmentation of a factory is mainly based on the quality of process chains, this part of the layout planning is crucial for the whole factory planning evaluation. As a reorganization of the machinery at a later point in time would lead to high costs, it does not take place in most of the cases, even if the current configuration and allocation of production entities is inefficient [17].

There are many computer aided procedures and algorithms to determine the material flow optimal arrangement of production resources. An overview about the existing procedures regarding layout planning was carried out in detail by [18] (see figure 1).

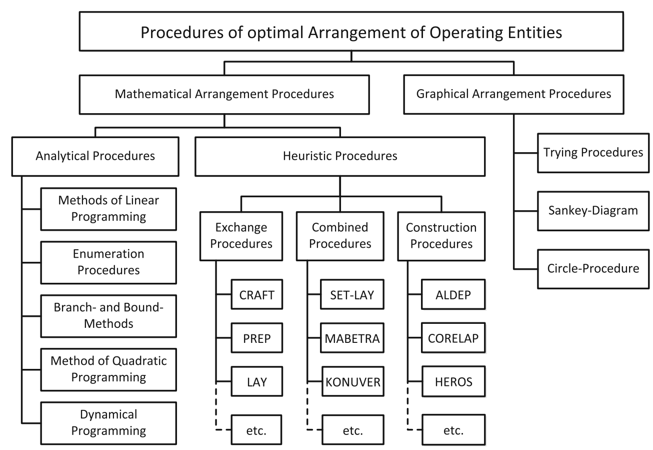


Figure 1: Layout Planning Procedures in Production Planning.

Conventional methods like graphical approaches were basically replaced by mathematical and analytical procedures. However, the graphical methods are still in use for factory planning. The evaluation of the planning results derived from these methods is mostly premised on specific performance figures which were taken into account uniquely for the current planning project. Referring to these performance figures, the factory planning consortium creates a point assessment system that is able to determine qualitative relations between different layout planning scenarios [19].

However, through this procedure, neither a quantitatively resilient evaluation of the factory layouts nor an assessment of the planning results across the borders of a single planning project can be realised. In order to reach this goal, mathematical methods have to be deployed. These methods are adequately explained in the relevant literature [20] [21] [22].

In addition to the analytical methods, which allow an exact calculation of the arrangement of resources with regard to a certain target figure, there are also heuristic procedures that are able to perform the layout planning with a reasonable expenditure of time and effort using algorithmic, iterative optimization methods. In order to provide a quantitatively based evaluation throughout the optimization process including a possible adaption of the procedures and methods as described above, an efficient data management and an application of high-performance Intelligence solutions are needed.

### 2.2 Intelligence Approaches within Production Planning

IT aided systems, which are applied in terms of factory planning, aim to provide a quantitatively traceable evaluation and analysis of different scenarios within the planning process and, through this, to ensure a decision support for the factory planner. As the currently utilised IT systems do not allow a holistic mapping of the production planning, innovative concepts with regard to production planning and production operations have to be realised. These concepts include Intelligence approaches and Data Warehouse systems.

A term that has characterized the fields of interest especially during the last years is known as *Business Intelligence (BI)*. In this connection, the term BI is based on the economic point of view of Intelligence solutions. BI was first introduced by Luhn in 1958 and was then mainly promoted by the Gartner Group starting in 1993 (see [23] [24]). In general, BI describes the analysis and usage of enterprise data using Information Technology in order to support decisions that have to be made by the user.

As there is no clear definition of BI at all, the concept was extended by several approaches in order to exploit the BI approach to further applications, e.g. operational BI, Process Intelligence, Corporate Performance Management or Business Performance Management. IT applications that are based on these Intelligence concepts have in common that they aim to *identify*, to *aggregate*, to *extract* and to *analyse* data of entrepreneurial processes [25].

In modern enterprises, data is collected through various instruments starting from applications to automatically generated data during production. One application domain of these advanced functionalities is represented by the term *Cyber Physical Systems (CPS)*. CPS can be regarded as a network of intelligent devices on the operational level. Data generated by these devices is collected and distributed by a network, which is known as the *Internet of Things*. In order to store the automatically generated data as well as data from various, heterogeneous computer applications using one consistent information model, a suitable structure for data integration is needed. The basic concept behind these functionalities is represented by the Data Warehouse systems, which are based on the modeling of multidimensional databases [14]. These database systems represent a necessary instrument to consolidate and to propagate information within enterprises.

The goal of DW systems consists of serving a structured storage of data and of enabling an efficient data access for everyone involved [14]. The founder of this concept characterises DW as a *subject-oriented*, *non-volatile*, *integrated* and *time-variant* database with the intention to support management decisions [26]. To establish DW systems in the field of production planning, their abilities of structuring big data are utilised. Due to the fact that production planning is practically based on models of ancient projects as well as on historical production data, DW systems provide the essential background to implement powerful Business Intelligence solutions.

An application of BI concepts within the management or operational level requires an aggregation of the different tools in use. Therefore, approaches were discussed that can enable a merge of different Intelligence systems. In this connection, the main literature distinguishes mainly between the operational Business Intelligence (OpBI) and Manufacturing Execution Systems (MES). Both systems have in common that they aim to analyse and to coordinate business processes, but in different segments of the supply chain.

In combination with BI technologies like Data Warehousing or Online Analytical Processing (OLAP), OpBI systems are able to serve real-time information [27]. This information is mainly used within sales and marketing [28]. On the contrary, MES serve IT support in the production environment. They are mainly based on engineering oriented concepts with a focus on the organisation of production plants in real-time [29].

A flexible and changeable planning can only be realised if OpBI and MES can be merged. In order to facilitate the transmission and the analysis of data from different sources, a central data storage is needed. The analyses performed using OLAP or Data Mining procedures can be used not only within strategic management, but also within tactical management. In this connection, a centralisation of OpBI and MES using a suitable data platform can lead to more transparency of the operational processes and thus can improve the performance of process design significantly.

## 3 VIRTUAL PRODUCTION INTELLIGENCE PLATFORM

### 3.1 Framework for an Integrative Information Model

The concepts discussed in section 2, that is the implementation and usage of decision support systems, provide the theoretical basis for the performance of successful production planning processes using Intelligence solutions. In order to provide the required Intelligence functionalities within the field of production planning, Business Intelligence approaches taken from the economic point of view have to be brought into accordance with IT systems that are currently used in production. Hence, in order to use the described approaches within production planning and to obtain an added value in the planning process, a suitable framework is needed to implement these conceptual ideas into a practical planning tool.

With regard to such a framework, the heterogeneity of available software needs to be overcome. Furthermore, the interoperability between distinctive planning modules and between the different Business Intelligence concepts needs to be established. Due to the substantial heterogeneity between the mentioned software systems, no suitable interfaces can be identified between the currently used planning tools. Hence, an interconnection of these software systems cannot be reached on a fundamental basis.

One possible solution for the interoperability issue can e.g. consist in the generation of a standardised data format. However, as earlier investigations have shown, the determination of a common data format is not feasible because of the high complexity of the provided simulation tools and the autonomy of the software developing enterprises [5]. Yet, a promising approach concerning the lack of interoperability among various simulation software consists in the creation of an integrated, canonical data model that takes into account multiple aspects of different data formats and structures and that is thus compatible with all simulation tools [30].

A data basis as described above synchronises the data from different simulations and business processes on the basis of an *Extract-Transform-Load (ETL)* process and thus avoids the adaptation of the whole IT infrastructure. The framework that provides the described functionalities is the *Virtual Production Intelligence (VPI)*, which was firstly introduced by [31]. The underlying platform is hence referred to as VPI Platform. Throughout the according configuration, the framework enables full collection and aggregation of data that is gathered during strategic, planning and tactical-operational activities within an enterprise.

The integration takes place within a two-stage database system. The first database represents some kind of preliminary stage for the data that needs to be integrated. In this database, the data collected during different processes is stored in a comparatively disordered structure. Based on this data basis, an ETL procedure is performed in which the data is integrated into a common, integrative data basis that is represented by a DW system.

### 3.2 Web Application – Interface to the VPI Platform

In addition to the functionalities provided by the VPI Platform, the accessibility and the control of the platform are of particular relevance. Hence, a suitable interface is needed that provides significant user interaction modules. The goal of this user interface is not only to provide a general overview of all applications that are embedded within the VPI Platform, but rather to aggregate requested data in a role- and user-specific way. The user interface enables people involved in the production planning project to get an overview of all the information that is important for their field of interest. Hence, well-founded and quantitatively resilient decisions regarding the progress of the production planning project become possible. In addition, the planning is supported by the analysis methodologies that are embedded within the information platform. An application that can serve as an appropriate interface to these requirements needs to be built up modularly and has to be able to provide a continuous data processing of the received data.

During the preliminaries of the current work, an appropriate web platform was developed that fulfils all demanded requirements. Using a framework that is based on the GWT-Framework, a web application was developed in order to enable simplified user access. Within this web application, an integration of various pre-implemented widgets can be performed. Based on an XML configuration methodology, rich domain and user specific applica-tions can be built up in terms of modular design principles. Due to AJAX (Asynchronous JavaScript and XML) functionalities and the related facility of asynchronous requests, the web applications that are based on the presented framework can be handled similarly intuitive as a desktop application without having huge disadvantages concerning functionality or performance.

The structure and functionality of such web applications can barely be distinguished from "offline" applications, but they are always up-to-date. Another advantage of using web applications instead of traditional computer applications is, in particular, their independency of the platform or of the computer system. Due to the design of the presented web application, it can be executed within every modern web browser. Hence, an execution of the web application can be performed on every operating system or hardware architecture. In addition, the use of CSS (Cascading Style Sheets) achieves a unified appearance of the application, which is independent of the system in use. Thus, in combination with the web application, the VPI Platform serves as a powerful planning tool for production planning. The concrete added value for production planning is de-monstrated on the basis of a use-case within the following section.

## 4 USE-CASE

### 4.1 Traditional Approaches of Production Structure Planning

In most cases, the factory planning process is based upon already existing data. This implies that in the conception of a new production structure, the first step normally consists in deriving the basic structures from already existing planning projects. Based on this "historical data", several production configurations are selected and compared to each other.

In the traditional approach, this selection is not entirely based on quantitative data, but also on subjective assessments and experi-ence. In this connection, an evaluation is either entirely qualitative or based on a point system, in which the given "ratings" are derived from the comparison to the planning success of preceding projects [32]. According to Wiendahl [32] and Tompkins [9] layout planning consists not only in the positioning of resources, but also in the definition of functional areas. Thus, different requirements can be imposed on layout planning, especially costs, space utilization, production efficiency, minimization of effort for material transport, transparency, flexibility and changeability as well as information and communication flow or the consideration of restrictions of any kind. The current work is hereby focused on the points space utilization and the minimization of effort for material transport, hence the positioning of resources. An optimization restricted to the points highlighted is also known as the derivation of the ideal layout.

Regarding the optimization of this ideal layout, heuristic approaches are the usual methods of choice. The results of these heuristics are based on qualitative guesses, which afterwards are developed into an "optimal" solution by using semi analytic or iterative mathematical processes. In production structure planning, this proceeding can be organized as follows: At first, the number of segments or production chains is set. Afterwards, according to the requirements, process chains are formed which are able to cover as many products as possible.

A visualization of this approach can be seen in figure 2. Each box represents a production entity, whereas the arrows show the flow of material.

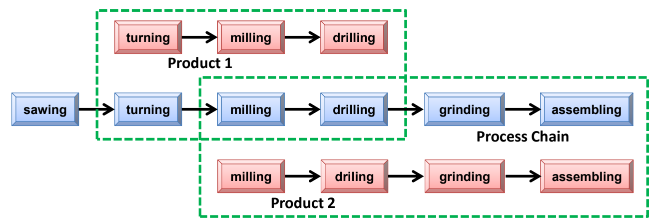


Figure 2: Mapping of products on a process chain.

This example shows that the central process chain is able to cover all manufacturing steps of both product 1 and product 2. The frames illustrate the process chains' sequences matching the manufacturing chains of the products. An optimal configuration goal is to configure process chains in a way that allows for the production of a maximum number of different products without entailing additional logistical work. Here, the phrase "adding logistical work" means that no step in the production chain needs to be skipped or repeated. Both products shown in figure 2 fulfil this condition.

In the practice of production planning processes, it is common that process chains are assumed and further optimized by the use of so called "testing procedures". These procedures are based upon the "expert knowledge" mentioned before and are thereby lacking a quantitative basis. Apart from these "testing procedures", heuristic procedures are used to optimize the production structure. The main difficulty is to integrate planning results into an overall model, which comprise all modules of the production planning. An evaluation of each process chain configuration is therefore associated with high effort as the results of previous planning modules usually have to be entered manually in further evaluation tools.

### 4.2 Process Chain Optimization Using an Iterative Algorithm

In the following, it will be shown that using Intelligence tools, especially the VPI Platform, within planning has significant advantages with regard to both heuristic and analytic methods over a dedicated approach to optimization. Therefore, in the present work, an iterative algorithm based upon historical production data was developed, which creates an optimized determination of process chains.

The difference by using the Virtual Production Intelligence Platform instead of a static optimization tool consists in the way of saving the results of the data treatment. According to current methods, one planning step has to be fully completed in order to continue with the next one. Thus, parameters have to be determined even before they can be evaluated holistically. This step-by-step approach causes higher working efforts, especially if parameters of early planning stages have to be changed. That is why the optimization algorithm, which is explained in the following, will be embedded into an information model that allows keeping "elastic" parameters for all steps of the factory planning.

The production data is represented by a list of products that also contains detailed information about the manufacturing steps of each product. This section is intended to describe the algorithm as such. Its position in the overall context as well as its functionality within Decision Support systems are discussed in the following sections. The algorithm performs an optimization, which is based upon historical production data. Therefore, process chains are created out of already existing product data. Afterwards, similarities and regularities inside these process chains are identified by quantitative measures that have been implemented on the basis of counting procedures. Based on these counting procedures, an A-Priori-assessment is made to identify useful process chains.

In a further step, these preliminary main process chains (hereafter referred to as *MainChains*) are evaluated by using statistical and heuristical methods in connection with an iterative optimization algorithm until a certain coverage amount of the products can be achieved. During the computation, it is checked which product chains can be covered by the *MainChains*. These product chains are referred to as *RegularChains* within the program logic. Besides *RegularChains*, the process also identifies product chains that cannot be covered by the *MainChains*. These chains are referred to as *SpecialChains*.

While processing the algorithm, the actual *MainChains* are evaluated within each iteration step first. Subsequently, a switching process replaces certain *MainChains* by process chains determined by a quantitative analysis of the *SpecialChains*. This process is repeated until a certain degree of coverage of all products is assured for the *MainChains*.

### 4.3 Dynamical Layout Optimization Using an ETL Process

The introduced algorithm provides an important contribution to the execution of a production planning project. However, to be evaluated completely, this static optimization of the production structure is not to be considered isolated from other planning modules, but must be placed in an overall context. In the course of the evaluation, a large number of parameter variations may be made in any of the planning modules to achieve an optimal solution for the given problem. The advantage in the use of an "Intelligence System", specifically of the VPI, is that the optimization algorithms are performed for a complete parameter corridor. Thus, the results can be stored in a way, which allows for a direct addressing of the results in the specific optimization of the overall problem.

This process is demonstrated using the optimisation algorithm described above (see figure 3). The process chain development algorithm was integrated into an *Extract-Transform-Load (ETL)* process commonly used in the context of Intelligence and Data Warehouse concepts. At the beginning of the process, the production data is loaded out of the database and is processed in order to generate process chains (*Extract*). Subsequently, the process chain optimization algorithm is used within the *Transform* process.

One parameter, which can be varied during the layout optimization process, is the number of main process chains (MainChains). According to the number of MainChains, the optimization algorithm can e.g. be executed on a span from 3 to 5 MainChains. The choice of an appropriate span can e.g. be based on architectonic limitations or on other factory restrictions. At the beginning of the computation, the user has to set a minimum (numMainChains [=3]) as well as a maximum number (maxMainChains [=5]) of considered MainChains. Based on these numbers, the algorithm is performed several times. The results achieved by each run are saved into a multidimensional database using a structure that allows for accessing each "planning scenario" separately.

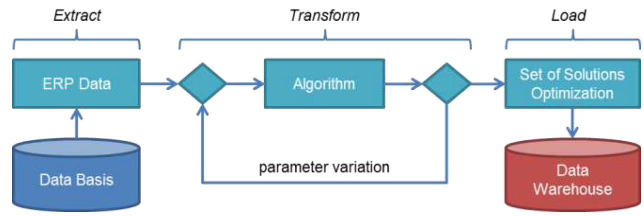


Figure 3: ETL process of the Layout Planning.

In addition to a variation of the number of *MainChains*, other parameters can be varied, as well. In a subsequent stage of planning, all results determined by the various algorithms are accessible for the whole parameter corridor that is relevant. Through this, a significant benefit is achieved for the planning process, as modifications can be performed at any time.

Hereby, a user utilizing the web application for a planning process requires no knowledge about the algorithms executed. As the production data as well as the results are processed by the VPI Platform, the user only receives the results that are specifically customized according to his parameters. The Data Warehouse system ensures the implementation of the given results into the holistic process of the production planning project. In further consequence, corresponding to the parameters chosen, the results as well as their dependencies to other modules are included into the complete evaluation of the planning.

## 5 CONCLUSION AND OUTLOOK

By means of a Use-Case derived from production structure planning, the advantages of using Intelligence systems, especially the Virtual Production Intelligence, have been stated. Using the VPI Platform, various boundary conditions and parameters can be taken into account during the modelling of production processes. Furthermore, the VPI Platform enables an integrative, holistic view on the different scenarios of a planning project. The results of single planning modules for different parameters and production configurations can be evaluated within the context of the overall planning. Hence, well-founded quantitative forecasts about the planning result can be made at any point in time during the planning process.

In the context of optimized production planning, the next steps will consist in advancing the presented concepts with regard to both algorithmic procedures and methodical aspects. Thus, firstly, new algorithms and performance indicators will be developed to take into account temporal aspects of the production, as well. Hence, the process chain term will be extended regarding its dimension. The result consists in multi-dimensional process chains which enable a consideration of temporal dependencies between the manufacturing steps of a product. In this connection, the process times can be taken into account in order to enable a multidimensional production structure optimization. Thus, for example, the process cycle can be harmonized by parallel connections of production entities to minimize waiting times.

As a methodological improvement, the presented concepts of integration and data management will be extended with regard to the different organisational sectors of a manufacturing enterprise. In particular, data exchange should not only be performed between Enterprise Resource Planning systems of the management and the tactical, respectively the planning level, but also between the operational and higher levels.

The resulting challenges for the integration and the data management will be approached by an extension of the Virtual Production Intelligence and the Data Warehousing concepts. In this context, data taken from the operational level (Cyber Physical Systems) will be processed in a way that the information can be integrated productively into Manufacturing Execution Systems as well as into Enterprise Resource Planning systems. Only through the realisation of interoperability between these systems, a holistic digital mapping of the production can be reached. On the basis of this holistic interconnection of data, tools for an active decision support can be derived. These decision support systems ensure a continuous improvement of the production process development by making use of the actual data from the production.

## 6 ACKNOWLEDGMENTS

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# Developing a Self-optimizing Robotic Excavator System with Virtual Prototyping Technology

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**Abstract**

Nowadays, a robotic excavator is widely applied in several fields of mining industry, agriculture, and forestry. Due to the complexity of dig environment such as slope of terrain profile, hardness of soil and unknown disturbances inside the soil, a versatile dig strategy avoiding obstacles has become a challenge to be addressed. This article presents an engineering model that describes the mechanical behavior of the robot excavators when it interacts with soil and generates an appropriate bucket path to adapt with each soil type, terrain profile and avoids buried obstacles as well. Based on a concept of the digging process, a robot excavator was designed in SOLIDWORKS and then exported to ADAMS environment. Whereas a soil model was modeled and analyzed by finite-element analysis (FEA) in ANSYS, then exported to ADAMS environment. The interactive simulation was implemented in ADAMS environment to investigate the dynamic behavior of robot and soil. Through the self-optimizing behavior of the robot in the digging process, an optimal bucket trajectory and an intelligent control strategy were generated in MATLAB/Simulink to control the robot tracking the desired bucket trajectory. The self-optimizing strategy was evaluated by effectiveness of the proposed algorithm in testing scenarios with many soil types and obstacles on the virtual prototype model.

**Keywords:**

Robotic excavator; self-optimizing system; modeling and controlling; virtual prototyping; intelligent control

## 1 INTRODUCTION

Nowadays, a robotic excavator is considered as a feasible solution for improving the productivity of construction, mining and forestry industries. This solution allows removing the operators from hazardous circumstances such as chemical and nuclear waste, rugged terrain of mining or mountain, and even enabling aerospace exploration. Due to the robotic excavator works in the complex dig condition, the determination of the accuracy of dig position and generating an appropriate bucket path are the challenges need to be solved. According to the conventional excavator, in order to achieve the high productivity, safety and efficiency, the excavator operators should be required over ten years of experience because their delicate skills are necessary for excavator operation [2]. These experts have the abilities of analyzing and predicting the dig environment based on their knowledge and experience. Generally, in order to carry out an effective digging process, the operator has to execute the following task sequences: Firstly, the operators decide the target area to trench after analyzing the shape of terrain and hardness of soil, second they determine the soil type and analyze the soil properties depending on their eyes in the trench target area. Finally, they generate the bucket path considering the safety of the excavator pose by the force translation and the maximum capacity of the bucket [2]. Normally, based on the given digging parameters such as the depth and distance of the trench, the experience operators can make many predictable trench paths, and decide the final trench path through analyzing the restraints such as the geometry, soil type as well as feeling the buried obstacle in ground from the engine situation. Therefore, it is difficult to generate an optimal bucket path which can get maximum soil bucket capacity and guarantee safety for human and machine. Moreover, in the dig works of the hazardous circumstances, eliminating the human operator is necessary to execute. From the above analysis, it is a necessity to develop a robotic excavator that is capable working independently in any harsh environment.

Because of the high potential in using of robotic excavator, several researchers were focused on automated earthmoving operation. The most of the studies were separated into three categories: modeling the digging process [3],[4],[5],[6],[7], planning the digging operations [8],[9], and controlling the automated digging process [10],[11],[12],[13].

As mentioned above, most of the studies have concentrated to solve the problems in each of individual situation of autonomous excavators. In order to compute the tractability in real time applications, it is a necessary to develop a digging prototype model that describes all functions of the robotic excavator, and the affecting factors of digging process. Based on this prototype model, a novel optimal strategy can be applied to improve the productivity or the efficiency of the autonomous excavation. This paper proposes a virtual prototype technology for developing a self-optimizing robotic excavator system. The virtual prototype technology is known as a co-simulation solution that uses the commercial software such as SOLIDWORKS, ANSYS, ADAMS, and MATLAB for developing a virtual mechatronic prototype [1]. Through this virtual prototype, the designs of mechanical and control systems would be executed, verified and modified before implementing in a real physical prototype.

## 2 ANALYSIS OF EXCAVATION PROCESS

The excavation dynamic is a complex process due to the complexity of machine dynamic and the interaction between the tool and its working environment. In order to investigate the dynamic behavior of an excavator, we observe a series of dig tasks in a specific dig cycle. The excavator can be controlled up to three degrees-of-freedom simultaneously and occasionally operating four degrees-of-freedom simultaneously for removing the soil depend on the soil hardness. The sequenced tasks in a digging cycle of robotic excavator for a trench is shown in Figure 1. These tasks can be described through the following operation states:

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1) The bucket position starts in over the trench.
2) The bucket is moved to contact the ground by the boom movement.
3) The robotic excavator generates the bucket path and the pose of bucket angle. The necessary parameters in this state are the geometry profile measured data of the trench, which collected from laser sensor attached on the excavator.
4) The bucket moves through the ground. This state includes the basic operations for soil removal such as penetration, drag, and curl. These operations can be modified according to the encountered conditions of the bucket with its working environment during excavation. Generally, based on the current geometry and properties of the soil, the excavator can be instructed to execute the following digging strategies:

   - *Penetrate and curl*: This strategy is used in the soft soil such as sand. Using this strategy, the operator firstly controls the boom joint to force the bucket into the ground following a near vertical direction. Once the penetration to a desired depth has been obtained, the bucket would be curled to collect soil into the bucket.

   - Penetrate and drag: This strategy is used for the hard soil which the bucket can not easily penetrate. In this strategy, the operator firstly controls the boom joint to push the bucket penetrating the soil, then adjust the attack angle of bucket in the ground to shear the material, and finally drag the bucket teeth in a straight line by moving simultaneously the boom and the arm. In this state, the operator is demanded to control more complex operations than the penetrate and curl strategy.
5) Removing the bucket from trench: The soil contained bucket would be removed out of the ground by the raised movement of the boom.
6) Moving the bucket to dump location: The operations in this state involves the boom motion, and rotation of excavator base to dump the bucket contents at the side of the trench.
7) Empty bucket: the bucket would be rotated to empty the soil, and then the process would be repeated.

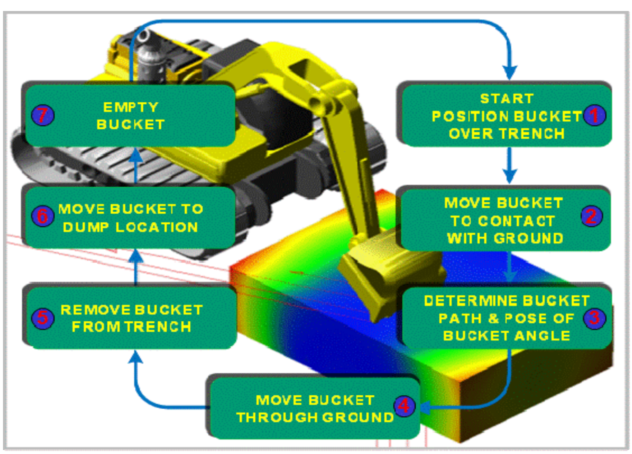
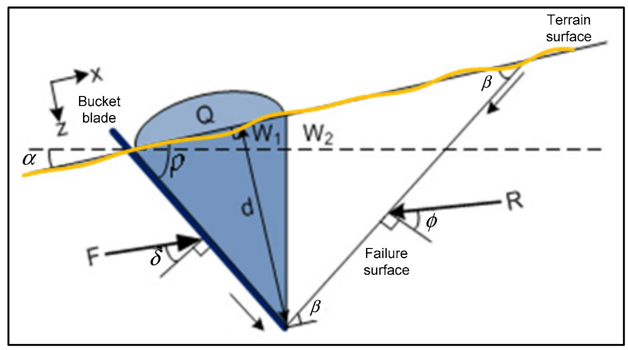



Figure 1. The sequenced tasks in a digging cycle of robotic excavator.

Through the analysed operation states while digging a trench, the bucket behaviour is considered a crucial task to achieve the optimal digging process. In order to obtain an optimal digging process, the states of "3" and "4" are known as the key states of the digging process in direct relations to bucket-soil interaction, which is very difficult to model.

The main objectives of this article is to develop an optimal digging strategy for robotic excavator. The robotic excavator is not only capable of digging in any soil type with high accuracy, but also can avoid the buried obstacles with fast response time. When the bucket penetrate into the ground, a resistive force occurs at the bucket tip against the bucket movement in reverse direction. This resistive force value is varied due to the influence of many parameters such as the penetration depth of the bucket, geometry of trench, attack angle of bucket to ground, physical soil properties in range from wet clay to hard gravel, and buried obstacles in ground. Therefore, the determination of the proper resistive force in soil when bucket-soil interaction is a challenge need to face.

Several studies were addressed to predict the resistive force of soil in the soil-tool interaction based on the mathematical models and experimental data [5], [6], [7], [8], [9]. A. R. Reece has developed the Fundamental Equation of Earth- moving Machine (FEE), and it was a pioneer equation for developing the modified mathematical models of earth-moving afterward. The FEE model is used to predict the resistive force of soil that acted against the tilling when it is moving horizontally in soil. The resistive force of soil is computed as a required force to shear a soil wedge out of the failure surface. The modified FEE model for predicting the resistive force in case of slope terrain is described in Figure 2.




*where, $V_s$ is a swept volume (material in shaded region), Q is the surcharge, $W_1$ is the weight of the material in the bucket, $W_2$ is the weight of the rest of the material in the wedge, $L_t$ is the length of the tool, $L_f$ is the length of the failure surface, $\phi$ is the soil-tool friction angle, c is the cohesiveness of the soil, $c_a$ is the adhesion between the soil and blade, $\delta$ is the soil-soil friction angle, $\beta$ is the failure surface angle, $\rho$ is the rake angle, d is the depth of the tool in the soil, R is the force of the soil resisting the moving of the wedge, and F is the force exerted by the tool on the wedge, and α is the terrain slope.*

Figure 2: The modified FEE model for predicting the resistive force of soil with slope terrain.

The adhesion forces such as $c_a$, $c$ can be ignored. The exerted force for shearing a soil wedge in slope terrain is computed as follows:

$$F = d^2 w\gamma g N_w + cwdN_c + V_s \gamma g N_q \tag{1}$$

Where, *d* is the depth of the blade, *w* is the width of the blade, $\gamma$ is the density of the material, *g* is the gravity of soil, $V_s$ is the swept volume of soil. The three factors $N_w$, $N_c$, and $N_q$ are calculated based on the geometry of the soil wedge.

As analyzed above, we find that the exerted force to shear the soil wedge is determined based on the geometry parameters of bucket-terrain intersection, and the soil properties.

$$F = f(G, P) \tag{2}$$

Where, *F* represents the exerted force acting on the bucket tip, *G = (d, α, ρ, $V_s$)* denotes the geometry parameters of bucket-terrain intersection, $P = (\gamma, \beta, \phi, \delta, c)$ express the soil properties.

The geometry parameters ($G$) can be obtained based on the measured data from the laser sensors. Meanwhile, the values of the soil properties parameters ($P$) are normally determined based on the data experiment and estimation methods.

Recent years, due to the continuous growth of the computation and the simulation software technologies have been growing, the soil-tool interaction model can be modeled easily and the resistive force of soil could be predicted accurately based on the finite element method [3], [4]. According to Ramin Jafari [4], a 3D finite element analysis of soil-tool interaction was carried out to investigate the behaviour of the soil-tool interface and study the effect of soil properties on predicted forces. The research results have been proved the finite element method enabling use to model the soil-tool interaction and predict the resistive force of soil.

## 3 ROBOTIC EXCAVATOR KINEMATIC

The kinematics formulation for a robotic excavator is a necessary step in the automation process. The kinematic model has been built to describe the robotic excavator as a robotic manipulator with three degrees of freedom. The reference point $0_1(0,0)$ is used as the coordinate base system in the Cartesian for kinematic analysis. It is attached on the boom joint that is connected to the vehicle. The values of the excavator joints variables ($\theta_0$, $\theta_1$, $\theta_2$, $\theta_3$) are determined based on the lengths of the actuators (boom, arm, bucket). The mathematical relations between these variables are determined based on the kinematic formulation of the excavator arms. The robotic excavator kinematic is shown in Figure 3.

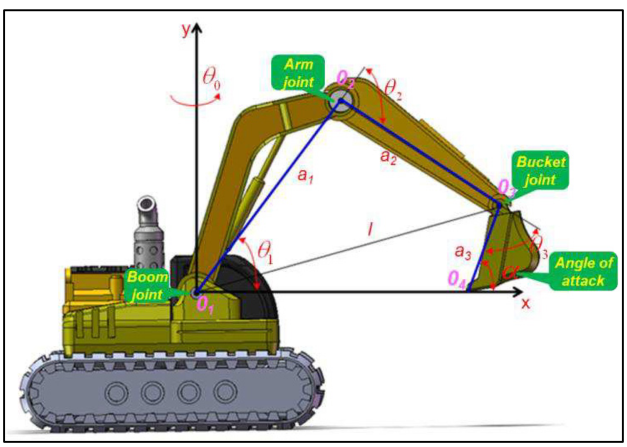



Figure 3. The robotic excavator kinematic.

### 3.1 Excavator Forward Kinematic

Forward kinematic of robotic excavator is used to describe the positions and orientations of the points on the robotic excavator in the Cartesian coordinate when the positions of joint angles are given during excavation. In order to determine the positions of the points on the excavator, the relations between the fixed coordinate base system and the other coordinate systems are necessary to express. The homogeneous transformation matrices relating two adjacent coordinate frames ($i$-$1$)th to the $i$th are given as [18]:

$$A_{i-1}^{i}=\begin{bmatrix}\cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & a_i\cos\theta_i\\ \sin\theta_i & \cos\alpha_i\cos\theta_i & -\sin\alpha_i\cos\theta_i & a_i\sin\theta_i\\ 0 & \sin\theta_i & \cos\theta_i & d_i\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (3)$$

Where $\alpha_i$ is the twist angle of the link $i$, $a_i$ is the length of link $i$, and $d_i$ is offset distance in link $i$, (i=1,2,3).

| Joints | $a_i$ | $\alpha_i$ | $d_i(m)$ | $\theta_i(rad)$ | motion |
|---|---|---|---|---|---|
| 1 | $a_1$ | 0 | 0 | $\theta_1$ | Rotate |
| 2 | $a_2$ | 0 | 0 | $\theta_2$ | Rotate |
| 3 | $a_3$ | 0 | 0 | $\theta_3$ | Rotate |

Table 1: Deravit-Hartenberg parameters of the robotic excavator.

A desired position and orientation of the excavator bucket tip can be described in the base coordinate frame as a position matrix:

$$A_1^4 = pos = \begin{bmatrix} n_x & o_x & a_x & p_x\\ n_y & o_y & a_y & p_y\\ n_z & o_z & a_z & p_z\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (4)$$

The end effect position of the bucket is determied by the equations:

$$\begin{aligned} x &= p_x = a_1 * c_1 + a_2 * c_{12}\\ y &= p_y = a_1 * s_1 + a_2 * s_{12}\\ z &= p_z = 0 \end{aligned} \quad (5)$$

Where $c_1=\cos\theta_1$, $s_1=\sin\theta_1$, $c_{12}=\cos(\theta_1+\theta_2)$, $s_{12}=\sin(\theta_1+\theta_2)$

### 3.2 Excavator Inverse Kinematic

The inverse kinematic equations for the robotic excavator are used to determine the values of the joint angles when the position and orientation of bucket tip were given in the base coordinate system. It is assumed that the coordinates of the points such as $O_1 \equiv Boj$ (Boom joint), $O_2 \equiv Aj$ (Arm joint), $O_3 \equiv Bj$ (Bucket joint), $O_4 \equiv Bt$ (Bucket tip) in Fig.3.

The position of the bucket joint ($x_{Bj}$, $y_{Bj}$) is determined based on the bucket tip position is given:

$$x_{Bj} = x_{Bt} + a_3 * \cos\alpha \quad (6)$$

$$y_{Bj} = y_{Bt} + a_3 * \sin\alpha \quad (7)$$

The position of bucket joint relative to the point of attachment of the boom to the vehicle is given by:

$$x_{Bj} = a_1 * \cos\theta_1 + a_2 * \cos(\theta_1 - \theta_2) \quad (8)$$

$$y_{Bj} = a_1 * \sin\theta_1 - a_2 * \sin(\theta_1 - \theta_2) \quad (9)$$

The inverse kinematic equations for $\theta_1$, $\theta_2$, $\theta_3$ are determined as:

$$\theta_2 = \cos^{-1}\left(\frac{x_{Bj}^2 + y_{Bj}^2 - (a_1^2 + a_2^2)}{2 * a_1 * a_2}\right) \quad (10)$$

$$\theta_1 = \tan^{-1}\left(\frac{y_{Bj} * (a_1 + a_2\cos\theta_2) - x_{Bj} * a_2 * \sin\theta_2}{x_{Bj} * (a_1 + a_2 * \cos\theta_2) - y_{Bj} * a_2 * \sin\theta_2}\right) \quad (11)$$

and

$$\theta_3 = \pi + \theta_1 - (\alpha + \theta_2) \quad (12)$$

where ($-65^o<\theta_1<85^o$), ($0^o<\theta_2<180^o$), and ($-30^o<\theta_3<150^o$).

## 4 PLATFORM AND TOOLS FOR DESIGNING THE ROBOTIC EXCAVATOR

The modern design process for a mechatronic system as the robotic excavator includes conceptual and functional design, command & control, digital mock-up, virtual prototyping, and testing [19]. The analysis flow chart of a design process for the mechatronic system is shown in Figure 4, and the submodels are described the following stages [20]:

- The main objective of the conceptual design is to constitute the best product concept based on the given conditions, and taking into account the criterion of science, technology, economy, market, culture.
- Structural model design is to identify and determine the number of bodies, the degrees of freedom of the system, the space motion of the system, type of joints, type of geometric constraints, and the relationship between the bodies in the system. The structural synthesis method was applied in this situation, and one of the collection of the obtained possible structural schemes is used in this study.
- The kinematic model includes the rigid parts which are connected through the geometric constraints and specific geometric parameters. The input of the kinematic model is created by the motion generators which enable to control the angular or position/velocity of the driving elements.
- The inverse dynamic model involves the kinematic model and the external & internal forces. This model is employed to determine the moment or force which is applied by the driving element.
- Dynamic model consists of the inverse dynamic model, but the input is created by the above determined torque/force. The goal is to evaluate the "real" behaviour of the mechanical system.

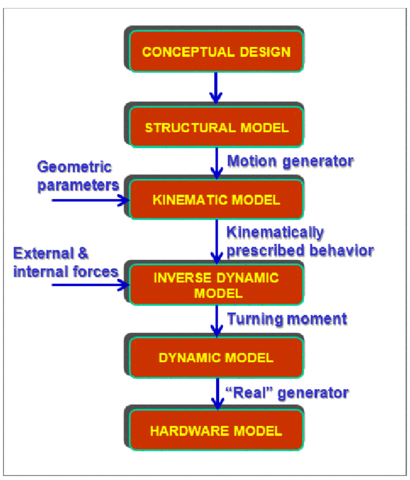



Figure 4: Analysis flow-chart for excavation design.

Since the computer graphic simulation technology has been growing, simulation of the real behaviour of the mechatronic is a priority stage in the design phase. In recent years, a novel type of study was discovered by using the MBS software, namely, virtual prototype technology. This technology consists mainly in conceiving a detailed model and using it in a virtual experiment, in a similar way with the real case [20].

Generally, the virtual prototyping platform involves CAD, MBS, FEA, and C&C. The CAD software is used to develop the geometric model of the mechanical system. This model includes the rigid parts with the shape and dimension of the physical model, and the information about mass and inertia properties of these rigid parts. The geometric model is then exported to the MBS environment using a file format as STEP (CATIA) or Parasolid.x_t (SOLIDWORKS). The MBS is the center component of the virtual platform. It is used to analyze, optimize, and simulate the dynamic behaviour of the mechanical system under real operating conditions. The FEA software is used for modeling the flexible components. The MBS has an ability to transfer loads to FEA and receive the flexible components feedback from FEA. This function enables the capturing of inertia and compliance effects, and predicting loads with greater accuracy, hence obtaining more realistic results. Command & Control (C&C) is a software product, which is used to design the control system. This software exchanges information with the MBS software. This exchange process creates a closed loop in which the outputs from the MBS model are the inputs for the control system and vice-versa. The outputs from the MBS model are the measured parameters that are necessary for controlling purpose, and the outputs form control system effect on the MBS simulation.

Based on these terms, the virtual prototyping platform was used in this paper as shown in Figure 5. The platform integrates the following licenced software: CAD-SOLIDWORKS, MBS-ADAMS, FEA-ANSYS, Control-MATLAB.

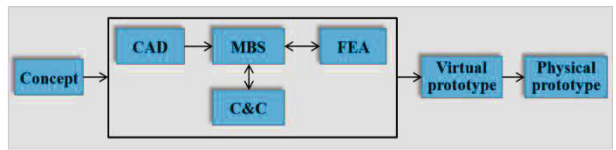


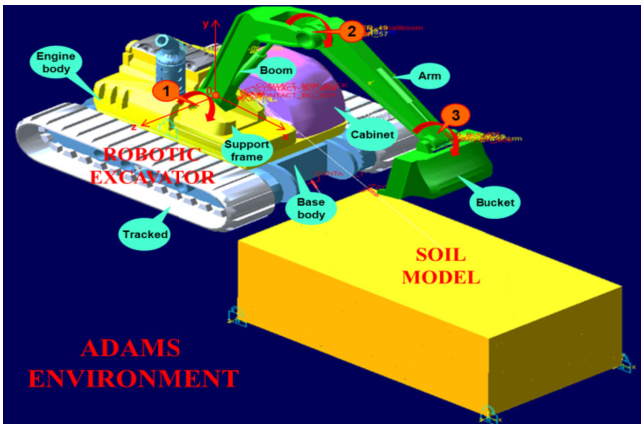

Figure 5: The virtual prototype platform.

## 5 CASE STUDY

### 5.1 Developing a Virtual Prototype of Autonomous Excavation

In order to apply the above-mentioned design algorithm, an autonomous excavation system which includes a flexible soil model and a robotic excavator model with three degrees of freedom has been considered here. The autonomous system is used to investigate the dynamic behaviour of the robotic excavator in integrating process with its digging environment. The main motions of the robotic excavator are the rotation motions of the boom joint, arm joint, bucket joint. These joints are directly driven by the rotary hydraulic pumps those enable to develop angular displacement up to 180°. The virtual prototype model of the autonomous excavation is shown in Figure 6.

The autonomous excavation model is divided into two sub-models including the robotic excavator model and the soil model. The 3D-solid model of the robotic excavator system was made using CAD software, namely SOLIDWORKS. The geometry was transferred to ADAMS/View using a file format as Parasolid.x_t. In the ADAMS environment, a virtual model of the robotic excavator system is created. This model is designed including the rigid parts such as engine body, sprocket-wheel, cabinet, boom, arm, and bucket. These parts firstly must be defined, and then mass and inertial matrices are generated automatically. They are connected one with other, respectively to the base body coordinate using the geometric constraints. The geometric constraints of the parts can be described as follows: the engine body, the cabinet, the sprocket-wheels, the support frame are fixed and connected to the base body using the fixed joints. The center of support frame is fixed on the center of the Cartesian coordinate. The center of the big head of the boom link is connected to the center of the support frame by a revolute joint (1), and the center of the small head is connected to the center of the big head of the arm link by a revolute joint (2). The boom joint is driven by a torque, and its motion trajectory is in the X-Y plane. In the same geometric constraints, the small head of the arm link is connected to the bucket using a revolute joint (3). The arm and bucket links are rotated in X-Y plane, and their revolute joints are driven by the torques. These links are contacted together in the rotary motions with the friction coefficient of the grease steels. Meanwhile, the soil model is modeled by the finite element method. This method is used to model the flexible body which expresses the characteristics of the modeled material such as elasticity and deformation. Finite element model of soil was developed and coded using ANSYS software V13.




1. Boom joint, 2. Arm joint, 3. Bucket joint

Figure 6: Virtual prototype of the autonomous excavation.

The sequence steps for developing the soil model using ANSYS:

- Creating the geometry shape of the soil model: the soil model was created as the cubic shape with the dimensions (length=1500mm, width=800mm, height=600mm).
- Assigning the material properties to the soil model: the soil elasto-plastic behaviour is completely defined by cohesion, internal angle of friction, modulus of elasticity and Poisson's ratio [17]. In this study, the soil model was modeled with the homogeneous properties of the sand soil, and the buried obstacles in soil as metal (steel).
- Meshing: the finite element method divides the large material part into small pieces that can be described with the equation for analysing and calculating processes. These small pieces are called finite element. The number of finite element should be divided based on the process speed of computer and the applied purposes.
- Interface point: the interface points which are the places to attach the flexible body in ADAMS environment were created.
- Finite element analysis: the created material model was analyzed and calculated based on the calculation of the finite element pieces. After finishing the processing, a modal neutral file (MNF) was created and exported to the ADAMS environment as a flexible body for dynamic simulation purpose.

The virtual prototype of the autonomous excavation model would be simulated in ADAMS/View to investigate the interaction dynamic behaviour of the manipulators to the soil model under "real" operating condition. From the realistic analysis results, the mechanical system design is modified and corrected. The mechanical adams_sys is created and then export to the MATLAB/Simulink for developing the control system.

### 5.2 Self-optimizing Robotic Excavator System

Self-optimizing control for an auto-dig process is a very complex task because of the complicated dig environment with unknown disturbances such as inhomogeneous material of soil type and buried obstacles in ground. Therefore, it is difficult to generate an optimal bucket path and to control the bucket tip tracking the generated bucket path. The self-optimizing control strategy for the robotic excavator system is developed based on the concept and structure of self-optimizing mechatronic system which was proposed in [21]. Through using the self-optimizing control strategy, the robotic excavator enables to optimize its behaviour by adapting the control objectives and adaptive control mechanisms when the excavation system is facing the disturbances such as buried obstacles in ground.

Figure 7 shows the control algorithm flowchart which describes the strategy for generating an optimal bucket path when meeting the buried obstacles. At initial state of the digging process, the bucket tip position is over the trench, the boom joint turns the bucket to contact with ground. Based on the predefined bucket path, the robotic excavator would generate the trajectories of the joints through the kinematic equations. The controller has a function controlling the joints tracking the generated trajectories. During the digging process, when the reactive force on the bucket tip is over the force threshold which was set based on the resistive force data of each soil types, a buried obstacle is detected on the bucket path. Based on the position of this obstacle, the robotic excavator would generate an appropriate bucket path, and the controllers would control the joints following this adaptive bucket path to finish a trench cycle.

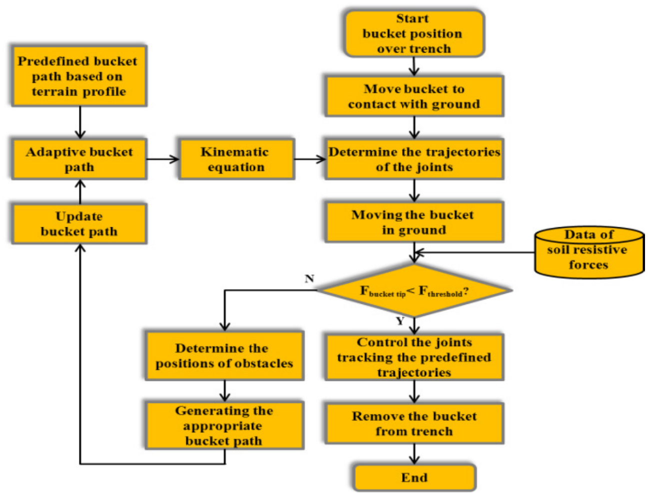



Figure 7: Control algorithm flowchart for bucket tip.

The self-optimizing control system of the autonomous excavator is shown in Figure 8. The self-optimizing control system scheme includes three levels, the idealized control level, the optimal process level, and the self-optimizing system level.

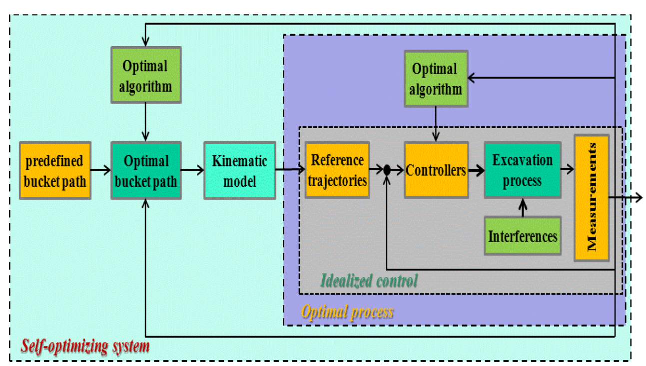



Figure 8: Self-optimizing control system of autonomous excavator.

- In the idealized control level, the control scheme is a conventional control system. The control objectives are three reference trajectories of three joints of the robotic excavator, and three controllers are to control for separate joints. The output of each controller is torque which enables to control the joint to the desired angular position. Three controllers are three Fuzzy-PID controllers.
- In the optimal process control level, the optimal algorithm is proposed to use the neural network with backpropagation algorithm to tune the input membership function's shape and the weight of the controller outputs during the system operation process.
- In the self-optimizing system, the adaptive bucket path is generated based on the fuzzy logic algorithm.

In summary, the proposed self-optimizing control strategy is applied to optimize the digging process so that highest efficiency and shortest process time can be achieved.

## 6 CONCLUSION

In this paper, the virtual prototype technology was applied for modeling the digging process of autonomous excavator, and a self-optimizing control system strategy for robotic excavator was also proposed. The advantage of this virtual simulation technology is the possibility to model the whole of a mechatronic system which includes the mechanical and control systems in an integrated model. Moreover, by the potential of virtual measurement in any point and in any component which permits the designer to apply or modify the control algorithm easily not necessarily equipped with the expensive sensors. On the other hand, integrating the control system in the mechanical structure allows the testing process is more simplified and the risks of the failure control algorithm are eliminated. The proposed technology brings many benefits by saving the production cost and time compare to the traditional build-and-test approach.

## 7 ACKNOWLEDGMENTS

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# Mass Customisation Assessment and Measurement Framework

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**Abstract**
Mass customisation involves three fundamental capabilities: Robust Process Design, Choice Navigation and Solution Space Development. A Survey has indicated that a number of companies have ceased mass customizing less than one year after initiating the effort. One reason for this is poor knowledge about the mass customisation progress and guidance of continuous improvement. This paper will conceptualize a framework for measurement and assessment of a company's mass customisation performance, utilizing metrics within the three fundamental capabilities. By assessing performance companies can identify within which areas improvement would increase competitiveness the most and ultimately enabling more efficient transition to mass customisation.

**Keywords:**
Mass Customisation; Assessment; Metrics; Capabilities

## 1 INTRODUCTION

To address the increasing customer demand for individually customized products, mass customisation has been widely adopted as a competitive business strategy during the last two decades [1-4]. Many companies have experienced that the implementation of MC is much more complicated than immediately anticipated and in some cases even jeopardized the existence of the company instead of increasing competitiveness. Meanwhile others like DELL, BMW, and ADIDAS have shown that success is indeed feasible [4].

The reason why shifting to mass customisation is so difficult is that it is fundamentally different from mass production. In product development, families of products must be developed instead of individual products. In the sales process, vast amounts of information must be exchanged between customer and company to configure the right product and allow the company to manufacture it. In manufacturing, products are manufactured in batches of one as opposed to mass production where batches are hundreds or thousands of identical products. This basically renders a mass production system useless in relation to mass customisation manufacturing. In relation to logistics, a specific product must be moved from the manufacturing facility to the end customer, whereas in mass production a number of products are shipped from the manufacturer to a warehouse to a retailer where it is sold to the end customer. This further introduces a challenge since mass customisation products cannot be stocked and can only be produced once a customer order is given. All the challenges described above need to be addressed if a company wishes to pursue an mass customisation strategy, which in many cases has proven more difficult than anticipated.

Due to the large difference in success for companies implementing mass customisation, analyses and method development has been addressed extensively in literature [5,6],[7]. Much research has focused on identifying the different enablers for achieving mass customisation and Silveira et al. [6] and Fogliatto [7] present an overview of the research into mass customisation enablers, which is by Fogliatto et al. [7] divided into the categories: 1) Methodologies, 2) design processes, 3) manufacturing processes, 4) supply chain coordination, 5) manufacturing technologies and 6) information technologies.

As pointed out above, manufacturing system flexibility is essential in mass customisation. It has also been generally acknowledged that a reconfigurable manufacturing system is an important enabler for mass customisation [8]. A reconfigurable manufacturing system is according to Koren et al. (1999) [9] a manufacturing system with adjustable structure allowing for scalability according to market demand as well as adaptability to new products. Since the aim of reconfigurable manufacturing system is to possess the capacity and flexibility needed when required [10], this manufacturing system type is highly relevant in relation to mass customisation [11]. Since mass customisation markets are typically dynamic and a continuous development of the solution space for products must be developed over time [4], the need for reconfigurable manufacturing systems compared to flexible manufacturing systems is further emphasized.

### 1.1 Mass Customisation Capabilities

Recent research has shown that the ability to transform a business into a successful mass customisation business depends primarily on

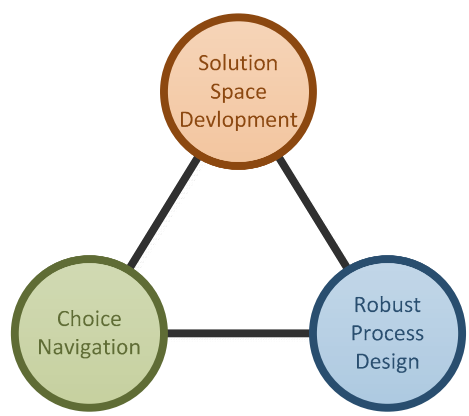


Figure 1: Mass customisation three fundamental capabilities [1].

M.F. Zaeh (ed.), *5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013), Munich, Germany 2013*,
DOI: 10.1007/978-3-319-02054-9_28, 

three fundamental capabilities [4,12] (Figure 1): 1) Robust Process Design – *Reusing or recombining existing organizational and value chain resources to fulfil a stream of differentiated customer needs*, 2) Solution Space Development – *Identifying the attributes along which customer needs diverge* and 3) Choice Navigation – *Supporting customers in identifying their own solutions while minimizing complexity and the burden of choice*. Robust process design, as termed in that research, is obviously closely linked to reconfigurable manufacturing systems. Robust process design is somewhat broader defined than only the manufacturing processes, since robust process design also involves business processes and logistics processes.

A company mastering each of the three capabilities will thus have increased chances of succeeding as a mass customizer [4]. Hence, in order to successfully implement mass customisation, companies must not only be capable of robust process design and thus the development of reconfigurable manufacturing system, but also the two other capabilities.

Although these three capabilities are identified and described theoretically in literature, mass customisation firms are still faced with a challenge when evaluating their capabilities to identify where performance lacks since no integrated method is available serving this purpose.

The objective of this research is to identify the relations between mass customisation tools and methods, mass customisation capabilities, the sales and operations in a company and ultimately the profitability and thereby competitiveness of the company. Furthermore the aim is, by identifying these relations, to be able to measure a company's performance within each capability and thereby indicating which tools and methods should be applied with the greatest improvement as a result.

### 1.2 Mass Customisation Performance Measurement

Performance measurement has long been applied as a tool for improving performance, and since tools like the balanced scorecard have emerged, focus within performance measurement has to some extent shifted from purely financial measures to non-financial measures [13]. Many publications indicate that performance measurement does in fact improve performance; the evidence has been much discussed in literature [14]. It has proven a tremendous tool for assisting in improving performance, performance measurement itself cannot guarantee performance improvement, since the effect of performance measurement depends on a number of factors [14]. Bourne et al. (2005)[14] analysed these factors and organized them into three groups: 1) context 2) content and 3) process. The context factors include the companies' external environment as well as internal factors such as structure, culture, strategy and resources [14]. The content factors are related what the performance measurement system actually measures, i.e. the definition of measures, dimensions and structure of the measures [14]. Finally the factors related to the process address the process in which the measures are 1) designed, 2) implemented, 3) used and 4) refreshed.

Hence a high number of different factors determine whether a performance measurement system has a positive effect on performance, both factors which can be influenced during the development of a performance management system, but also the contextual factors.

Relating this to a mass customisation context, a performance measurement system for mass customisation should be designed with these different factors in mind, but it also implies that one single performance measurement system will not fit all mass customisation companies, since these companies will have different contexts. However, literature generally agrees that performance measurement systems should be aligned with the companies' strategies [13].

In order to develop the three fundamental mass customisation capabilities described by Salvador et al. [4], performance measurement is considered an important enabler, however the performance measurement system must be developed specifically to fit mass customisation and for a specific mass customisation company to be effective. In this research we look into the specific content, rather than context and process of performance management systems to address the three fundamental capabilities.

In the research presented in this paper we identified the metrics needed to develop a performance measurement system for mass customisation, assuming this will be a valuable tool for companies to be able to establish themselves as mass customizers or for existing mass customizers to improve performance. The research question is:

*What metrics can be used to measure performance and thereby assess capabilities for choice navigation, solution space development and robust process design and how can these be determined?*

The research question has been answered through first defining each capability, and in overall terms, what should be assessed. Then a literature review is conducted to identify related metrics already defined in literature. These metrics are evaluated, whether they are descriptive in relation to the choice navigation, and a final set of metrics is developed for each capability. In previous papers, thorough literature reviews have been conducted and metrics defined in greater detail [15-18]

## 2 METRICS

The metrics for assessing a company's mass customisation progress as well as their development of capabilities need to reflect the process. Furthermore metrics need to be measurable; otherwise they are per definition not metrics. This means that for each metric, the required data should preferably be readily available in the company or should be easily obtainable. Luckily, most mass customisation companies have information systems which could support this, such as configurators, Product Lifecycle Management (PLM) systems, Enterprise Resource Planning (ERP) systems, Engineering Change Management (ECM) systems etc., which we expect would provide most of the required data.

### 2.1 Choice Navigation Metrics

The choice navigation capability is related primarily to the capabilities of the configuration system, and its ability to configure a variety of products. The customer experience from a product configuration process should aim for a result where the customers recognize that the configuration process supports the customer's requirements and offers the products which fulfil the customer's exact needs [4].

Supporting the customer in the process, making the product configuration easy and fast, is a matter of making it easy to match characteristics of needs, empower customer in building models of needs or embed the configuration in the product [4], from an assessment point-of-view this is potentially measurable. Measuring how well the choice navigation ensures a 100% fit between customer needs and the goods configured by the customers however seems more difficult. Using set theory we have defined and introduced sets to identify areas of interest and potential measurable areas. For assessment of choice navigation 3 sets have been defined and 6 areas of interest have been identified (Figure 2)

Analysing Figure 2, intersections B and C are consequences of a mismatch between the actual demand and solution space, where B implies variety which is part of the solution space but has no demand thus potentially implying unnecessary complexity costs. C implies a demand for variety that is not met by the current solution space and which may indicate an intersection where the development of the solution space could increase sales. The D intersection is seemingly less interesting in terms of choice navigation, since they relate primarily to the capabilities within solution space development.

In intersection D the customer configures a product that does not meet the demand nor is it contained in the solution space. This is not a typical situation but is nevertheless undesirable, and would likely be indicated by the customer abandoning the configuration. In intersection E, there is a match between the variety offered by the company and the customer demand; however the customer does not configure the product. This is likely a result of a user interface unable to guide the customer satisfactory through the configuration process. Intersection F indicates configuration which match a customer demand, but is outside the actual solution space, i.e. a product that can be configured but not produced. Finally, in intersection G the customer configures a product that is within the solution space but does not meet the demand thus resulting in a customer disappointment.

The description of the sets CC, CDV and SS above has been used as criteria for evaluating and developing different metrics used for assessing choice navigation capabilities, since metrics indicating variety outside SS∩CDV∩CC (Area A) will indicate sub optimality.

In order to evaluate which metrics are usable for evaluating choice navigation capabilities, the different set intersections illustrated in Figure 2 have been addressed individually. For each intersection, it is evaluated which metrics can support the assessment.

In intersection E the customer will start to configure a product, but never reach a final configuration which is purchased, although the solution space supports the requirements. This is difficult to distinguish from the case where requirements cannot be met within the existing solution space (intersection C), however it has been found that a high configuration abortion rate (CA) [19] metric can be used as an indication since customers that cannot configure a product to meet their requirements will likely abandon the configuration.

In intersection F the customers configure products which are within the customer demanded variety but outside the solution space, i.e. a product is configured which cannot be delivered. This would likely result in the order being cancelled by the company, since it cannot be manufactured. Alternatively, the company will change the configuration to fit within the solution space by e.g. upgrading the product. High values of Seller Order Cancellation rate (SOCR) [18] and Seller Order change rate after purchase (SOCRAP) [18] would indicate configurations within intersection F.

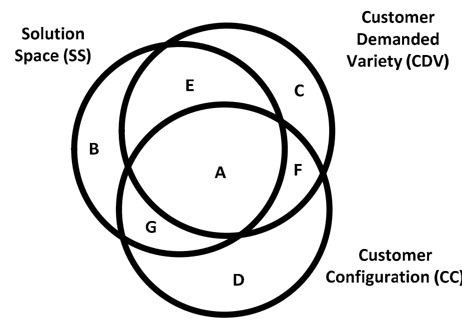


Figure 2: Intersection of Solution Space, Customer Demanded Variety and Customer Configuration [18].

In intersection G the customer configures a product which is within solution space but does not correspond to the customer's requirements. In this case several things could happen. If the customer realizes that the product is not satisfactory prior to delivery, the customer may cancel the order or change the configuration which could be expressed as Customer Order Cancellation rate (COCR) [18] and Customer Order change rate after purchase (COCRAP) [18]. In other cases, customers will not realize that the configured product does not meet requirements, until it is received. In this case the customer may return the product which could be found as Customers Return Rate metric (RTR) [20] or complain (indicated by Customers Complaints Rate metric (COR) [19]). Also repurchase rates (RR) [20] metric and churn rates (CR) [5] metric would be expected as indicators. Configurations within intersection G are found to be indicated by high values of COCR, COCRAP, RTR, COR, and CR and low values of RR.

In intersection D the customer configures a product with properties that the customer does not have a demand for and is not part of the solution space. In this case either the customer or the company can react to this and either cancel or change the order. Hence configurations in intersection D will be indicated by High values of SOCR, SOCRAP, COCR and COCRAP. It may however be difficult to determine whether high values of SOCR and SOCRAP are due to configurations in intersection D or F. On the other hand, the customer does not receive the product no matter which are the configuration is in, so whether the customer had a demand for the product may be less important.

Since configurations within intersection A should lead to a sale, then an increase in Configuration sales rate metric (CSR) [18] would indicate an increase in configurations within intersection A.

### 2.2 Solution Space Development Metrics

In order to establish metrics for solution space development and developing measurement techniques, it is important to have some sort of idea of what constitutes a "good" solution space or even an optimal solution space.

The optimality of a solution space can be described by defining two sets of products: 1) the different products offered by a mass customisation company, defined as the set SS (Solution Space) [16] and 2) the variety of products which are demanded by the customers, defined as the set CDV (Customer demanded variety) [16]. As illustrated in Figure 2, the intersection of the two sets will represent the products offered by the mass customisation company which correspond to products demanded by customers. The intersection of the two sets (A∩E) thus represents the products that customers may buy, given they are able to find and configure the products and willing to pay the required sales price.

The metrics for assessing a company's solution space as well as their solution space development capabilities need to reflect the requirements described above. The metrics are divided in five categories depending on what they are intended to measure. These categories are shown in Figure 3 and described in the following along with the specific metrics.

Within the profitability category, it has not been possible to identify metrics in the literature. What this category of metrics is supposed to measure is how profitable the mass customized products are. The reason why this should be measured is the assumption that the capability for solution space development is a prerequisite for being a successful mass customizer, i.e. profitable mass customizer. Hence, a profitable product portfolio will indicate a well-developed solution space. The following metrics has been defined: Aggregate solution space profitability (ASSP) [16] is a measure of how profitable the solution space is as a whole and should be measured over a period of time, a metric measuring profitability per product family (PFP) [16], calculated similarly over a period of time and metric for Configuration Variable Profitability (CVP) [16], which is somewhat less trivial to determine. However if historical configuration data is available with sales price and manufacturing costs registered for each configuration it is possible to generate a linear model describing the variation in price and cost from the configuration variables using the methods described by Brunoe & Nielsen [21]. What is also interesting is how many configuration variables (percentage) have negative profitability (NPCV) [16]. Obviously, this metric should be as low as possible, and will indicate how well a company is able to develop only configuration choices which are beneficial. Furthermore we propose a metric for the skewness of the distribution of profitability (CVPS) [16]. A positive skew will indicate that a few configuration variables are very profitable, whereas a negative skew would indicate that a number of configuration variables contribute significantly to a lower profitability.

The utilization category addresses how well the solution space is utilized by the customers, i.e. how much variety is offered vs. how much does actually make sense compared to the customers' requirements. This is what the metric defined by Piller [20] (referenced from [19]) called Used Variety (UV) is intended to measure. However, using this metric may be difficult in practice, since the number of perceived variants is not readily available. A more practical way of assessing the utilization would be to calculate the frequency by which each configuration variable is chosen by a customer. By dividing this by the frequency of which configurations are made in general, the percentage of configurations containing a certain configuration choice could be calculated, thereby describing the utilization of a certain configuration variable. If these percentages are analysed statistically, two metrics can be derived: Mean Configuration Variable Utilization Percentage (MCVUP) [16] and Configuration Variable Utilization Percentage Variance (CVUPV) [16]. These two metrics can provide insight into the magnitude and differences in frequently by which certain parts of the solution space are actually creating value for customers.

Sales are intuitively a metric that can be used to indicate how satisfied customers are with the variety offered by a company. However, sales can be influenced by many other factors than the solution space, e.g. marketing efforts, sales processes, pricing decisions etc. We do however believe that it can give some kind of indication.

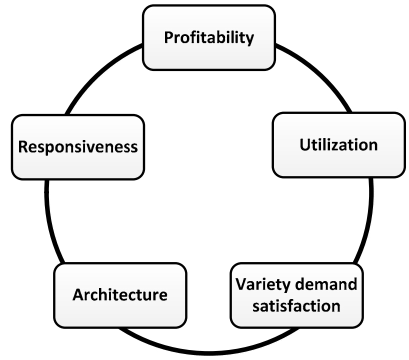


Figure 3: The five categories introduce to measure Solution Space Development.

The metric Repurchase rate (RR) [20] describes to what extent customers repurchases a product, or to what extent customers return to the mass customisation company to buy another product.

The metric configuration abortion rate (CAR) [19] can also be a measure of how satisfied the customers are with the offered variety. If a customer initiates a configuration and is not able to select the desired product properties, and is thus unsatisfied with the offered variety, that customer is likely to abandon the configuration and purchase a competing product. Hence, a high abortion rate could indicate that customers are dissatisfied with the offered variety and vice versa.

The product architecture is very central in solution space development, since good product architecture will greatly reduce development and manufacturing costs when increasing variety, whereas a suboptimal architecture will imply rapidly increasing costs when increasing product variety. Simply put, the product architecture allows efficient generation of product variants and this also indicates how efficient a company is at solution space development. Covered extensively in literature, several relevant metrics were found in the literature review. The multiple use metric (MU) [22] indicates how many modules are required to produce all variants within the solution space. However, as mentioned previously in this paper, this number may soar to astronomic numbers, rendering the metric less useful.

The modules commonality metric (MCM) [19] is a measure of how many modules are common to all variants relative to the total number of different modules. Generally a higher module commonality will indicate more efficient product architecture, since higher commonality will usually imply lower manufacturing and development costs. A metric for parts commonality (PC) [19] is used to measure the relationship between common parts and the total number of different parts in the same way as the module commonality metric. A high part commonality also indicates an efficient product architecture since that would imply higher purchasing volume for each different part further implying lower purchasing costs.

The metrics within the responsiveness category are intended to measure how fast a company is able to develop its solution space e.g. in response to changed market requirements. The first metric is the rate of which new configuration attributes are introduced

(RNCA) [16]. This is determined by summing up the number of added configuration choices during a certain period. Similarly, the number of eliminated configuration attributes should be measured resulting in the metric (RECA) [16]. A high RNCA indicates that a company frequently introduces new options for customers and would indicate that the company reacts to a broad spectrum of changes in the market. A large difference between RNCA and RECA would indicate that the solution space is either growing or shrinking. The two metrics described above describe the change rate of the solution space, but not the lead time for changes, which is also essential when competing in a rapidly changing market. We therefore introduce a new metric called average lead time for configuration variable changes (ALCVC) [16].

### 2.3 Robust Process Design Metrics

The most postponed manufacturing setup is expected to support highly robust manufacturing processes. A good indicator of robust process design is differentiation Point Index (DPI) [23]. The Setup Index (SI) [23] addresses the cost of setup of manufacturing processes compared to the total cost of a product, and is an indicator of a low robustness.

Metrics have been identified which are related to time performance of the manufacturing system, i.e. the Quality of Order Reception (QOR) [24], the Order Delay Time (ODT) [24] and Customisation Process Indicator (CPI), the latter indicates the relationship between the actual manufacturing time of a customized product and the time a customer is willing to wait for a custom product [24]. Although these metrics are not direct indicators of process robustness, it is expected that highly robust manufacturing processes will have a good time performance and good performance within these metrics will indicate robust processes.

The metric Number of different modules manufactured per process (NMP) [17] gives a measure of the average number of modules manufactured in the different manufacturing processes; a higher NMP will indicate robust processes, since each process will be able to manufacture more different modules and thus a higher number of end variants.

The metric Degree of manual labour (DML) [17] can be used as an indirect indicator of process robustness, since a low need for manual processing will indicate that the non-manual manufacturing processes are able to supply a high variety.

Setup Index (SI) is the cost of setup of manufacturing processes is considered good measures of process robustness towards new variety. Process variety increase (PVI) [17] indicates how much the variety of manufacturing processes increases when a new product option or product is introduced in the manufacturing system. The PVI metric, calculated as an average during a period in time, a low PVI will indicate a high robustness since this implies that few new processes need to be introduced when a product option is introduced and thus that the existing processes can accommodate new product variety. The capacity expense (CAPEX) increase when introducing a new option is introduced (CAPIV) [17]. This is done since a high PVI does not necessarily come a high cost, given a new process is implemented on existing flexible equipment. The CAPIV metric is calculated as an average over a period of time.

The time and cost to introduce new product variety are also important metrics to assess process robustness, since robust processes will imply low cost and fast introduction of new product variety. The metrics Time to introduce a new option in the manufacturing system (TIV) [17] and Cost of introducing a new option in the manufacturing system (CIV) [17] have been defined.

## 3 DISCUSSION

It is evident that the application of these metrics poses certain requirements related to data availability and quality. However, most mass customisation companies already have systems in place which are very likely to contain the data required for calculating the metrics presented in this paper.

There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability. If for instance the profitability of the solution space changes, instead of changes in the solution space, it could be due to changes in the manufacturing processes lowering manufacturing costs or changes in choice navigation leading customers to choose products sold at a greater price.

One example is the metric configuration abortion rate which we argue indicates how well choice navigation is implemented. However, the configuration abortion rate will be strongly influenced by the solution space, i.e. how well the offered variety matches the demanded variety. In future research the relationship between the capabilities should be established and the links between all three capabilities need to be analysed. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

When performing an assessment and interpreting the values of the metrics, the interpretation should take into account the product type. Also when benchmarking, companies manufacturing different products cannot necessarily be compared directly. The reason for this is that several metrics are based on the customers' actions, and these actions will depend on the product type. For example a customer buys a customized car compared to a customized bag of muesli, the customer would probably then be more likely to complain or return the car if it has a wrong colour compared to the muesli, if a wrong ingredient has been added. In that case, the difference would be due to the difference in cost of the products. Furthermore a metric like the repurchase rate makes more sense for some product types than others. For example, customers are likely to repurchase muesli more often than cars. So this metric would depend on to what extent a product can be characterized as a consumable or a durable, and in case it is a durable, how long the life cycle is.

## 4 CONCLUSION

In order to support the development of production in mass customisation, metrics are needed in order make performance measurement, assessment and benchmarking. To establish these metrics, relevant literature has been reviewed and several applicable metrics has been identified. Further metrics have been defined in areas where no sufficient metrics could be identified in literature.

In relation to research in mass customisation it is the intention to apply these metrics in different types of mass customisation companies to analyse what distinguishes successful mass customizers. It is the intention that these metrics can be used in mass customisation companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve.

This work concludes a preliminary research of assessment and measurement of the mass customisation process. We have with this paper finalized a general approach how to assess and measure mass customisation and set a framework of potential metrics, whether this is for the purpose of internally performance indicators or it is used for benchmarking in general. The next stage in this research will be test and evaluation of these potential useful metrics.

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# Formal Modelling of Process Planning in Combined Additive and Subtractive Manufacturing

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**Abstract**
Decision-making models for manufacturing technologies are becoming increasingly complex due to on-going rapid developments in additive and subtractive (Addtractive) manufacturing. Decision-making in manufacturing technologies should be based on machine and resource capabilities. Currently, multi-process manufacturing models have many shortcomings when describing machining capabilities, and in some cases, modelling approaches used in decision-making are ambiguous and poorly constrained. In this research, a formal modelling approach is proposed to facilitate modelling of machining capability and associated Addtractive operations. This mathematically based formal method allows system properties to be described in a well-defined manner. The ISO-standardised Z notation (named after Zermelo-Fraenkel set theory) has been utilised to build a state-oriented formalism model for machining capabilities and associated operations.

**Keywords:**
Manufacturing decision-making; Machine capability; formal modeling

## 1 INTRODUCTION

Decision-making has been emerged as a dominant factor in process planning of combined additive and subtractive manufacturing (Addtractive manufacturing) for achieving the goal of providing products in a shorter time and at a lower cost. Addtractive terminology has been used to categorize a subset of manufacturing processes and resources that have capabilities beyond those in the previous generations [1,2]. New technologies for layered manufacturing known as rapid prototyping (RP) are now becoming more prominent as the classic manufacturing technologies are no longer capable of coping with the complexity of industrial needs [3]. Process planning for Addtractive manufacturing requires detailed investigation of a machine's capability profile to corporate manufacturing technologies, which minimize cost and time of production. Although many researchers work in the area of process planning, constraint based models of manufacturing processes are rarely presented [4] and multi-process research, in particular, has not received much attention in the literature [5]. This research gap has implications for future of multi-process manufacturing and thus, in this paper an effort is made to construct a theoretical framework for underpinning emerging research in this area. The modelling approaches should be capable of describing machining status in each single operation comprehensively to facilities decision-making modelling considering resource limitations [1]. Ambiguous and poorly defined models limit decision makers in their pursuit in finding the best machining scenarios [6]. Methods such as data flow diagram and CASE tools provide few criteria to determine whether a design is correct, or to choose the best of several plausible designs [7]. Formal methods were developed in the late 1970s by Oxford University programming research group, and were used for the first time to specify the IBM customer information control system (CICS) [8]. Also, a qualitative survey was conducted on twelve industrial applications (such as an airline collision avoidance system, ship's engine monitoring system and altitude control of the satellite), which developed formal methods, shows satisfaction results [7]. The use of formal methods is the area of computer science that is concerned with the application of mathematical techniques to the design and implementation of complex systems [9]. One such approach is the use of the Z language [10] to specify complex systems; this is a comprehensive and precise approach for defining system components. In this paper, a formal model has been developed for decision-making in Addtractive manufacturing systems followed by two case studies presenting the fitness of the model.

## 2 PROCESS PLANNING IN MANUFACTURING SYSTEMS

Process planning is the decision-making process for determining methods to manufacture a part according to its design specification and the selection of parameters and necessary production processes in order to transform raw material into a part. A process plan specifies the machines, setups, tool specifications, etc. required to convert raw material into a finished part [11]. In effective process planning and scheduling, the trade off among cost, time and quality should be taken into consideration [12]. Through manufacturing organisations considering Addtractive manufacturing, there is the possibility to compress the time to manufacture and inspect products compared to today's processes. Process planning is an active area in manufacturing research where researchers aim to optimise various aspects of this activity [5].

### 2.1 Additive and Subtractive Process Planning

Subtractive technology deals with material removal manufacturing techniques. For operations comprising this technology, material is removed from a single workpiece, forming a new workpiece with examples including metal cutting (i.e. milling, drilling, turning etc.). Additive technology deals with operations where either material is added to an existing workpiece or deposited to form a new workpiece. (i.e. fused filament fabrication, selective laser sintering, etc.). The well-defined integration of additive and subtractive techniques optimizes the resources utilized during manufacturing. Decision-making for Addtractive production of a part considers manufacturing capabilities for the part geometry using both additive and subtractive techniques. The modelling approach used for formulating Addtractive technology has to be comprehensive and

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precise enough for defining the complex manufacturing process. For instance, Figure 1 shows the possible combinations of additive and subtractive manufacturing techniques used for machining a designed test part. Optimum selection of different manufacturing scenarios has to be done in an innovative mathematical formulation considering the complexity of Addtractive process planning and the diversity of manufacturing background [13].

### 2.2 Analytical Modelling of Process Plans

Previous studies in building analytical modelling for process planning has been done in several layers, which each layer representing different process knowledge about the specific manufacturing technologies [14,15]. Others have adopted prototype-oriented definitions for multi process manufacturing, which uses hierarchical modelling techniques [16,17]. Some researchers have limited the multi process manufacturing definition to the combination of various material removal technologies [18]. Also, previous studies in computer-aided process planning show limited developments for combined additive and subtractive process planning [5]. Process planning for manufacturing needs to be defined clearly and comprehensively, as a system with inter-connected classes. Each class represents information about the process retrieved from the upper level classes. In this research formal methods are used to construct a new type of model for Addtractive manufacturing processes.

The aim of this research is to define an appropriate formal model for Addtractive manufacturing to be used in decision-making considering the following aspects: The manufacturing capability required for producing specific solid geometry; generic model development for various manufacturing technologies; and, clearly define certain aspects of manufacturing without it being necessary for other aspects to be defined.

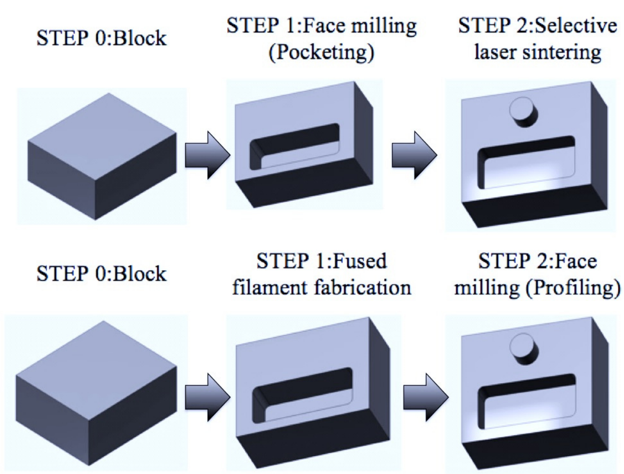


Figure 1: Possible combinations of additive and subtractive manufacturing techniques.

## 3 USING Z NOTATION FOR PROCESS PLANNING

Formal methods are mathematical based methods for describing system properties in a well-defined and non-ambiguous manner [6]. In this research, Z has been selected as the formal method of choice as it allows some aspects of a system to be defined without it being necessary for the other aspects to be specified in any manner. It is also noteworthy that the Z notation has been standardized as ISO/EIC 13568 [19]. Z notation forms an abstract and analytical description of the system under study.

The abstract model built based on the formal specification can be checked with peers, clients and against other formal specifications and standards to make sure that the problem and specifications are correct. It is possible to check that solution against the formal specifications to make sure that the proposed solution will correctly solve the problem. If not, the abstract problem model and the methods can be changed until the solution meets the specifications. Formal declarations such as Z are distinguished from less formal notations such as data flow diagrams [20] because they have a formal semantics that assigns a precise meaning to any formula in the declaration.

The framework developed for the Addtractive process with formal methods is depicted in Figure 2. As shown in the diagram, the CAD model of the part to be manufactured represented within the abstract data model. The abstract model constructs with the geometric representation of the solid model. An extended version of the abstract model requires information about machining capabilities and manufacturing technologies. After analysing all combinations of additive and subtractive techniques, the best scenario for manufacturing the part will be selected at final stage.

The fundamentals of Z, as required to enable the logic of this research to be understood can be summarised as follows (for full specification of Z, the readers are referred to [7]):

- $\mu$ is used to denote there is a unique object exists with a certain property.
- $\forall$ is used to denote that a property holds true for all objects of a certain type.
- $\cap$,$\cup$ and \ are used to denote union, intersection and subtraction respectively.
- $\subseteq$ is used to show that set is a subset of another set.
- $\mathbb{P}$ is used to denote a power set. The power set of a given set, contains all of the subsets of that set as elements.

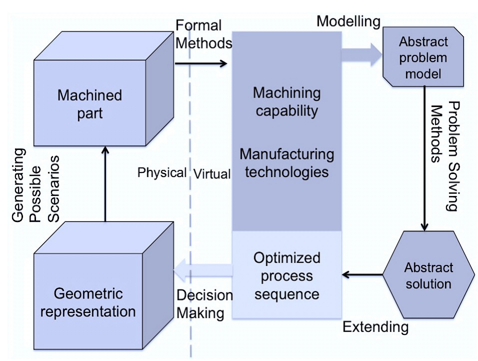


Figure 2: Formal model development for Addtractive manufacturing.

- $\in$ is used to show occurrence of an object in a certain type.
- $\Delta$ is used to denote changes in the state of a system.

- $\rightarrow$ is the set of all total functions from one set to another.
- Symbols ($\neg$,$\wedge$,$\vee$,$\Rightarrow$, and $\Leftrightarrow$) are used to denote negation, conjunction, disjunction, implication and equivalence respectively.

Every entity in Z should belong to a certain type and it is only possible to compare entities from the same type. Types are defined in multiple ways in Z, with most simple being surrounding the name of the type in brackets; this signifies that a type is being defined without further information about its structure being given at the time of definition.

### 3.1 Z Schema Structure for Manufacturing

To avoid the unstructured application of Z language, which results in a description that is difficult to understand, a schema based definition has been used. A schema is a pattern of type declaration and constraint. So, it will help to understand manufacturing concepts defined by mathematical models. Each schema includes a constraint on the object that is being defined. For instance, the format of a schema definition expressing that "for every object x of type s the predicate p holds true" is as follows:

$x : s$
———
$p$

### 3.2 Formulating Additive and Subtractive Manufacturing

Before building a model for subtractive and additive process, some primitives need to be defined. The only parameter that changes during machining a solid model is a set of Cartesian points. The points are influenced by each sequence of operations and constructed new shape. So, a Cartesian point's basic type, which presents the actual cutting locations, has been defined as follows:

$[POINT]$

Consequently, The workpiece should be expressed as a solid shape, which is defined by all its subsets of points. Completion of any manufacturing techniques may result in a workpiece changing to another workpiece.

*Workpiece*
$points : \mathbb{P}\, POINT$

Subtractive manufacturing has been perceived as a cause of changing the workpiece into a new workpiece while cutting the material out of its surface. So, changes in workpiece and Cartesian points type including constraints may be defined as follows:

*subtractive*
$\Delta\, Workpiece$
$subbed : \mathbb{P}\, points$
———
$points' = points \setminus subbed$
$points \cap subbed \neq \emptyset$

Consequently, the additive process may be defined as it shown below:

*additive*
$\Delta\, Workpiece$
$added : \mathbb{P}\, points$
———
$points' = points \cup addded$
$points \cap added \neq \emptyset$

The new primitives that are used for creating the machining capability are machine and resources. Machine is a type of machine tools use for manufacturing a part. The single machine tool may use different manufacturing techniques for producing finished parts. Resources are defined as tools, auxiliary devices, human expertise and everything else apart from the raw workpiece and machine tool that are required for performing a manufacturing operation.

$[MACHINE, RESOURCES]$

*Manufacturing Capablity*
$machine : MACHINE$
$resources : \mathbb{P}\, RESOURCES$

A manufacturing process is a sequence of operations that can take place on a set of workpieces, which are ultimately transformed into another set of workpieces. So, an effective operation on the workpiece and process is defined as below:

*Operation*
$\Delta\, Workpiece$
$\Delta\, Manufacturing\ Capablity$

*Process*
$\Delta\, Workpiece$
$i? : \mathbb{P}\, Workpiece$
$o? : \mathbb{P}\, Workpiece$
$operations : \text{seq}\ Operations$
———
$\text{ran}(operations(i) \subset \text{dom}(operations(i+1))\ \forall\, i : 1 ... \#operations - 1$

Finally, the optimum scenario for producing a part is determined by the lowest machining time. So, the following Z notations identify optimum process:

$Time : Process \rightarrow \mathbb{R}$

$$\mu\, p : Process \mid \forall\, p_1 : Process \mid p_1.i = p.i \wedge p_1.o = p.o \bullet (p = p_1 \vee Time(p_1) > Time(p))$$

## 4 CASE STUDY ONE

The designed test workpiece has been tried out for the fitness of the approach. The workpiece has been designed so as to find the best scenario of machining with the efficient process planning. The optimum scenario is the one, which consumes less machining time. Machining resources have been neglected in this research for simplicity, but it will be possible to extend the abstract model for more details. Figure 3 shows the design used for model evaluation.

The test workpiece includes a positive cylinder and a negative pocket. The model formulation has been done for each feature based on the Cartesian coordination position in that shape. The formal definition of the workpiece has been used for the designed test piece.

Regardless of the additive technology used for machining the cylinder, the Cartesian points are transferred to their new position for shaping a cylinder. So, the formal definition of the additive process has been defined as follow:

*Adding Cylinder*

$\Delta Workpiece$
$X?, Y?, Z?, R?, d_{add} : \mathbb{P}\, points$

$points' = points \setminus \{\forall\, p : points : (X(P) - X?)^2 + (Y(P) - Y?)^2 \leq R?^2\}$
$points \cap X?, Y?, Z?, R?, d_{add} \neq \emptyset$

Similarly, milling the pocket causes the same changes in the negative direction.

*Subtracting Cuboid*

$\Delta Workpiece$
$X?, Y?, Z?, l, w, d_{sub} : \mathbb{P}\, points$

$points' = points \setminus \{\forall\, p : points : X(P) = X? \leq l$
$Y(P) = Y? \leq w$
$Z(P) = -d_{sub}\}$
$points \cap X?, Y?, Z?, l, w, d_{sub} \neq \emptyset$

Since each line consists of an infinite number of points, the length and width of the pocket has been defined as sets of points. Also, $d_{add}$ and $d_{sub}$ denote the height of cylinder and depth of pocket respectively.

To demonstrate that the shape has been machined on the surface of the block, it needs to be illustrated that created feature and workpiece have common points. So, the last predicate added at the end of each schema for constructing a single solid shape.

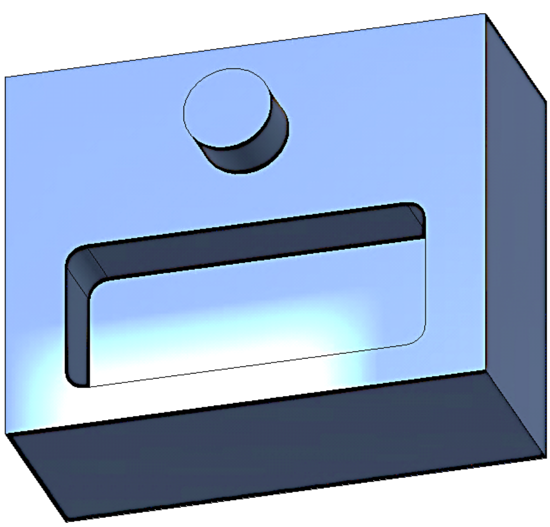

Figure 3: 3D view of the designed test piece.

Based on the manufacturing scenario presented, the formal model has been built for specific Addtractive operation on the workpiece.

*Manufacturing Scenario*

$raw : Workpiece$
$final : Workpiece$
$machines : \mathbb{P}\, MACHINE$
$DFM\ resources : RESOURCES$
$Milling\ resources : RESOURCES$

*Adding Cylinder*
*Subtracting Cuboid*

Finally, The problem associated with finding optimized process plans for producing a part correlated with different manufacturing scenarios could be generated from the above schema.

## 5 CASE STUDY TWO

The second case study has been designed with 4 different machining operations for the multi-feature test workpiece presented in Figure 4. The finished part includes one open slot, one closed pocket and two steps on each side. Similar to the previous case, machining resources and machining technology have been neglected for simplicity, but it will be possible to consider those by adding more details to the abstract model.

A similar procedure to the previous case study has been formalized for modelling designed artefacts. Regardless of the additive technology used for manufacturing the block, it has been assumed that the Cartesian points are transferred to their new position for shaping the block, and other features are to be machined out of the block in next steps. So, the formal definition of the additive process has been defined as follow:

*Adding Block*

$\Delta Workpiece$
$X?, Y?, Z?, l, w, d_{add} : \mathbb{P}\, points$

$points' = points \setminus \{\forall\, p : points : X(P) = X? \leq l$
$Y(P) = Y? \leq w$
$Z(P) = d_{add}\}$
$points \cap X?, Y?, Z?, l, w, d_{add} \neq \emptyset$

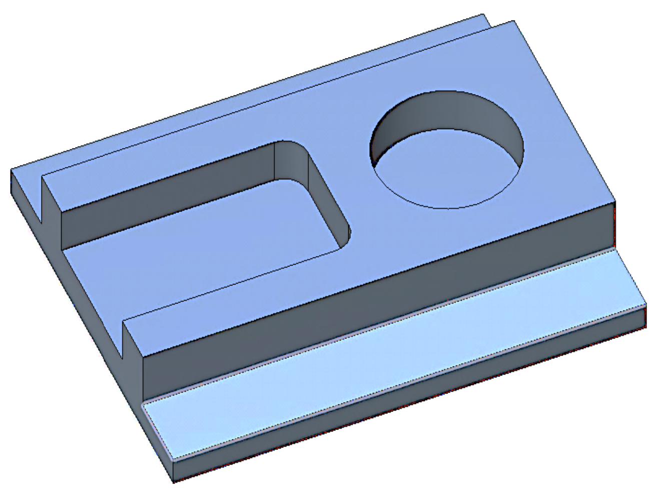

Figure 4: 3D view of the test workpiece.

Subtractive operations have been modelled by considering the fact that a finite number of points have been machined out of the added block in the negative direction. So, for subtracting the open slot, closed pocket and steps following schemas have been developed:

*Subtracting Cylinder*

$\Delta$ *Workpiece*
$X?, Y?, Z?, R?, d_{sub} : \mathbb{P}\, points$

$points' = points \setminus \{\forall\, p : points : (X(P) - X?)^2 + (Y(P) - Y?)^2 \leq R'$
$Z(P) = -d_{sub}\}$
$points \cap X?, Y?, Z?, R?, d_{sub} \neq \emptyset$

*Subtracting Slot*

$\Delta$ *Workpiece*
$X?, Y?, Z?, R?, d_{sub} : \mathbb{P}\, points$

$points' = points \setminus \{\forall\, p : points : X(P) = X? < l$
$Y(P) = Y? \leq w$
$Z(P) = -d_{sub}\}$
$points \cap X?, Y?, Z?, l, w, d_{sub} \neq \emptyset$

*Subtracting Steps*

$\Delta$ *Workpiece*
$X?, Y?, Z?, R?, d_{sub} : \mathbb{P}\, points$

$points' = points \setminus \{\forall\, p : points : X(P) = X? \leq l$
$X(P) = X? \geq -l$
$Z(P) = -d_{sub}\}$
$points \cap X?, Y?, Z?, l, w, d_{sub} \neq \emptyset$

Machining scenario has been modelled based on the formal specification defined by Z as follow:

*Manufacturing Scenario*

*raw* : *Workpiece*
*final* : *Workpiece*
*machines* : $\mathbb{P}$ *MACHINE*
*DFM resources* : *RESOURCES*
*Milling resources* : *RESOURCES*

*Adding Block*
*Subtracting Cylinder*
*Subtracting Slot*
*Subtracting Steps*

Having defined suitable models to describe the geometrical representation of the features shown in Figures 3 and 4, the next stage of the research shall address the need to identify optimal process plans with respect to manufacturing time. Various mathematical techniques could be used for testing different process sequences, and finding the optimum solution. The general optimization problem can be defined as follow:

$$\text{Minimize Time(p)}$$
s.t.
Manufacturing Scenario

## 6 DISCUSSION

The proposed formal framework has the unique ability to deal with the complexity of the Addtractive process. However, the mathematical model presented here was an abstract model of requirements while the practical implementation of the approach needs more detailed knowledge about the Addtractive operations itself, this process is called refinement in Z notation. Furthermore, a quantitative analysis needs to be done according to manufacturing capability and process comprehension for discovering the feasibility of formal methods. Adding more classes to the abstract model, which is one of the benefits of using this method, may extend the presented model. Also, a more layer based model increases the appropriateness of Z notation for being applicable in multi-process manufacturing.

## 7 CONCLUSION

The combining of manufacturing processes enables shorter delivery times for manufactured parts, and provides greater manufacturing flexibility. Process planning for combined additive and subtractive manufacturing has emerged as a potential improvement of current manufacturing techniques. Finding the best scenario for manufacturing a part requires innovative mathematical methods covering the complexity of Addtractive manufacturing concepts. Z notation has been shown as a possible method for building an abstract mathematical model for describing the process planning for Addtractive manufacturing. The proposed formal framework was demonstrated through the use of two test pieces correlated with machining capability analysis and time restrictions. This research can be interfaced with object-oriented modelling and programming for further extension by developing Addtractive manufacturing technology databases for different feasible scenarios.

## 8 ACKNOWLEDGMENTS

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# Dynamic Reaction to Fluctuations in Demand through Line Balancing in Commercial Vehicle Manufacturing

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**Abstract**

The commercial vehicle industry is characterized by a dynamic market environment, which implicates changes in the product portfolio as well as fluctuating quantities of demand. Depending on the model-mix, these cause diverse assembly tasks. In addition, changing production quantities cause an adjustment of cycle time to match demands in the medium term. In this rapidly changing market environment, assembly lines must quickly adapt to changes in order to remain competitive. Therefore, an approach for assembly line balancing was developed, which allows a faster adjustment of assembly lines in order to respond to fluctuations in demand. This approach focuses on two aspects: to respond to quantity as well as model-mix fluctuations. In order to increase volume flexibility, workers are allocated to the assembly stations thus pre-planned cycle times can be operated without the need of huge rebalancing. Furthermore to accomplish more flexibility in variants, operations are assigned to stations according to their impact on the assembly task time.

**Keywords:**

Line Balancing; Dynamic Assembly Capacity; Variant Control

## 1 INTRODUCTION

Due to globalization and the saturation of markets, industrial companies have to focus more and more on the requests of their customers [1]. To fulfil customer´s individual needs, the number of products and product variants offered increases, while product lifecycles decrease [2]. Furthermore, these conditions lead to dynamic markets with high fluctuations in demand [3]. These fluctuations paired with the increasing number of variants pose challenges for production-oriented companies, especially for their assembly lines. Different product variants lead to different assembly processes with varying process times and therefore to a rising complexity in the design of assembly lines [4]. Furthermore, the capacity requirements on assembly lines change due to fluctuations in demand. To remain competitive an adaption of the balance of assembly lines is necessary since they are dominated by manual workforce and therefore responsible for a high percentage of production costs [5].

The commercial vehicle sector is particularly affected by these conditions. It is characterized by a high variety of components and product variants and a market with high business fluctuations [6]. This can be seen in Figure 1. On the one hand the range of the capacity requirements using the example of heavy range trucks in terms of target times is shown. On the other hand the influence of changing demands in terms of variants and therefore changing average time is illustrated, i. e. caused by seasonal effects [7]. It is of particular note that the lowest equipped variant requires nearly half of the assembly time than the highest equipped variant.

As common in the whole automotive sector, commercial vehicles are produced in mixed-model assembly lines, which are characterized by a one-piece flow of different variants on the same assembly line with no or just minor setup activities [8]. Because of the dynamic market situation, assembly lines in the commercial vehicle sector must be able to react fast on changing demands. However, balanced assembly lines are argued to be very inflexible due to fluctuations in demand. To understand the impacts of these fluctuations, the state of the art of balancing mixed-model assembly lines is described in the following section.

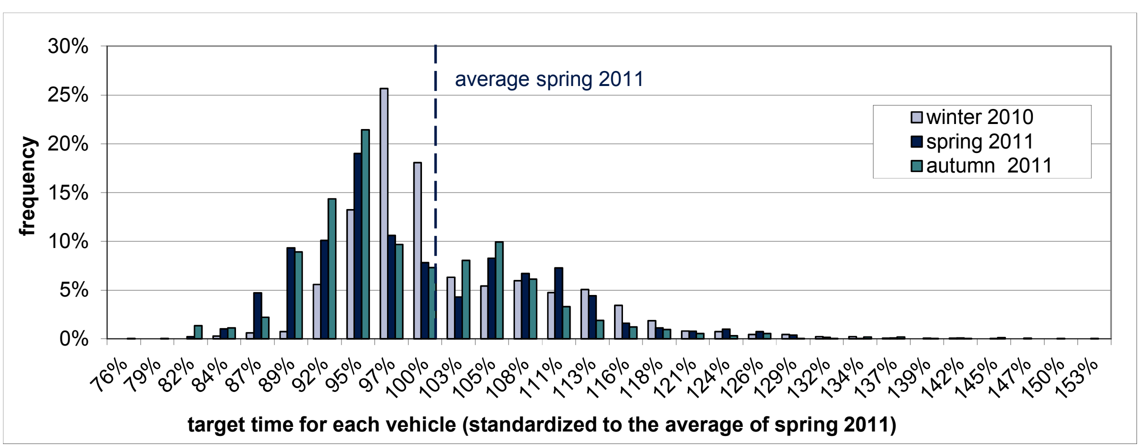


Figure 1: Fluctuations in capacity requirements in the commercial vehicle sector [7].

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## 2 MIXED-MODEL ASSEMBLY LINE BALANCING

Assembly lines consist of consecutive stations, which are arranged according to the assembly process. The stations are connected by a conveyor or another form of transportation system and the products are carried in one-piece-flow from one station to another. In each station a defined number of workers execute several assembly tasks. To coordinate the assembly process and to avoid stagnation, the duration of a product in each station is limited by the cycle time. Therefore, in intervals of the cycle time a new product enters and another one leaves the assembly line while the other products are transported to the next station. So in general the duration assembly tasks in every station must not exceed the cycle time [8, 9].

Assembly line balancing describes the process of assigning assembly task to the stations in order to fulfil predefined goals, i.e. to minimize the number of stations or the cycle time or to maximize utilization, under consideration of restrictions given by the product, the assembly line or human factors [10]. In mixed-model lines complexity rises due to the different task times for the variants. There are two common strategies to cope with these variations [7]:

- Balancing on the maximum-variant, so that every variant can be assembled in every station in cycle time.
- Balancing on an average-variant, so that the average production program is mastered in cycle time, but difficult variants take longer than cycle time. The average-variant is calculated by weighting all variants according to their frequency.

The last strategy is common in commercial vehicle manufacturing, since the first one leads to high waiting times and therefore low productivity [7]. Figure 2 shows the effect of the average-variant strategy. The result is an assembly line with a high average utilization, but the workers have to cope with the peaks of fully equipped variants (see variant C in Figure 2).

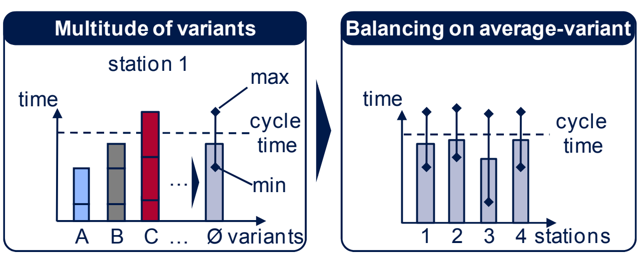


Figure 2: Utilization of mixed-model assembly lines.

To manage products with assembly tasks higher than cycle time workers are allowed to drift. Therefore workers are given the possibility to leave their station to finish the product or to start at the pervious station. Products with a lower utilization are used to drift back to initial situation or to start earlier [10, 11]. To provide the maximum impact of drifting, the sequencing of the products becomes very important [12]. If there is no possibility to drift on several stations or if the scope of drifting is not sufficient enough, additional workers have to be assigned to finish the product or to take over a whole product. These workers are called 'jumpers' [11], 'auxiliary workers' [13] or 'floaters' [14]. Since these jumpers lower the productivity of assembly lines, one aim of line balancing is to minimize their number and the frequency of their assignment [14].

To solve assembly line balancing problems, a huge amount of research has been done in developing exact or heuristic algorithms, which take different restrictions or types of assembly lines in consideration. A literature review and a classification of assembly line balancing problems are given by [15]. They structure the literature according to the characteristics of three elements: precedence characteristics, station and line characteristics and objectives of the algorithms. However, a huge amount of data is necessary for these algorithms, i.e. the precedence constraints of all variants. The effort to update this data is very high and the algorithms are not able to depict all restrictions. Therefore, the application of these algorithms is fairly low in the industry and line balancing experts often only trust their personal experience [10, 16]. However, the complexity of mixed-model assembly lines results in a time-consuming line balancing process. So, there is demand for research in rules to balance assembly lines manually and by integrating these experiences. An approach is presented in the following, which considers the requirements of a faster adaption of balancing, since fluctuations on demand have a significant impact on assembly lines.

## 3 IMPACT OF FLUCTUATIONS IN DEMAND ON BALANCED ASSEMBLY LINES

Balanced assembly lines have many advantages like a usually high utilization and little manual handling, but they are also said to be inflexible in terms of fluctuations in demand due to the high degree of preplanning and coordination [8]. As mentioned before the dynamic market situation forces industrial companies to react on these fluctuations and to adapt their assembly systems. The aim of the approach introduced in this paper is to enable assembly lines to react faster and more flexible. There are two types of fluctuations in demand, which distinguish in their impact on assembly lines:

- Fluctuations according to product variety (model-mix fluctuations)
- Fluctuations according to quantity

Since the line balancing approach discussed here pursues different strategies to cope with these impacts, they are detailed hereinafter. In Figure 3 an overview of both types of fluctuations and their consequences is given.

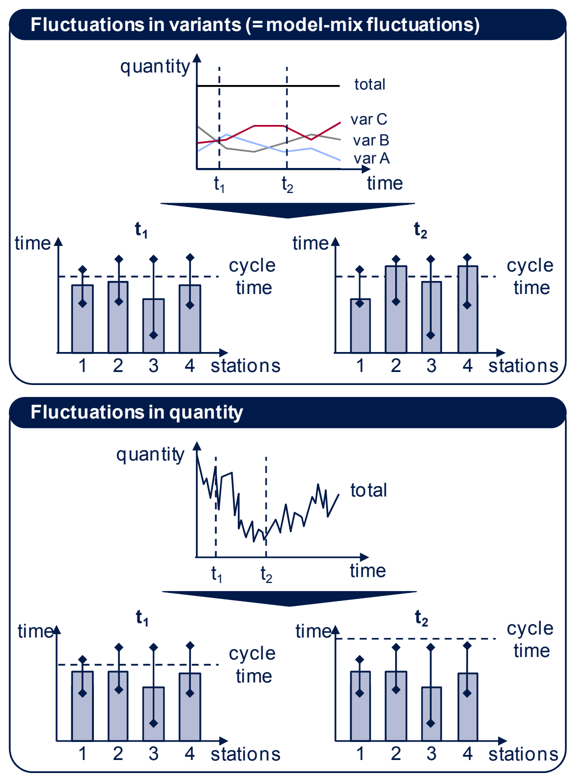


Figure 3: Impact of model-mix or quantity fluctuations on assembly lines.

**Model-mix fluctuations** result due to a changing demand in product variants, while the total quantity of all products remains constant. Since cycle time determines production quantity, there is no need for an adaption of cycle time. But the mixture of produced variants and therefore the average utilization on every station is affected. Short-term measures reach their limits, like drifting of workers, or become very expensive, like a further allocation of jumpers. To remain productive, a rebalancing of the assembly line is necessary to avoid capacity over- or underload.

**Quantity fluctuations** lead to an adaption of cycle time in the mid-term, since the output of the assembly line has to meet demand to avoid over- or underproduction. A cycle time adaption has far-reaching consequences for assembly lines as the available capacity is changed for every station and therefore the utilization changes for every variant. High effort is necessary to rebalance the whole assembly line, since every station is affected and over- or underloaded. The need for rebalancing is further discussed by taking Figure 4 into consideration. Figure 4 a) visualizes the utilization of one station depending on cycle time assuming that no rebalancing is executed. Since workers can only be allocated in whole numbers this characteristic curve results as a new worker is needed when utilization reaches 100% [17]. Without rebalancing there are only several appropriate operation points for each station. Every station shows another utilization curve and therefore there is no mutual optimal operation point for the whole line (see Figure 4b). Although the average utilization rises for decreasing cycle times, the number of workers per station growths in a way that they are constraining each other at the stations. Therefore a rebalancing of the entire assembly line with high planning effort would be necessary to remain productive.

To deal with this two characteristics, a line balancing approach for an existing assembly is introduced, which enables this line to faster react on fluctuations in demand.

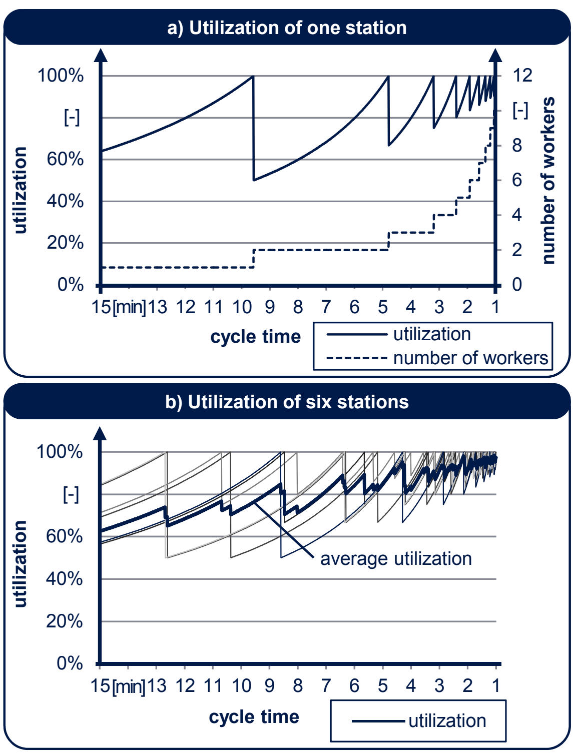


Figure 4: Impact of cycle time changes on the utilization a) of one station [17]. b) of six stations of an assembly line.

## 4 LINE BALANCING APPROACH FOR COMMERCIAL VEHICLE PRODUCTION

### 4.1 Overview

The developed line balancing approach focuses on the challenges mentioned before and fulfils the requirements of commercial vehicle production. The intention is to enable mixed-model assembly lines in commercial vehicle production to react faster on fluctuations in demand by adapting the balance of the assembly line. Currently, the main obstacle to achieve this goal is the high planning effort required to change the balancing. Past scientific research focused on developing algorithms to solve line balancing problems and to achieve fast and optimal solutions. However, these algorithms are not accepted in the industrial practice of the automotive sector and can not be utilized due to the effort of data required [10, 16].

Since commercial vehicle production is dominated by even more variants and components [6], the approach illustrated here emphasizes on guidelines to balance assembly lines by hand while taking the experience of the local experts in consideration. Furthermore, to handle the complexity of mixed-model assembly lines, simulation software is used to support the planning process and to visualize the results.

Since there are two types of fluctuations in demand, which affect assembly lines in different ways, the approach consists of two main aspects (Figure 5): to face **quantity fluctuations** an allocation of workers is considered which takes the possibility to quickly change cycle times into account. **Model-mix fluctuations** are met by assigning assembly tasks to different stations according to their influence on the task time. Both aspects need to be implemented simultaneously to achieve the goal of volume and variant flexibility.

In the following the basic ideas behind both concepts are described, while in the subsequent sections the detailed planning proceedings are explained.

To respond to **quantity fluctuations**, employees are allocated to the assembly stations in a way that no large rebalancing is necessary to operate with different cycle times. This is achieved by introducing allocation-rules to coordinate the number of workers at each assembly station. Regarding the impact of cycle time adaption, shown in Figure 4, the result is an overlap of the utilization curves of the different stations. Thus, certain pre-planned cycle times can be operated by adapting the number of employees without the need to change the assignment of assembly tasks. Technical or organizational restrictions at individual stations are met with increased team work between neighbouring stations, so that the combined stations suffice the assignment principle together. An example can be seen in Figure 5, where a worker needs to take over tasks from two stations when cycle time is increased by 1,33-times. Depending on the movability of these tasks they can be combined on one station or the worker needs to switch between two stations.

Furthermore, to respond to **model-mix fluctuations**, a separate allocation of work content depending on the influence of variants is considered. The aim is to create workstations which are not affected by different variants as well as stations which unite all variant-specific content. The former are independent from production program and therefore always operate at the same capacity utilization. Therefore they need not be considered in case of model-mix fluctuations. Thus the framework for adaptions is reduced as much as possible and therefore the complexity of the line balancing problem is limited to the variant-stations. In addition, short-term operational measures to handle variants, like drifting and jumpers, can be controlled more efficient, since only variant specific stations are relevant at this point.

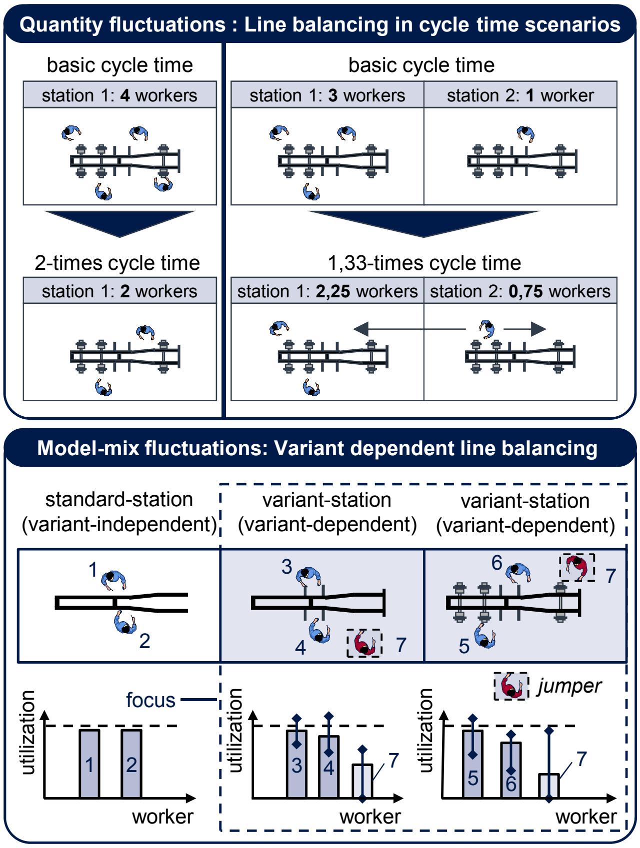


Figure 5: Two aspects of the line balancing approach in order to face fluctuations on demand.

### 4.2 Line Balancing in Cycle Time Scenarios

Adjustment of cycle time is treated in two ways in literature: Keeping the same cycle time to provide high productivity [17] or rebalancing the whole assembly line to achieve a new cycle time [15]. The first strategy is contrary to the conditions of a dynamic market, while the second strategy creates high effort in commercial vehicle production. Therefore, the approach combines both mindsets by giving the possibility to change cycle time in pre-planned steps on one hand, but without the need of plenty rebalancing on the other hand. Figure 6 gives an overview of the steps required to achieve this. First, the multiples of cycle time, which are possible according to the assembly process and structure, must be defined. Then the cycle time according to these multiples and to the demand of the costumers are determined. Thereafter, ideal worker allocation is planned by taking the different cycle time scenarios into account. In a final step, if the ideal allocation was not possible, strategies for changing the cycle time have to be planned. These steps are described in the following.

With the average utilization of Figure 4 in mind, the aim of this line balancing approach is to create an overlap of the utilization curves to achieve peaks at the same cycle time for every station. Therefore, the numbers of workers on every station needs to be coordinated throughout all stations. In a first step, the multiples of cycle time are determined, which are possible in the assembly line in focus. The main restriction is the maximal number of workers per station, which is especially affected by the size of the product and by the means of production required for assembly. I.e. in truck assembly a maximum of six workers per station is possible without interference. In addition, the minimal number of workers is also important, if there

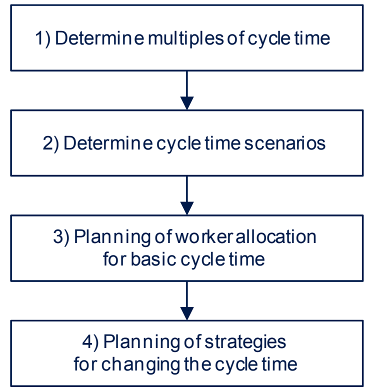


Figure 6: Planning proceeding of line balancing in cycle time scenarios.

are assembly tasks which require more than one worker. Since an existing assembly line is regarded, the actual most common number of workers at each station can also be reflected. By taking all this data into consideration, the rules for worker allocation are established to accomplish multiples of cycle time. The aim is to achieve nearly identical numbers of workers at each station or at least combined with neighbouring stations. According to the possible allocation of workers this results into different multiples of cycle time, without knowing the cycle time per se. The example of Figure 5 shows a target allocation of four workers per station, which leads exemplary to the factors 1,33 and 2 for cycle time adaption. The cycle time per se is specified in a second step.

Cycle time needs to be oriented to customer demands in order to avoid over- or underproduction. Due to the approach described here, the assembly line is able to manufacture in several pre-planned cycle times. To define which exact cycle times are required in the second step, a forecast of the expected volume range is necessary. This is the quantity range the assembly line will be designed for. Since only several cycle times are possible, other measures are required to adjust capacity in smaller steps, i.e. by changing the number of shifts or the duration of a shift [3]. By taking these measures into consideration, every cycle time not only covers one specific quantity, but rather a range of it (see Figure 7). Therefore the basic cycle time $c_b$ is calculated, which is the lowest cycle time required. In conjunction with the multiples of this basic cycle time and the other measures the whole quantity range needs to be covered. The aim is to avoid as much other measures in addition to cycle time as possible to cover demand. Since both the multiples of cycle time and the cycle times themselves are determined at this point, the line balancing according to these two aspects follows in the third step.

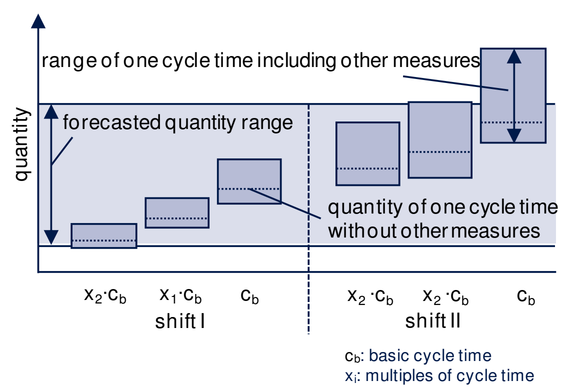


Figure 7: Covering demand with multiple cycle times.

In this step the actual assignment of assembly task occurs. The process is analogous to state of the art line balancing taking the experience of experts according to precedence restrictions, worker restrictions and other restrictions into consideration. But on top of that, the rules for worker allocation mentioned before have to be taken into consideration. Therefore, not only cycle time determines the capacity available at each station, but also the number of workers possible due to the cycle time scenarios. The cycle time required for line balancing is the basic cycle time $c_b$ calculated in step 2, since this is the basis of all the other cycle times which requires the most workers. In cases the ideal number of workers is not possible due to restrictions, the neighbouring stations are included to fulfil the rules (as seen in Figure 5). Furthermore, the aspects of variant depending line balancing (see section 4.3) have to be taken into account here.

After step 3, the assembly line is balanced to run at the basic cycle time and since the allocation of workers followed the rules of cycle time scenarios, it is enabled to switch between the considered cycle times. However, the step before just ensured that the number of workers required changing cycle time is at least met by neighbouring stations. The assignment of tasks to workers to actually change the cycle time is the last step to achieve more volume flexibility. Therefore, a balancing of the exceptions is necessary, where not only one station is affected. There is not much effort required, since only some stations have to be taken into consideration. The focus is to reassign the assembly tasks of the neighbouring stations so that the workers available can handle them. The main goal is that every worker is allocated on one station. But due to equipment restrictions it might not be possible to divide all assembly tasks and therefore one worker needs to switch between two stations (as Figure 5 shows). If the station is affected by variants, it is also possible to treat capacity peaks with drifting, jumpers or other strategies mentioned in the following section.

As a result, the allocation of workers allows a short-term adaption of cycle time to pre-planned values. To achieve fast reactions to model-mix fluctuations, a simultaneous variant dependent line balancing approach is considered.

### 4.3 Variant Dependent Line Balancing

The aspect of variant dependent line balancing follows the approach of [17], which describes the advantages of clustering assembly tasks according to their influence on task time. Since there is a huge variety in commercial vehicle manufacturing, the clustering of tasks needed to be extended to achieve more standard stations. For the same reasons, the handling of variants is detailed and to reduce complexity a simulation is considered for support. An overview of the planning proceeding is shown in Figure 8.

In the first step to accomplish a separation of assembly tasks, all tasks are clustered according to their frequency and their variation of task time. Processes with a high frequency and little variations in process time are standard tasks. The detailed limits depend on the assembly context, but frequency should at least be higher than 80%. All other tasks have variable context. To avoid a huge overlap of variant stations a further classification is introduced. There are assembly tasks, which appear not in a high frequency, but are related to other tasks in a way that either this task or the other one is necessary. If both combined appear frequent and are nearly similar in their task time, they can be classified as “either-or”-tasks (analogous to the logical operation “XOR”). It is also possible to combine more than two tasks to achieve this XOR-relation, though complexity rises. If processes are neither standard- nor XOR-tasks, they are classified as variant-tasks.

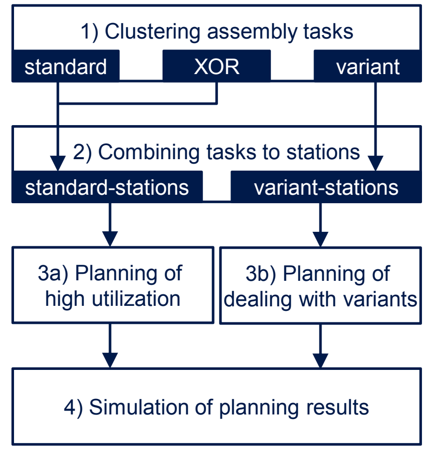


Figure 8: Planning proceeding of variant depending line balancing.

The clustered tasks are assigned to the two different types of stations in response to their classification in a second step: Standard- and XOR-tasks are joined in standard-stations and variable task are put together in variant-stations. The experience of planning experts is required here, since restrictions in assignment have to be considered, i.e. precedence constraints or equipment required. Furthermore, if it is not possible to separate the task in different stations, a division to different workplaces at the same station is also possible.

Analogous to [17], the objective for standard-stations is to reach high utilization and standardization (step 3a), since all the advantages of single-model assembly exist there. Furthermore these stations are one main aspect for the variant flexibility of the balanced assembly line, as no further rebalancing is necessary due to model-mix fluctuations. On top, the rules for worker allocation explained in section 4.2 are crucial to not only become variant flexible but also volume flexible. Of course, the corresponding basic cycle time is also equivalent to section 4.2.

Most effort is required for the planning of variant-stations in step 3b). To handle the higher amount of variability different possibilities are taken into consideration. Drifting is still one of the most efficient ways to handle peaks according to variants. Since variants are now much more concentrated in these stations, the amount of drifting rises and therefore the stations have to be designed with this in consideration. So it is necessary that resources can be used beyond the end of the starting station. Another possibility is to unite workplaces to enhance teamwork, since fluctuations can be compensated more easily by a larger group [17]. Furthermore, preassembly stations can be used to handle variants. Because these are usually not tied to cycle time and are separated from the main assembly line by buffers, free capacity can be used to support variant-stations or the other way around. This is kind of an allocation of jumpers, but with additional task for them. If these possibilities are not enough, the classic allocation of jumpers is an alternative. Since the impact of model-mix fluctuations is concentrated to fewer stations, the allocation of jumpers becomes more productive, as the management of the jumper teams is less complex and less walking is necessary. To handle to huge variety the stations cannot be utilized to 100% in average. The amount of average utilization possible is determined by simulation.

The fourth step of the planning methodology intends to validate the planning results by simulation. Simulation is required according to two aspects. First, due to the huge amount of variants, it is not possible to take all different combinations possible into account.

Second, since the complexity of ways to handle variants rises in the variant-stations, simulation supports their planning and controlling. Therefore, a simulation tool is used, which is described in detail by [7] and [11]. This tool is capable of all requirements needed here. It uses actual data of the production program and is also able to draw up a fictive production program. Furthermore, it is possible to assign assembly tasks to different stations to analyse the effects of line balancing. But the main advantage is the capability of simulating and visualizing the potential of flexible reactions to variants, like drifting, teamwork and jumper allocation. Since the simulation model is not only used for the planning process, but is also required for the monitoring process to recognize the need of adaption, the effort of modelling creates long-term benefit.

## 5 SUMMARY AND OUTLOOK

Balanced assembly lines are said to be very inflexible in reacting to fluctuations in demand. Especially, quantity fluctuations lead to high planning effort in changing the balance of the assembly line, since a rebalancing of the whole line is induced by a change of cycle time. The approach described in this paper enables assembly lines to adapt more quickly according to fluctuations in demand by preplanning the assembly line with the need of later rebalancing in mind. Two aspects are taken into consideration to be prepared for changes in demand. To meet quantity fluctuations the allocation of workers is matched up between stations so that a cycle time adaption is possible by nearly just changing the numbers of workers per station. The impact of model-mix fluctuations is reduced by assigning assembly tasks to stations according to their variant depending influence on task time. The results are stations with no variation in process time and stations which sum up the variant depending tasks. Former are independent of model-mix fluctuations, so rebalancing can focus on the last type of stations. To handle the complexity of mixed-model assembly lines and the huge amount of variants, simulation software supports the planning process. Altogether, this approach enables assembly lines to faster adapt according to fluctuations in demand.

First executions of aspects of the approach have proven their practicability at an industrial partner. The implementation of simulation software for evaluation of assembly line balancing shows first positive effects [7]. Also variant dependent line balancing was established in an assembly line section consisting of twelve stations and 28 workers. However, more research is necessary to validate the whole described approach. The next step is the validation of line balancing in cycle time scenarios in reality. Therefore, the interactions between the two mentioned aspects of the line balancing approach need to be investigated and the rules for worker allocation need to be detailed. Furthermore, to prove the holistic framework, an approach for monitoring the assembly line balanced in the way described here and for triggering the adaption process is necessary.

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# Meeting New Challenges and Possibilities with Modern Robot Safety Technologies

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**Abstract**
In recent years, human-robot co-operation has been of increasing interest in research, and new types of modern safety technology have emerged on the market. These include safety sensors, machine vision based safety systems, laser sensors and safety controllers for robots. The new technology enables flexible fenceless safety systems and dynamic safety regions alongside a host of other attractive features for human-robot co-operation. The safety systems can also be integrated into a transferable robotic platform. While this modern technology opens up wholly new possibilities, it also creates new and fairly complex challenges in safety design. This paper introduces some case examples of handling these challenges.

**Keywords:**
Robotic production systems; Robotics; Robot safety; Human-robot co-operation

## 1 INTRODUCTION

In recent years, human-robot co-operation has been of increasing interest in research, and new types of modern safety technology have emerged on the market. These include safety sensors, machine vision based safety systems, laser sensors and safety controllers for robots. The new technology enables flexible fenceless safety systems and dynamic safety regions alongside a host of other attractive features for human-robot co-operation. While this modern technology opens up wholly new possibilities, it also creates new and fairly complex challenges in safety design. This paper reflects on how these challenges have been handled, particularly in the case of transferable robotic systems, but the results also have a wider significance. At the end of this paper, it is introduced based on our findings a new type of human-robot interaction within dynamic safety regions.

The background to this study is a research project on a transferable robotic system reported by Salmi et al. [1], and the findings are derived from earlier results [2]. The motivation for transferable systems is the need for flexibility and configurability. Product life cycles are shrinking, the variety of products is expanding, and production volumes are fluctuating. At the same time, production costs should be decreased. Tight competition brings pressure for automation, while the need for flexibility makes automation difficult with well-established technologies. As a result, industry is seeking new approaches. Transferable systems are considered to have a leading edge for enabling configuration/reconfiguration of production systems, lines and workshops. The capacity could be transferred where needed and investment risks could be reduced. Another potential area for transferability is to process big products with mobile devices; necessarily large movements could be achieved by transferring the devices instead of the product. The development of transferable systems focused to two solutions that were considered to have the most potential:

- A transferable universal robotic module/platform for the material handling of machine tools
- Processing tasks of large products with a transferable robot system.

The target of the research was to develop methods and tools to enable the rapid building and transfer of production capacity in changing production situations. The main development areas were methods for achieving flexibility and ensuring safety.

This paper focuses on a safety design where unexpected and difficult challenges have been encountered. The assumption was that new modern safety technologies could open up fresh possibilities for the building of new transferable safety systems. This turned out to be correct, but several new challenges arose that needed to be resolved. These are relevant not only for transferable robotic systems, but also when using the advanced features of the new safety technology.

## 2 INVESTIGATING POTENTIAL SAFETY SOLUTIONS

Transferable robotic systems set the following requirements for the safety system design:

- The system set-up after transfer should be made fast and easy.
- Investments in safety should be cost-efficient: safety devices should be relatively cheap and the safety system preferably wholly integrated into the transferable platform.
- The safety system should allow efficient utilization of space.

The safety system should be suitable for many different situations and production environments without extensive changes to the factory floor layout. Usually there is not too much space in workplaces, and safety arrangements cannot require large additional safety areas.

Safety solutions can be divided into two groups: freely transferable robotic systems and systems that have multiple prepared regular workplaces (e.g. for machine tending) between which the robot cell is transferred according to production needs.

Safety of the transferable robotic cell is considerably easier to achieve with prepared bases than if the robotic platform is freely transferable. However, many problems still arise that are not encountered in stationary robot cells. Safety devices can be mounted on each robot cell or can be carried with it depending on the costs of multiple safety systems versus one. There are several ways of designing a safety system for this kind of robotic cell.

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### 2.1 Physical Barriers Preventing Human Access to the Robot Working Area

A safety fence is a simple and robust way to separate humans and robots, and prevents human access to the danger zone. Thus a safety fence saves floor space particularly if the machine stopping time is long. It also acts as a shield from dangerous flying objects, debris, welding sparks etc. and reduces noise, if made of solid material like Plexiglas. A simple fence is cheap. However, possible automatic doors add to the cost, as does having to replicate the fence or part of it in several places.

If a transferable robotic system is considered, one of the disadvantages is that the fence is physically large and slow to set up. It also makes logistics and human interaction more difficult. On the market it is available as a commercial solution, where easily set-up foldable and reasonably lightweight fences are transferred with a transferable robotic system.

### 2.2 Making the Robot Safe

Slowing down and padding the robot can make the robot safe, but it means that cycle times will be longer. Further, the robot arm will be bulky and no dangerous tools can be allowed. Also, avoiding the risk of crushing requires that the robot forces are limited to within a safe range. This would prevent the handling of steel components. Several solutions have been proposed for light robot arms that would make close operation between robots and humans possible [5, 6 and 7], but with bigger and stronger robots the situation is much more difficult. When designing safe robots it is important to keep in mind that most severe robot accidents are caused by crushing between the robot arm and a rigid or heavy object. This can affect the safety measures needed in different applications. [8]

### 2.3 Sensor-Based Safety Devices

New possibilities for transferable robotics are seen in new types of safety sensors, laser-based scanners or vision-based safety systems that allow safety systems to be integrated into the transferable platform. The so-called safety controllers that most industrial robot suppliers can now offer have complementary features. Safety controllers offer an easy way to restrict the robot working area in 3D. Further, they offer a safe and easy way to monitor the speed of the robot. The starting point for the development was that by combining safety controllers and new sensor technology it would be possible to create space-saving, intelligent dynamic safety areas with easy transferability. Further studies revealed that there are several complex questions to be addressed.

Sensor-based safety devices require larger safety distances than physical fences, because they do not prevent human access to the robot working area. Especially faster and larger robots with a longer stopping time require a long safety distance. Once a human operator has caused the safety sensor to stop the robot, the robot needs enough time to stop moving before the operator reaches its work zone.

It is also possible to combine both physical and sensor-based safety devices. By combining the best properties of each, a transferrable robotic cell could be built with a relatively low footprint yet good accessibility. For example, one side of the danger area could be protected by a light curtain while others are fenced.

A safety light curtain requires both a transmitter and a receiver, which must be accurately placed in relation to each other. Setting up the light curtain every time a robot is moved is very time consuming. However, a light curtain is relatively cheap and has a fast response.

With the novel safety machine vision systems, a safety area with warning fields can be easily and rapidly configured in 3D after an initial setup [4]. Different safety area scenarios can be set up easily for different prepared robot bases. Setup and function of safety machine vision requires locating several target discs in the machine vision surveillance area, but they are cheap and can easily be duplicated for each prepared base. However, one problem with safety machine vision in mobile usage is that it has to be mounted high to gain a wide enough field of view. In order to ensure a sufficient safety distance in diameter for a medium sized robot, the safety machine vision camera has to be mounted at least 6 metres high. A safety machine vision system is expensive, which means that it must be carried with the cell. The camera unit itself is small and light, but the controller is quite large and bulky. For transfer the mounting pole must be telescopic. Even small vibrations caused by a moving robot can be problematic when transferred along a long mounting pole. The other alternative is to have a stationary rack with an adapter at each workplace. The first commercial 3D safety machine vision system appeared on the market just a few years ago, and as a novel product has some problems in usage. It works fine when monitoring the edges of tidy unchanged areas, but e.g. flying debris, welding sparks, dirt on the floor and minor changes in the monitoring area cause problems. Also traditional machine vision problems caused by ambient light, reflections and shadows may occur.

Safety laser scanners are another potential solution for a transferable robotic cell. The safety area is easy and fast to configure, many safety area scenarios with warning fields can be created, and the function is robust and has been tested by industry. The safety scanner scans the environment in a single plane from one point. Objects within the scanning area and blind angles are problematic if the scanner (scanning plane) is horizontally mounted on the transferable cell. If the scanners are mounted vertically (Figure 1), at least three scanners are needed to cover the whole cell and warning fields cannot be used.

By using a warning field, robot productivity and co-operation with a human operator can be improved, because emergency stops can be avoided. Also the detection of a human in the warning field can be reacted to by reducing speed and making the safety area smaller, or the robot can turn away from the operator to other tasks.

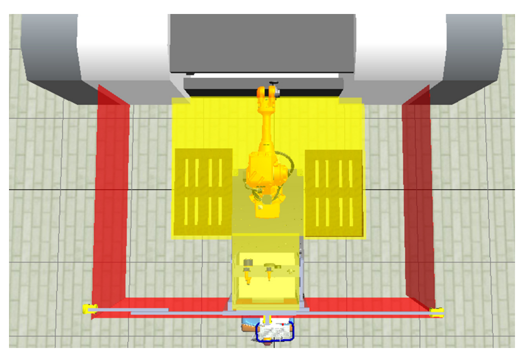


Figure 1: Transferable cell equipped with a laser scanner in machine tending operation. The robot working area is highlighted in yellow.

## 3 SAFETY AREAS

The biggest problem when using sensor-based safety devices like a safety scanner is that they require lots of extra space compared to safety fences. Dangerous machine/system stopping time has the greatest effects on the safety distance around the robot work area. Further, depending on the sensor, its response time may considerably affect the safety distance.

For the laser scanner, stopping time S is calculated with the following formula [3]:

$S = 2000 \times (T_M + T_S) + 8 \times (d - 14 \text{ mm})$ [mm], where:

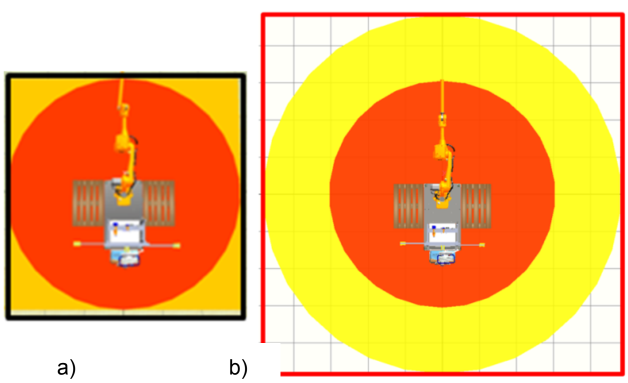
S = Safety distance [mm],

$T_M$ = Stopping/run-down time of the machine or system [s],

$T_S$ = Response time of the laser scanner [s],

d = Resolution of the laser scanner [mm].

Robot with a 45 kg payload and 2 051 mm reach was used in the case. Its stopping time according to the supplier is 890 ms in category 1 stop, which means controlled stop in the programmed path. Emergency stop is not recommended with sensor-based safety systems even it gives slightly shorter stopping times. Safety distance was calculated to be 1 776 mm, which is the necessary safety distance from the robot working area in all directions. This means that the robot cell layout dimensions should be at least 2 x 2 051 (reach) + 2 x 1 776 mm = 7 654 mm. A tool and a work piece will increase the dimensions even more. The cell area would be 93.2 $m^2$,(figure 2b) which is too much for most purposes. Physical safety fences offer a much smaller footprint of 37.2 $m^2$ (figure 2a). Because the laser scanner offers the necessary flexibility for the transferable robotic cell, it is necessary to find methods for attaining the required safety with smaller safety distances. Modern so-called safety controllers offer new possibilities for that purpose. Nowadays, a safety controller is available from several robot suppliers as an optional function.



a) b)

Figure 2 : Comparison of the required space between a fenced robot cell (a) and a sensor-based monitored (safety laser scanner) cell (b).

## 4 METHODS FOR REDUCING SAFETY AREAS

A robot safety controller is like a second axis computer that monitors the robot speed and position. The system makes it possible to limit the robot working area in 3D. It is also possible to define several operation areas and define the maximum allowed TCP (Tools Centre Point) velocity or maximum velocities for each robot axis. If the robot speed or position differs from the setup values, the safety controller commands the robot to stop.

Possibilities to restrict the working area and maximum velocity of the robot are the best ways to reduce required safety distances. The basic physics formulae ($v = at$; $F = ma$; $s = ½ at^2$, $E = ½ mv^2 = F * s$) demonstrate that reducing the robot velocity is an effective way to reduce a robot's stopping time and also especially its breaking distance.

However, the use of a safety controller is more complicated than first assumed. It should be noted that the axis computer of the safety controller only monitors the current speed and position of the robot. It does not reduce the speed automatically, nor does it reduce the speed before the area limit is reached. It does not even prevent the robot from crossing the determined limit. It only reacts once a limit has been crossed. Therefore, especially a larger robot with a longer stopping time may run far from the determined area before stopping. A robot can cross the limit due to e.g. a programming fault or a faulty position obtained from the vision system.

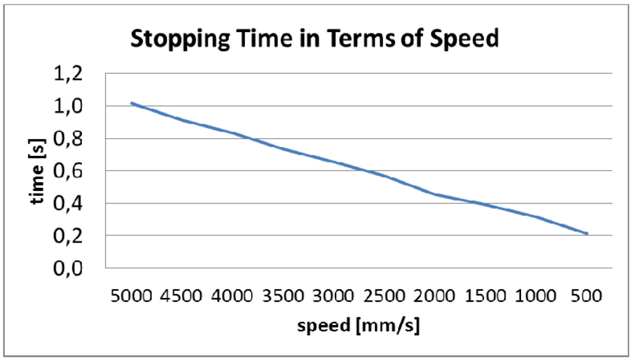
As mentioned above, the robot speed can be reduced in order to cut the robot stopping time. A safety controller can reduce TCP velocity. The robot joint positions are different in each robot position and the same TCP velocity can be a wholly different situation kinematically. In terms of the stopping time, the worst case is related to the 1st axis, when a robot is in maximum reach and has maximum speed; in that case the other axes stop faster. This assumption is given in the robot standard. If the other axes also move simultaneously, the TCP velocity is higher, but the other axes have no effect on the stopping time. Therefore the stopping time is not directly dependent on the TCP velocity. The restriction of axis speeds is more exact, but difficult to figure out in robot programming. Theoretically the stopping time of a robot is proportional to the axes' speed reduction excluding the effect of the reaction time. The effect on the stopping distance is even greater, but this depends on the robot position and direction of movement.

### 4.1 Measuring Stopping Times

Robot manufacturers publish only the worst case stopping times with a full load and speed. The other values have to be measured by the customer. Thus tests were performed to determine stopping times of the 1st axes with a full load in maximum reach and at varying velocities.

The aim was to measure the robot's stopping times both with a real robot and the simulator. Verification that the kinematic model of the robot simulator matches the real robot precisely enough was needed. A test configuration was made according to EN ISO 10218-1 and the related robot stopping time measurement standard. The robot was loaded with a full 45 kg payload. The test was programmed with the simulator software and the tests were run with a straight robot arm. After the tests, the same program was transferred to the robot controller and the corresponding tests were run with a real robot. According to the results, the dynamic model of the robot simulator corresponded well with the real robot. The difference between stopping times was max. 0.02 sec.

Delays in the robot controller and the software were tested by performing the stopping time test at extremely slow speed. This gave a delay of about 0.1 sec, which is amazingly long and could partly be attributed to a delay in the control software giving information about a robot stop after a movement. The results were congruent with each other and with the theory. The measurements were therefore considered trustworthy, although the maximum stopping time from the stopping signal was 0.1 s longer than the published stopping time.



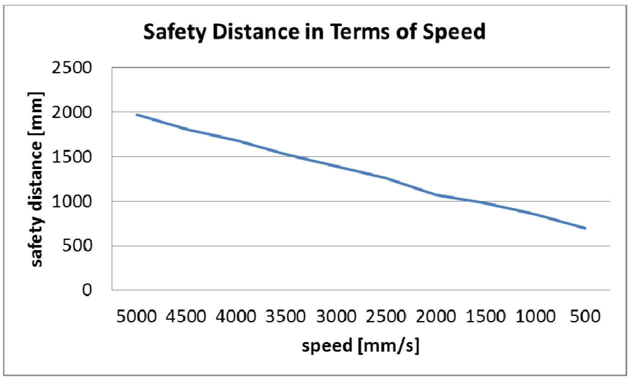




Figure 3: Measured stopping times of the 1st axis with a full load and in a robot maximum reach position in terms of robot speed. Necessary safety distances resulted from calculations for different robot maximum speeds.

Stopping time tests were then run with a simulator using different speed values (Figure 3). A safety distance graph was then calculated from the stopping time data.

The following generalizations can be made from these test results:

- As the speed drops by 50%, the stopping time drops by roughly 50%, and the safety distance drops by 60% from the original. The stopping distances with full speed were more than 2 meters and the TCP speed was then about 5 m/s. The decrease of speed reduces the stopping distance more than the stopping time. Speed reduction is a clear and effective method to decrease stopping times and stopping distances.
- The simulation software and robot seem to work congruently, at least in this kind of simplified situation.
- Stopping distances with high speed were so great that restriction of the robot work area by safety control does not have a big effect on safety distances, if other restrictions are not put in place.

If both the human and the robot can move after activation of the safety system, the safety distance is determined by the formula (according to ISO/TS 15066)

$S = K_R (T_S + T_R) + B (K_R) + C_{Tol} + K_H (T_S + T_R + T_B)$, where:

- $B (K_R)$ is the robot stopping distance
- $C_{Tol}$ is a factor based on the recognition abilities; here the formerly used factor 8 × (d – 14 mm) is used, where d = 40 mm => $C_{Tol}$ = 208 mm
- $T_S$, $T_R$, $T_B$ are the reaction times of the sensor, robot and the robot stopping time
- $K_R$ is the approaching speed of the robot
- $K_H$ is the approaching speed of the human operator (1.6 – 2.0 m/s).

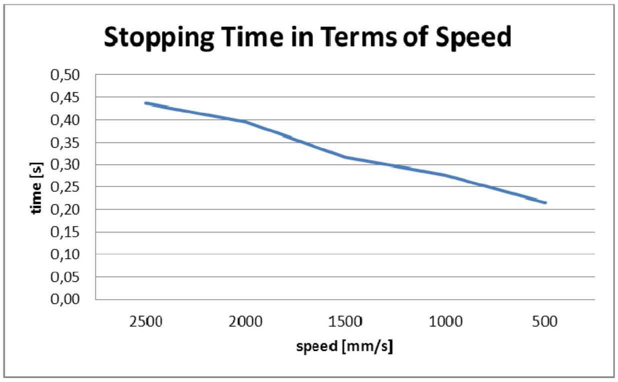
The robot stopping time was possible to determine by the reduction of axis speed. It is more difficult to determine the effect of TCP speed on the stopping time and stopping distance. It is not an easy task to define the worst case stopping time accurately for a certain kind of working area, because the robot's top speed at the edge of the working area will vary with the path depending on which joints are travelling, and every situation is kinematically different. Every working area restriction offers the robot different freedom of movement. The approach has been to develop a very flexible solution, which means that there cannot be tight restrictions on robot movements or loads, etc. The worst case could be calculated in theory, but it would be necessary to know first the kinematics of the robot, the mass of each axis, and the features of the motors and servo drives. These facts are only known by the robot manufacturer. Other methods for finding the worst-case scenario are needed; thus a study of such a scenario in a restricted work area as shown in Figure 1 was initiated.

The study began by working with the simulation system and making a qualified guess of the worst-case movement possible within the area. The movement was performed mostly by the 1st axis to which were added movements of the 2nd and 3rd axes, following a slightly downward path (Figure 4).

On this basis it was noticed that to achieve markedly smaller safety distances the robot speed had to be reduced significantly. It was found that a TCP speed of 1 m/s gave a stopping distance of 205 mm and a stopping time of 0.18 sec. The 0.5 m/s TCP speed gave a 79 mm stopping distance and a 0.12 sec stopping time. These values are within the right range to provide some advantage from the restricted working area. These values lead respectively to safety distances of 1.01 m and 0.76 m on one side, and are satisfactory for the considered applications.

Full certainty that the absolute worst-case scenario had been found could not be achieved, but it can be assumed that we were fairly close. To confirm this, a study was carried out using randomly selected paths. The results seem to be quite congruent, but slightly bigger values were obtained. Stopping ranges that were 0.04 sec and 32 mm greater were obtained. In this simulation the slowest stopping time was equal to the case shown in Figure 3, but the stopping distance was slightly greater. This simulation study should have been more extensive to ensure that the worst case was really identified. Not finding it poses a risk, because the stopping distance is dependent on the position where the limits are crossed, and on the position and direction aimed for. Therefore it can be recommended that an additional safety factor is used in the estimated safety distances. From the tests it is difficult to say whether it should be a constant factor or related to speed.

Additional verifications to the simulation tests will be performed and the simulated worst cases will be tested in a real environment. More exact determinations will be available subsequently.



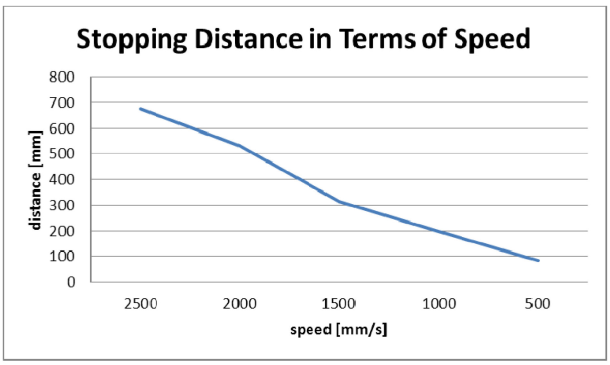




Figure 4: Stopping times and distances of a supposed worst-case movement when the robot has crossed the working area limits at varying speed.

It seems necessary to restrict the robot speed to a fairly low value to keep safety distances suitable for practical industrial applications. It is worth dividing the robot work area into several zones with different speed limits. The lowest speed limits are used only in the border area of the robot working zone. It is also suggested that the highest speeds should be avoided in fenceless robot systems. In most cases, acceleration is more dominant over cycle time than maximum speed.

Safety distances must be determined case by case. Although a safety controller offers the possibility to arrange a fenceless robotic solution, this needs careful study on the safety and case-specific test arrangements.

Mechanical limits for axes can be used as an additional reliable method to restrict the working area in critical directions, but these do not offer free determination for the 3D working area.

## 5 FREELY TRANSFERABLE SYSTEM

Freely transferable systems could be used to process big products in applications like welding or grinding (Figure 5). The idea is to transfer the robot to the product for certain process phases. Possible manual and automatic phases may alternate: a worker can perform some preliminary phases following automatic phases, possibly followed by manual finishing phases. The robot works within its given range, and after finishing is transferred to continue its work around the product. The limited range of the robot is compensated by transferring it around the product. The optimal solution could be a situation where the operator and robot simultaneously process the same product in different areas. These types of products are often tailor-made, one-of-a-kind products.

The safety system should guarantee that the robot is working only in a restricted area and human intrusion into the robot area stops the robot within the safety area. The robot area should be restricted only to the necessary directions to minimize space utilization. A safety controller could be used for this purpose.

The robot area is possible to protect from humans with laser-scanner-based safety sensors on each side. Typically there is a processed object in front of the robot. The safety sensors work well, if there is a free space in the supervised area. The difficult point from the safety perspective is a safe connection between the sensor-supervised area and the product surface. The product surface is not usually flat; various parts can protrude from it. The seam between the product and safety system-supervised area should be tight, and in the worst case a new setup for the sensor-based safety system is required each time the robot cell is moved. Otherwise, if the sensor-supervised area crosses the product surface, the sensor will inform the safety system of the protrusion and halt the robot.

It is not practical to always perform a set-up after moving the platform. It takes too much time and needs expertise with the safety equipment present. If the product is always similar and the robot can be transferred to a stationary spot, set-ups can be done beforehand. Safety systems should be easier to configure for these kinds of applications.

The basic idea in this application is to move the robotic platform freely. To date a satisfactory solution to the problem has not been found with commercial components. However, there are some possibilities to build an acceptable arrangement. One suggestion is to use adjustable short fences at the connection points of both sides. The sensor recognizes the ends of the fences assuming that the fences are mounted. This suggestion has some practical limitations. Another possibility is to set up an arrangement whereby the robot platform as well as the whole product is wholly separated from humans. It is not easy to arrange a standardized connection to the environment with a freely transformable robotic platform, and satisfactory solutions are still under development.

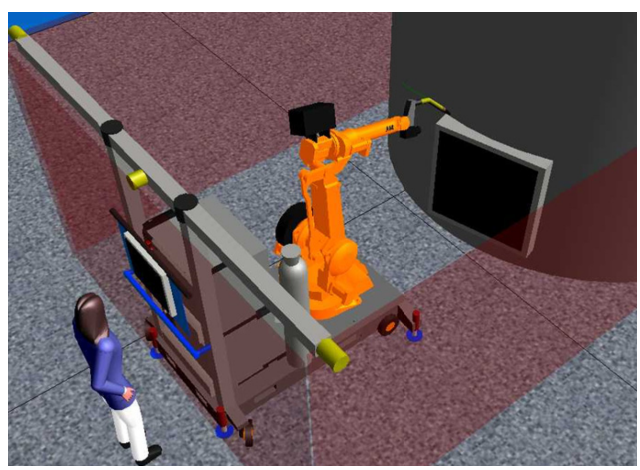


Figure 5. Concept of a freely transformable robot platform used in a process application.

## 6 ADVANCED HUMAN-ROBOT CO-OPERATION WITH DYNAMIC SAFETY AREAS

Based on the above results, a demonstration has been set up where a robot and a human co-operate in a packaging process of large items. The human worker and robot perform their own tasks independently in their own areas, but some phases are carried out together. The working areas of the robot and worker partly overlap. The robot handles the heavy components and the worker guides the robot in the final positioning with a force feedback system when placing them in the package. The worker concentrates on the tasks that require flexibility and decision-making, such as adding the right accessories to the package and handling packaging materials that are difficult (soft) for the robot. There is also a guidance system that helps the worker select the right components for the package.

Movements of the worker are detected by two systems: the primary system is based on Microsoft Kinect; the secondary system meets the needed safety standards and is based on a Piltz SafetyEye sensor. Kinect is a 3D sensor that can detect humans from its sensing area. The Kinect-based system also calculates the predicted worker distance to the danger by calculating the speed from the two last Kinect-specified locations to the closest danger point of the worker. The danger can be defined as the distance to the centre point of the robot, the tool centre point of the robot or the workstation. The predicted location is the future position within a defined amount of time where the worker would be if he/she continued in the same direction with the same speed. According to the predicted position the robot speed is reduced so it can be stopped safely before the human comes into contact with it.

Kinect is not a certified safety sensor; thus such a sensor must be installed to ensure that the robot will stop if the person comes too close to it while its speed is too high. SafetyEye is a ceiling-mounted vision-based safety system in which several 3D safety zones can be defined. Other safety sensors could be used as well, such as safety laser scanners with multiple safety zones. Safety zones consist of a warning area and a stopping area. The safety zone is switched to a smaller zone as the robot speed drops and vice versa. The robot signals SafetyEye to change the safety zone. A robot with a safety controller option is used in the demonstrator. This option is required to guarantee safe speeds, safe standstills and safe areas. The software written by user in a robot controller actually moves the robot and tells it to work at certain speeds, in a certain area or in the standstill position according to Kinect or SafetyEye outputs. The safety controller merely monitors predefined speed and area value sets. Different pre-programmed value sets can be chosen by raising certain safety controller input up. The safety controller cannot be programmed during robot program execution. It is basically a second axis computer that monitors that a set speed, the standstill or area function is not violated. If a violation occurs the emergency stop is executed.

According to the information on worker movement information, provided by Kinect to the robot controller, the robot speed and place are altered. If the worker moves close enough, the robot will eventually stop because the standstill monitor function is used in the robot safety controller. In normal operation the stop area of SafetyEye is never entered while the robot is moving, because Kinect base system informs the robot to stop and monitor standstill is activated in time. Thus no emergency stop is needed even though the worker comes close to the robot. Altogether this system creates flexibility for human-robot systems by creating a fenceless environment and avoiding unnecessary emergency stops.

Human worker can be assisted with ceiling mounted projector to point out assembly or packaging directions and locations of parts. Also the safety areas and areas, where the worker should not enter can be projected on the floor.

The demonstration demonstrates that new safety technology enables a dynamic safety system that adapts intelligently to on-going situations and enables flexible human-robot co-operation.

## 7 SUMMARY

Modern safety technology is opening up new types of possibilities for human-robot co-operation and new types of robot applications. Sensor-based safety systems and safety controllers offer advantages for achieving transferability of the production system. The new technology also bring new challenges, especially in the case of heavier robots. Solving these challenges in industrial applications needs careful case-by-case study. Modern safety technology is also allowing more adaptive and flexible human-robot co-operation.

## 8 ACKNOWLEDGMENTS

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# Toolpath Generation for CNC Milled Parts Using Genetic Algorithms

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**Abstract**

As manufactured products become increasingly more complex, generating machining toolpaths to manufacture these products are also becoming more complicated. Toolpath generation algorithms struggle when dealing with large numbers of data points due to the complex features on a design. In this research, a genetic algorithm is proposed to solve a variation of the travelling salesperson problem to generate a machining toolpath. Genetic algorithms are a more flexible approach to generating toolpaths as it is independent of the geometry of the part. Novel algorithms for the fitness function and mutation operator are proposed to ensure an optimal toolpath is generated without the genetic algorithm converging prematurely.

**Keywords:**

Genetic Algorithm; Toolpath Generation; Traveling Salesman Problem

## 1 INTRODUCTION

As manufacturing industry is becoming increasingly more automated with the industry's shift from craft production to mass customisation, several paradigm shifts have occurred for this to be possible. From the use of machines to replace hand-made parts, through the use of production lines to increase the volume of products being made, to the use of robots to ensure repeatable quality in all of the products produced.

In the manufacturing world today the main challenge is keeping up with the fast pace of technology development and making sure manufacturing technology is flexible enough to keep up. One of the main issues that need to be tackled is the time taken between design and manufacture. Every time a new prototype is designed or a design is modified, a new CNC machining program needs to be developed to manufacture the part. This can be very time consuming to do manually.

This paper proposes a method of generating the machining toolpaths required to create a CNC machining program using a genetic algorithm. Genetic algorithms are independent of part geometry and so can generate toolpaths for many different types of parts. As designs are becoming increasingly more complex, the number of data points required to describe the product increases as well, hence making analytical methods of generating toolpaths very time consuming.

## 2 TOOLPATH GENERATION

There is a wide variety of literature available on toolpath generation as there are many methods of generating toolpaths. A pioneering survey paper was written by Dragomatz and Mann [1] in 1997 which covers many of the widely used methods used to generate toolpaths as well as a few non-traditional methods.

Traditional methods of generating toolpaths usually involve drawing parallel lines to the contours on the part [2]. This can be done in a variety of ways; one method is to use Voronoi diagrams to segment the space within a boundary into sections and then using offset curves to generate the toolpaths in each space [3]. Toolpaths have also been generated from large amounts of point cloud data by separating the points into bands and drawing toolpaths along the band lines [4]. The drawbacks to this method are the lack of a finishing cut toolpath and the difficulty in verifying the accuracy of the finished product.

The problem with these methods is that they are not very flexible as they are usually designed to generate toolpaths for specific types of features or using a specific machining strategy. A universal algorithm is required which can generate a machining toolpath for any feature as defined by the ISO 10303 standard [5] and for any machining strategy as defined by the ISO 14649-11 standard [6].

Heuristics have been used for path planning in several applications one of them being spray forming [7]. A study was done comparing the use of genetic algorithms and ant colony optimisation on path planning in spray forming. It was found that genetic algorithms produced faster results at the cost of lower quality solutions [7].

## 3 SHORT OVERVIEW OF GENETIC ALGORITHMS

A genetic algorithm is effectively a heuristic technique used to optimise a problem to a specified goal. Genetic algorithms were inspired by the biological method of natural selection which can be seen in evolution. Genetic algorithms are used to optimise many different designs from structural engineering [8], manufacturing [9], aerospace engineering [10] as well as many more. Genetic algorithms were first used to solve the travelling salesman problem in 1985 by Brady [11]. This was later developed further by Goldberg and Linge [12]. A full review on using genetic algorithms for the travelling salesman problem was done by Larrañaga in 1999 [13].

To represent a solution for the travelling salesman in genetic form, each gene will contain a city/point. The chromosome will then contain the order in which all of the cities/points are visited. Each point can only be visited once and all of the points have to be visited. An initial random population is created and then assessed in terms of its fitness. The fitness function will measure how well each species in a population is performing with respect to a specific goal. A new population can then be created by mating the fittest species of the previous generation together to ensure the best patterns of genes are carried over into the next generation. Mutation of genes can be applied at this stage to ensure the search space of the genetic algorithm is wide enough to converge on the optimal solution. There are many methods of crossing over genes during mating as well as mutation algorithms for ordered chromosomes which will be discussed later.

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## 4 TOOLPATH GENERATING GENETIC ALGORITHM STRUCTURE

The genetic algorithm structure can be used to generate toolpaths for machining by dividing the surface of a modelled part into a grid and treating each coordinate of the grid as a city in the travelling salesman problem. By comparing the starting billet surface to the end product surface at each cut depth, a toolpath can be generated by solving the travelling salesman problem for each cut.

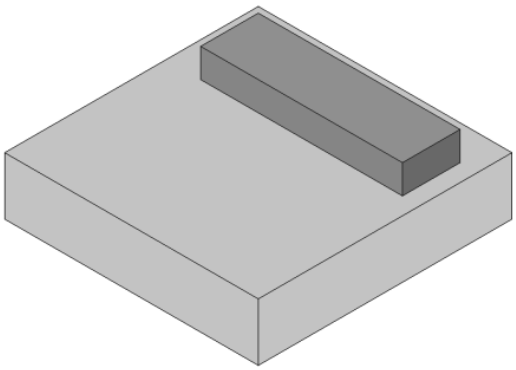

Figure 1: Example part.

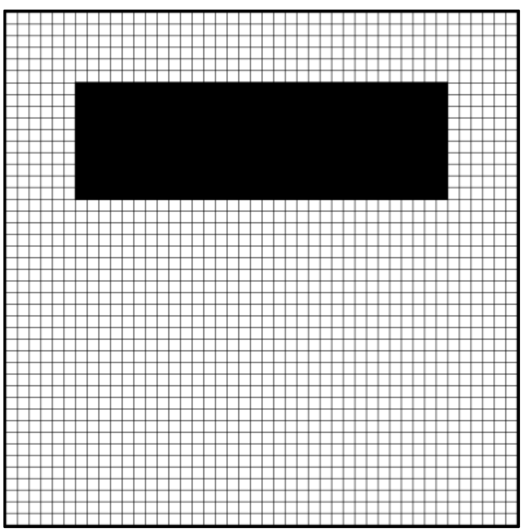

Figure 2: Grid of points for example part.

| | | | | | |
|---|---|---|---|---|---|
| 30 | 31 | 32 | 33 | 34 | 35 |
| 24 | 25 | 26 | 27 | 28 | 29 |
| 18 | 19 | 20 | 21 | 22 | 23 |
| 12 | 13 | 14 | 15 | 16 | 17 |
| 6 | 7 | 8 | 9 | 10 | 11 |
| 0 | 1 | 2 | 3 | 4 | 5 |

Figure 3: Detailed view of the grid in Figure 2.

Figures 1 and 2 illustrate how this grid system could be applied to an example part. As the part is described using the STEP data structure [5], all of the boundaries of the features on the part would be known so that the grid would omit these points. In Figure  the white points would indicate material that would have to be removed and black points would be avoided by the machining toolpath to create the required features. Figure  is a closer look at the grid in Figure 2. Each point in the grid has a number as well as a coordinate. Each point can be referenced either by its coordinates or by the point number (i.e. 0-35).

### 4.1 Developing the Genetic Algorithm

To design the genetic algorithm for generating toolpaths, the nature of a toolpath has to be converted into a genetic structure. Each point that the toolpath passes through can be seen as a city in the travelling salesman problem. To represent a toolpath in a genetic form, each point's location can be stored as the genotype of a gene in a chromosome. A chromosome in this context represents a particular toolpath through all the available points. Each species in a population will represent a possible solution to the problem of finding the most efficient toolpath. A population represents a collection of toolpath solutions in the current generation.

| Gene | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Genotype | 0 | 1 | 2 | 3 | 4 | 5 | 11 | 17 | 23 | 29 | 35 | 34 | 33 | 32 | 31 | 30 | 24 | 18 | 12 | 6 | 7 | 8 | 9 | 10 | 16 | 22 | 28 | 27 | 26 | 25 | 19 | 13 | 14 | 15 | 21 | 20 |

Figure 4: Example chromosome for grid in Figure 3.

Figure illustrates the structure of the ordered chromosome. Each number in the genotype refers to one of the points in the matrix shown in Figure . To create a toolpath from the data in the chromosome, the points have to be joined in a linear fashion in the order described by the chromosome. The toolpath for the chromosome in Figure can be seen in Figure 5.

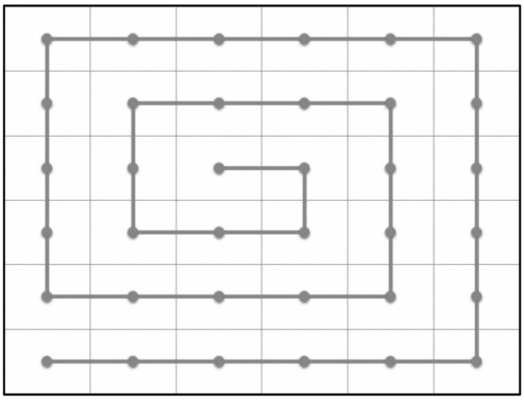

Figure 5: Example toolpath for chromosome in Figure 4.

By separating the three dimensional model into multiple two dimensional layers by the cut depth, the travelling salesperson problem can be simplified. Instead of solving the travelling salesperson problem on the whole model, the genetic algorithm can solve the problem for each layer of the model. This greatly reduces the amount of time required to solve the problem as can be seen by the following:

$$\text{Number of Possible Solutions} = (XYZ)! \quad (1)$$

where $X$ = points along X axis, $Y$ = points along Y axis, and $Z$ = points along Z axis.

$$\text{Number of Possible Solutions} = (\frac{Z}{D})(XY)! \quad (2)$$

where X = points along x axis, Y = points along Y axis, Z = points along Z axis, and D = cut depth.

A simple calculation can be done to show the benefit of separating the model into layers. For example a cube with 5mm sides and a cut depth of 1mm:

$$Number\ of\ Possible\ Solutions = (5 \times 5 \times 5)! = 1.88 \times 10^{209}$$

$$Number\ of\ Possible\ Solutions = \binom{5}{1}(5 \times 5)! = 7.76 \times 10^{25}$$

### 4.2 Fitness Function

To assess the quality of each species, a fitness function is used. The fitness function will compare one or more features in the species to one or more specific goals. For this genetic algorithm, the goal is to generate a toolpath with the shortest length possible while being as straight as possible.

To measure the performance of a species, the length of the toolpath needs to be calculated. This can be done using a simple calculation which sums the distance between all of the ordered points in the species' toolpath.

$$\text{Total Path Length} = \sum_{n=1}^{p} \sqrt{(x_n - x_{n-1}) + (y_n - y_{n-1})} \quad (3)$$

where p = number of points, x = position in x axis, and y = position in y axis.

At this point the fitness function can be modified to accomplish secondary goals. As the secondary goal is to keep the toolpath as straight as possible, a second equation can be inserted into the fitness function to reward continuation of a previous direction. This will shorten the path of movement through points while moving a constant direction. Each subsequent point travelled in the same direction will reduce that segment of the path by fifty %.

$$Virtual\ Path\ Length = \frac{1}{2^{P-1}} \quad (4)$$

where p = number of consecutive points along same direction.

| Number of consecutive points | Virtual Length | Percentage of Original Distance |
|---|---|---|
| 1 | 1.00 | 100.00% |
| 2 | 1.00 | 50.00% |
| 3 | 0.75 | 25.00% |
| 4 | 0.50 | 12.50% |
| 5 | 0.31 | 6.25% |

Table 1: Benefit to the path length for continued path direction.

Through using the virtual path length for the fitness function it will ensure that it is always more beneficial for a species to have one more consecutive point than the last species. This will ensure that a straighter toolpath will be chosen over one with more turns.

### 4.3 Gene Crossover

To create a new generation of species, a selection of the fittest species from the previous generation need to share their genes with each other. This allows the population to retain superior gene combinations while discarding inferior combinations.

There are many algorithms for crossing over genes in an ordered chromosome. There is the Partial Mapped Crossover (PMX) [12], Ordered Crossover (OX) [14], Position Based Crossover (POS) [14], Edge Recombination Crossover (ER) [15], Sorted Match Crossover (SMX) [11] as well as many others. The chosen method will depend on the computational effort required and the time required to reach an optimal solution. According to Larrañaga et al., the methods which require the least iterations are the PMX, POS and ER methods [13]. Of these three, ER is said to generate the most optimal solutions [13].

While developing the genetic algorithm, all three crossover strategies (PMX, POS and ER) will be tested to see which of three strategies performs best in terms of time to converge as well as quality of the solution given by the genetic algorithm.

### 4.4 Mutation

To ensure the genetic algorithm converges on an optimal solution, it is important to keep the available genes in the gene pool as diverse as possible. One way to do this is to insert new gene combinations into the gene pool by adding a mutation function into the genetic algorithm. As the algorithm is dealing with an ordered chromosome, mutating a gene value to a random number can cause a point to be visited twice and another point not at all. To avoid this, a method of mutating the current gene to one of the nearest neighbours of the previous gene is proposed. This method calculates the nearest neighbours of the previous gene and randomly selects one of the available neighbours.

The sequence of figures from Figure 6 to Figure 9 illustrates the nearest neighbour mutation method. Figure 6 is an example of a toolpath which is not completely optimal. In Figure 7 the gene targeted for mutation is highlighted along with its nearest neighbours. The genetic algorithm will then select one of these nearest neighbours at random to become the next point in the toolpath order.

In Figure 8 the optimal nearest neighbour is selected and its position is then switched with the original gene to ensure order is kept in the chromosome. The result of the mutation can be seen in Figure 9 where the two switched genes are highlighted. The toolpath is now of optimal length and direction.

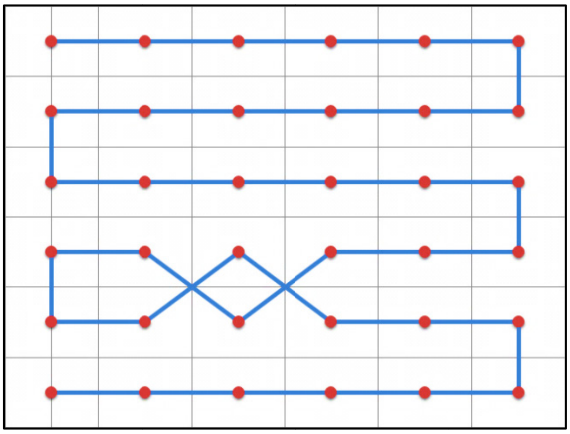

Figure 6: Non optimal toolpath.

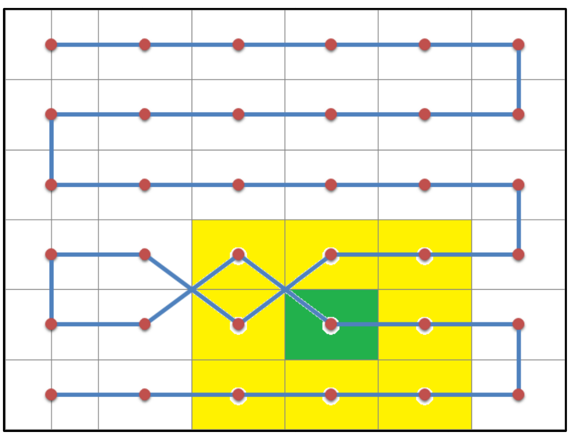

Figure 7: First gene location with nearest neighbours.

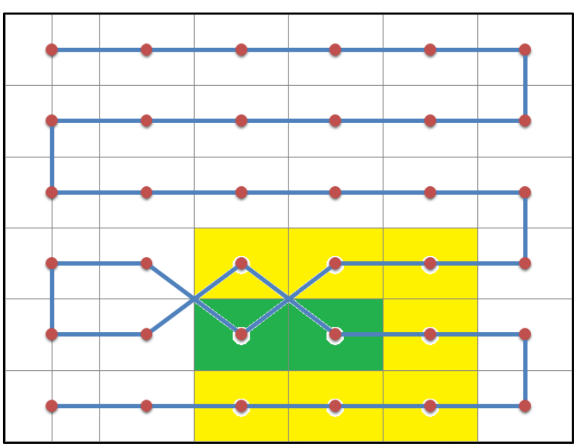

Figure 8: Nearest neighbour selected.

The nearest neighbour (NN) method increases the probability of the mutation being successful by minimising the available genes that the selected gene can switch positions with. The following calculation verifies the benefit of using this method.

$$Probability\ of\ Successful\ Mutation\ without\ NN\ Method = \frac{1}{XY^2 - XY} \quad (5)$$

where, X = points along X axis and Y = points along Y axis.

$$Probability\ of\ Successful\ Mutation\ With\ NN\ Method = \frac{1}{NXY} \quad (6)$$

where, X = points along X axis, Y = points along Y axis, and N = number of nearest neighbours.

Therefore there is an $\frac{XY-1}{N}$ increase in probability of having a successful mutation when using the nearest neighbour method.

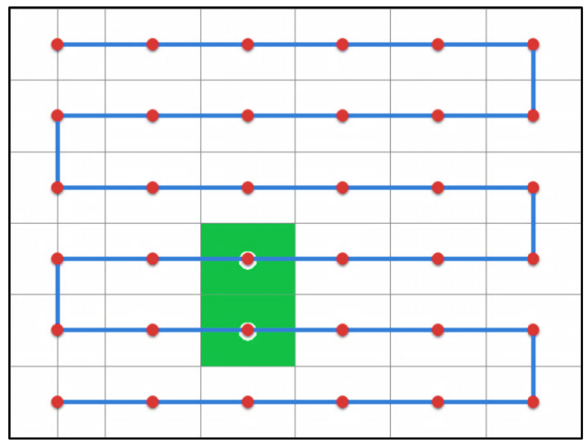

Figure 9: Next gene location switched with nearest neighbour.

## 5 VALIDATING THE GENETIC ALGORITHM

To validate the genetic algorithm a test needs to be designed that will ensure the solution provided by the genetic algorithm is the optimal solution. This can be done by testing the genetic algorithm on a standard part which can be analysed manually and an optimal toolpath developed without the genetic algorithm. The part needs to be described using the STEP data model to see if a toolpath can be generated from a STEP model. The two solutions can then be compared in terms of length and number of turns to see if the solution generated by the genetic algorithm is valid. The solution can then be run on CNC simulation software such as VERICUT® to ensure the toolpath will create the specified part without any problems. Finally the solution can be tested on an actual CNC milling machine to determine whether the machined part is within tolerance and design specifications.

The part to be used to validate the genetic algorithm will be the part described in ISO14649 Part 11 Annex F.

This part has several features which can be used to test the genetic algorithm's capabilities in handling non-uniform surfaces. This part is also described using the ISO14649 standard and can be used to test the genetic algorithms capabilities in understanding the boundaries of the features from a STEP part 21 file.

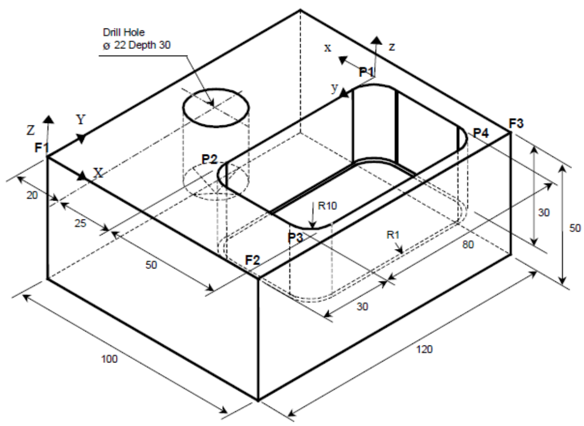


Figure 10: STEP-NC ISO14649 Test part [6].

## 6 DISCUSSION

As manufactured parts become more complex, the number of data points required to describe the part accurately will increase. Therefore to account for this the techniques used to generate toolpaths for these parts will also become more complex. Genetic algorithms are a very efficient method of converging on a solution where there are a very large number of possible solutions.

There are a number of problems that can arise while developing a genetic algorithm to tackle the toolpath generation problem. The first problem that might be encountered is avoiding convergence on a non-optimal solution. Care must be taken when designing the fitness function to ensure that only species with the desired characteristics are given a high fitness. Another problem is that the closer the population gets to the optimal solution, the less chance there is of the population improving. Therefore the mutation algorithm needs to be designed so that an improvement in the species' genes is statistically feasible. The third major problem to be solved is how the genetic algorithm decides if the solution at a given point is truly the optimal solution or if more generations are required to provide a better solution. As the optimal solution is not known, the fitness function will provide a relative measure of the species performance. To overcome this problem, a method of determining the rate of convergence needs to be developed so that the genetic algorithm will stop once the rate of convergence drops below a desired level.

Future developments which would be useful to toolpath generation problem would be to have an algorithm that would reduce the number of data points required to describe a part feature. Points could be clustered around boundaries and features with fewer points in spaces between these boundaries and features. This would greatly increase the efficiency of the genetic algorithm as fewer data points would mean fewer possible solutions and hence less time to converge on an optimal solution. Another useful area of research is to develop the fitness function in such a way to generate toolpaths with specific machining strategies (e.g. bidirectional milling or spiral milling). This could be achieved by rewarding or penalising certain path patterns.

## 7 CONCLUSION

This paper provides a framework for developing a genetic algorithm which can generate a machining toolpath for a part described by the STEP data structure. This has been realized by having a novel algorithm for the fitness function that will allow the genetic algorithm to converge on an optimal solution from which a CNC machining toolpath can be easily written. A new mutation algorithm has been developed which will increase the probability of successful mutations by using the nearest neighbours method. This will in turn also increase the likelihood of the genetic algorithm generating an optimal toolpath.

## 8 ACKNOWLEDGEMENTS

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# Human-Robot-Collaboration System for a Universal Packaging Cell for Heavy Electronic Consumer Goods

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**Abstract**
The Project CustomPacker – Highly Customizable and Flexible Packaging Station for mid- to upper-sized electronic consumer goods using Industrial Robots aims to design a flexible and scalable packaging cell for heavy electronic consumer goods. In this project human-robot-collaboration is used for the packaging task to reduce the cycle time. Human-robot-collaboration demands some specific targets, for example safety aspects and ergonomic issues. Within the project, the robot, the gripping mechanism and other components were developed and built up. This paper introduces a method to develop such handling systems. The procedure adepts the "Münchner Vorgehensmodell" to the special requirements of packaging systems.

**Keywords:**
Safety; Compliant robot system; Flexible gripping mechanism

## 1 INTRODUCTION

For human workers handling heavy electronic consumer goods is exhausting. On the one side, fully automated robot systems are used to support the worker packing the goods. On the other side, handling systems are used for this task. In both cases the worker is not able to prepare for example accessories during the handling of the good, because he has to stay outside the workspace of the robot, that nowadays is not safe, or to handle the handling system.

Through human-robot-collaboration, one main goal of the project, the processes fulfilled by the worker and the one's executed by the robot can take place parallel to each other also in the same workspace and for that reason reduce the cycle time within the packaging process, another main goal of the project. The system build up for the packaging under human-robot-collaboration should be as universal and flexible as possible, regarding different packaged products. Therefore some methodical steps have to be conducted.

This paper first shows the selection of the method (section 2). Afterwards some few steps of the method are represented.

## 2 METHODS SELECTION

The development of the robot and the gripper is mainly a prototype and process development. There are different procedure models that can be divided into three levels. The level of strategic planning includes approaches for the project management, considering project sections or whole project phases, such as the V-model. In the level of operational planning, there are models that support the implementation of individual operations. Here, on the one hand approaches on elementary thinking and action levels (e.g. PDCA, TOTE) and on the other hand procedures at the level of design steps (e.g. after Ehrlenspiel [1]) can be distinguished. The last level is the result level. It includes the results of the other levels. [2]

The so called „Münchner Vorgehensmodell" attempts to unify the common principles of the individual procedure models and their advantages by minimizing their disadvantages. It serves as a tool for the planning of development processes, as guidance in problem solving processes and as tool for the analysis and reflection of the approach. [2] The "Münchner Vorgehensmodell" is very flexible and has been adapted to meet the requirements of the design of packaging systems using human-robot-collaboration as part of the project.

In this paper the parts 'target analysis', 'structure of problem', 'identify solution ideas', 'identify properties' and 'reach decisions' are focused on, as seen in Figure 1. Within the target analysis and the structuring of the problem the requirements to the packaged product and the packaging process are focused on. Also requirements depending on human-robot-collaboration are focused on. To identify different solution ideas the requirements and the mechanisms for handling systems are compared and analysed. From this step different properties to the solution are identified. The different solutions lead to a final solution for the used packaged product in comparison with the properties.

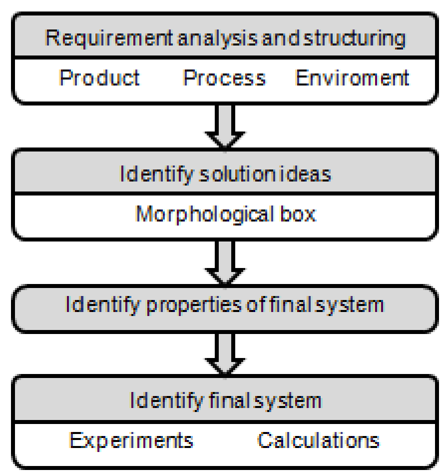


Figure 1: Methodical procedures.

## 3 REQUIREMENTS ANALYSIS

This section includes the steps target analysis and structure of problem. The first step for the development of a handling system, consisting of a robot and a gripper, includes a requirement analysis

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depending on the product, the packaging process and the human-robot-collaboration. The characteristics of the product, which are influencing the handling system most, are the size, the weight and the surface to which the gripper has contact during the handling process. Therefore this section shows the properties of the products foreseen in the project. To ensure shorter packaging cycles human-robot-collaboration is indispensable. Hence both requirements caused by the packaging process and requirements on basis of human-robot-collaboration should be taken into account.

### 3.1 Product Analysis

Consumer goods represent goods that are not assigned to the production of other goods, but for consumption by consumers and to serve their needs satisfaction. Consumer goods may be durable goods or goods for single consumption. [3] The goods considered in the project are goods that are used for a long time. For example washers, dryers, microwaves, cell phones and TV-sets belong to electronic consumer goods. The project aims to support and to relieve the worker from the packaging of heavy electronic consumer goods. Looking on ergonomic aspects a weight bigger than 10kg (for women with frequent activity [4]) or bigger than 20kg (for men with frequent activity [4]) is stressful for humans in a continuous packaging of goods. Therefore small and lightweight goods are not considered in detail below. To reduce the solution space the packaged goods are classified in different groups. Therefore heavy goods can be classified according to different criteria. Reasonable attributes that influence the gripping mechanism and the robot itself are the weight and the size of the products. Other criteria are special characteristics, such as the sensitivity of the surface or the surface itself.

With the size, goods that have a large size in one or two directions and a smaller size in one direction (e.g. TV-sets) can be distinguished. Furthermore, you can recognize products (e.g. microwave, toaster, coffee machine) that are medium-sized in all dimensions (<30 ° lateral angle of inclination of the upper arms, regarding ergonomics [5]) and goods (e.g. refrigerator, washing machine, oven) that are only large size (> 30 ° lateral angle of inclination of the upper arms regarding ergonomics [5]). Within weight you can distinguish moderate and severe to very severe products. The third category contains properties that are more product-specific and not dependent on size and weight. These include the sensitivity of the product and customer requirements, e.g. contamination on the surface. The properties of various electronic consumer products presenting different manufacturers are shown in Table 1. [6] [7] [8] [9] [10]

The different dimensions lead to various demands on the gripper. The gripper must be designed to handle both, smaller and larger products. Furthermore, it must be designed to fit to different surfaces without damaging them in any form or to soil them. The weight has a main influence on the load capacity of the robot. Similarly, robot and gripping mechanisms have to be constructed considering product-specific features, such as fixed orientations of the goods.

### 3.2 Packaging Process

Large and heavy electronic consumer goods are mostly provided by the top to pallets or in cartons. To prepare the pallet, the box, or the consumer good, the worker always needs direct access to the packaging and to the packaged product. This must also be considered regarding the safety of the worker. Through the communication of the worker with the robot, the robot should be controlled individually.

### 3.3 Human-Robot-Collaboration

This shared workspace leads to human-robot collaboration and provides additional requirements to the system. Important for human-robot-collaboration is that the machine – in this case the robot – provides no hazard to the worker. In case of hazards especially pressure and force limits are observed divided by body regions, which are shown inTable 2. Therefore the robot must be as soft as possible despite the severe extent that it manages, so that the forces it exerts at higher speeds, can be intercepted.

An advantage of direct collaboration is, that the robot can be used as a power assistance for the human especially if the human can guide the robot manually [11]. For this kind of collaboration an enabling switch is necessary. The target of human-robot-collaboration to combine the advantages of the human, e.g. the sensomotoric abilities, with the ones of the robot, e.g. to work without break and fatigue, is of particular importance during direct collaboration and also has to be considered during the development process and the dividing of the tasks to be done. In direct collaboration the load, the robot has to handle, has a great influence on the forces exerted on the human in an emergency case. Therefore special safety concepts have to be developed.

## 4 CONCEPTUAL DESIGN

Within the conceptual design, different solutions for the gripping and the robot mechanisms are surveyed. Therefore the tool called morphological box can be used to create different solutions for one problem. Within this collection of solutions the different properties regarding the product, the packaging process and the human-robot-collaboration should be considered. To assess the different solutions, experiments, for example to determine the friction between gripper and surface of the packaged good, and calculations, for example for the stiffness of the robot, need to be done. This section shows some details of the main properties of the handling system.

| Product | Depth in mm | Width in mm | Height in mm | Weight in kg | Specifics |
|---|---|---|---|---|---|
| Microwave, Samsung CE109MTST | 495 | 517 | 310 | 150 | Handle and control panel on the front, glass door on the front |
| TV-set, Panasonic TX-L42WT50E | 321 with foot<br>27 only screen | 956 | 647 with foot | 135 | Very small frame |
| Washing machine, Miele W 1989 WPS | 656 | 595 | 850 | 990 | Glass and control panel on the front |
| Dish washer, Neff S48M53N3EU | 573 | 448 | 815 | 340 | Control panel on the front |
| Fridge, AEG S63300KDX0 | 658 | 595 | 1540 | 550 | Handle on the front |

Table 1: Properties of various electronic consumer goods.

| Body model<br>Main and individual regions with codification | | | Limit values of required criteria | | | |
|---|---|---|---|---|---|---|
| BR | | Region | CSF | IMF | PSP | CC |
| | | | [N] | [N] | [N/cm²] | [N/mm] |
| 1. Head with neck | 1.1 | Skull/Forehead | 130 | 175 | 30 | 150 |
| | 1.2 | Face | 65 | 90 | 20 | 75 |
| | 1.3 | Neck (sides/neck) | 145 | 190 | 50 | 50 |
| | 1.4 | Neck (front/larynx) | 35 | 35 | 10 | 10 |
| 2. Trunk | 2.1 | Back/Shoulders | 210 | 250 | 70 | 35 |
| | 2.2 | Chest | 140 | 210 | 45 | 25 |
| | 2.3 | Belly | 110 | 160 | 35 | 10 |
| | 2.4 | Pelvis | 180 | 250 | 75 | 25 |
| | 2.5 | Buttlocks | 210 | 250 | 80 | 15 |
| 3. Upper extremities | 3.1 | Upper arm/ Elbow joint | 150 | 190 | 50 | 30 |
| | 3.2 | Lower arm/ Hand joint | 160 | 220 | 50 | 40 |
| | 3.3 | Hand/Finger | 135 | 180 | 60 | 75 |
| 4. Lower extremities | 4.1 | Thigh/Knee | 220 | 250 | 80 | 50 |
| | 4.2 | Lower leg | 140 | 170 | 45 | 60 |
| | 4.3 | Feet/Toes/Joint | 125 | 160 | 45 | 75 |

| | | | |
|---|---|---|---|
| BR | Body region with codification | IMF | Impact force |
| Re-gions | Name of the individual body region | PSP | Pressure/Surface pressure |
| CSF | Clamping/Squeezing force | CC | Compression constant |

Table 2: Limit values for collisions [12].

### 4.1 Gripper

The prehension process can be realized in different ways. Grippers can be divided into the following typical gripping mechanisms [13]:

Impactive gripper

"A mechanical gripper whereby prehension is achieved by impactive forces, i.e. forces which impact against the surface of the object to be acquired."

Astrictive gripper

"A binding force produced by a field is astrictive. This field may take the form of fair movement (vacuum suction), magnetism or electrostatic charge displacement."

Ingressiv gripper

"Ingression refers to the permeation of an objects surface by the prehension means. Ingression can be intrusive (pins) or non intrusive (e.g. hook and loop)."

Contigutive gripper

"Contigutive means touching. Grippers whose surface must make direct contact with the objects surface in order to produce prehension are termed contigutive. Examples include chemical and thermal adhesion."

In general industry impactive grippers are the most used, as well as astrictive grippers based on vacuum suckers.

Adjacent to the gripper mechanism high quality grippers have the following properties: [14]

- Optimum adjustment of the structure of the gripper to the operations to be performed.
- Wide adjustment and the ability to capture parts of different shape and size.
- Reliability in terms of tolerance of the objects (stability of the object position and orientation).
- Variation of gripping options, depending on the object mass, shape and size.
- Varying the holding force depending on the object mass.
- Less installation space and low weight, durability.
- High reliability combined with easy service.
- Prevention of damage and deformation of the object during the grasping process.
- Sufficiently high positional accuracy of grasped objects.
- Good wear resistance.
- Easy to operate and short cycle times.

Other very specific requirements include:

- Ability to selectively access objects close to each other.
- Quick gripper replacement.

In order to achieve the gripping force without damaging the surface different tribological tests were performed. Hereby, the friction of elastomers to rigid surfaces is determined.

Friction is the resistance to the relative motion of contacting bodies [3]. Friction can be divided into two types, the static friction and dynamic friction. Static friction is the kind of friction, in which no motion is present. A force that is greater than the static friction force is required for the start of a movement. If bodies move relative to each other, there is dynamic friction. The dynamic friction is the force that is required to support the movement. The static friction coefficient is generally greater than the coefficient of dynamic friction, but it can also be similar. [14]

These properties and the various gripping techniques should be taken into account in the development of a new gripping device.

### 4.2 Robot

The robot itself can be designed mechanical in any form, e.g. Cartesian robots if tipping is required and SCARA robots, if no tipping of the packaged good is required.

To ensure the safety of the robot, there are also several possibilities. The collaboration between humans and robots should be monitored in all cases by means of sensors. Furthermore, the speed and force of the robot should be limited in the collaboration zone, e.g. by a flexible structure. The person should be able to relieve himself against crushing in any case. Moreover, there are further steps for the creation and retention of the safety. The robot can be separated of the environment on multiple sites with fences. The robot and the human should be monitored by sensors, and thus make the system more save, or it should be guaranteed that the robot is intrinsically save by his construction. [14]

The **sensors**, which provide the safety for the worker, must be selected carefully. These sensors have specific criteria based on the risk of the application (high, medium and low) satisfy: [15]

- For high-risk, only approved sensors are used which have a performance level (PL) of d, or e and a safety integrity level (SIL) of 2 or 3 and a type 3 or 4. Representatives of such devices are light curtains, laser scanners, safety mats, etc.

- For medium risks, sensors with a PL c, a SIL 1 and a type 2 are applied. This would include, for example, RFID tags and video cameras.
- For low risk, almost all other sensor types can be used.

People trust the safety devices and if a safety device fails it usually leads to a dangerous situation. Therefore, these devices must also work safely (fail-safe) if they have an error. If unreliable sensors are used for safety, some additional security measures are required. If two or more (different) sensors are used to monitor the same goal, the safety can be increased, especially if failures of the system are well supervised. However, when the heterogeneous sensor network or the processing of the resulting data is too complex, it may be very difficult in practice, to prove the safety of the whole system. [15]

The results of a market study for safe and reliable robot controls and robot arms are shown in Table 3. If the robot is intrinsically safe and should be certified, the measured values for the hazards must be smaller than the values mentioned above.

For the certification of a safe robot in a human-robot-interaction scenario two components in relation to the robot hardware are required. These are briefly described below.

Safe robot control [15]

- Axis specific and cartesian security areas.
- Redundant controlled position of the robot arm.
- Safely controlled velocity.
- Monitored security position of the robot arm.
- Monitored stopping.
- Controlled orientation of the tool.
- Self-Monitored robot control.

In an emergency, the system reboot must be performed. In order to automatically restart the system after an emergency stop, a modern security control (or an equivalent security device) in the control is necessary. Otherwise, a manual restart or some additional safety measures are needed.

Safe robot arm

- Redundant encoders on the axes.
- No areas with crushing, no sharp edges.

| Name of Company | Product name | Web link |
|---|---|---|
| FerRobotics | compliant lightweight robot arm ROMO | http://www.ferrobotics.at/ |
| KUKA | lightweight robot arm LWR | www.kuka-robotics.com |
| MRK Systeme | safe interaction SI | http://www.mrk-systeme.de/e_produkte_interaction.html |
| MRK Systeme | SafeGuiding | http://www.mrk-systeme.de/e_produkte_guiding.html |
| KUKA | KR C 4 | http://www.kuka-robotics.com/en/products/controllers/kr_c4/ |
| Universal robot | UR-6-85-5-A industrial robot | http://www.universal-robots.com |
| Neuronics | Katana Intelligent Personal Robot (IPR) | http://www.neuronics.ch/ |

Table 3: Results Market Study Safe Robots and Controller.

- A compliant, flexible robot arm.
- Robot as a manual manipulator (similar to gravity compensation) performed by the worker.
- Separation of vertical and horizontal movement -> horizontal movement without high force.
- Stopping the robot without high force.

In general, the weight of the moving masses should be as small as possible in order to reduce the impact forces. [15]

## 5 REALISED SYSTEM

In this part the different concepts are reduced to one solution regarding the choice of products. The products used in the project are TV-sets. Therefore the gripping mechanism and the robot are developed. The target of universality and flexibility are also taken into account.

### 5.1 Gripper

In Figure 2 the developed mechanical gripper is visible. Gripping different TV-sets results in a impactive gripper. This form of gripper should be flexible in two directions to handle different sizes of TV-sets. Therefore the gripper consists of four fingers, which can be moved by three linear motors. The gripping area covers all (closely) rectangular objects, which have at least one gripping side that is less than 1000 mm. [16]

Figure 2: Developed gripper [16].

The fingers have rubber lips to ensure the gripping force and to avoid damage of good and human. Rubber friction is caused by adhesion and deformation. Adhesion is referred as a surface effect, and occurs during the making and breaking of bonds at the molecular level. The deformation, which is referred as hysteresis friction, is caused by the delayed reset (viscoelastic behaviour) of the deformed rubber. The energy is discharged through the internal damping in the rubber, and is therefore referred as a material property. Nevertheless it is regarded as a resistance force of the movement at the interface between two bodies. [14]

The static friction of the rubber is not that strong compared to dynamic friction. Most references describe experimental studies, but none of them gives a full explanation for the mechanism of static friction [17]. Some experiments were carried out by Barquins [18] on hemispherical glass samples in contact with soft elastomer samples. The creation of the contact area has been recorded by means of a camera, which was mounted on an optical microscope. The superposition of the images showed a contact surface which has a central, adhesive zone, which is surrounded by a ring of slip.

The experiments of Adachi et al. [19] with rubber balls in contact with glass plates also showed the occurrence of partial slip and its increase with increasing tangential force. The static friction force was investigated by Roberts and Thomas [20] for smooth rubber hemispheres in contact with glass plates. Their experiments with (soft) rubber suggest that the size of the static friction force is related to the deformation of the rubber before elastic instabilities appear. [14]

Static friction of polymers is not examined in detail [14]. However, the data in the literature shows that the static friction is affected by various parameters such as pressure, displacement and micro-roughness [17].

Gripping experiments have shown that masses up to 30 kg can be handled without problems. Higher masses have not been tested yet. [16]

To ensure the safety of the gripping process ultrasonic sensors are mounted between the fingers, which can detect slippage of the grasped object and in case of slippage increase the gripping force. Furthermore, a so-called safety bumper is mounted on the housing of the gripper, which is directly connected to the safety controller, and prevents further movement of the robot. In an emergency stop, the gripper is not opened, it maintains in its position. [16]

For quick removal of the gripper a quick gripper changing system is mounted on the robot. The gripping strength and positions can be specified of the control depending on the object. Proper monitoring of the gripping force can avoid damage of the grasped object. [16]

### 5.2 Robot

TV-sets will need no tipping while packaging. Therefore the robot consists of a linear axis, three rotational joints and a flexible flange, the so called active contact flange. The movement is thus divided into a vertical and a horizontal movement. The working area of the robot arm is 1300mm, depending on the size of TV-sets. The horizontal movement is safe due to the low performance of the motors. Similarly, in an emergency by a small force on the robot, an emergency stop is caused. The flange is used for gravity compensation. Furthermore, it can minimize the collision in the vertical direction in the automatic mode and serve as guidance for the linear axis in the manual mode. [14]

Generally it has been attempted to keep the speed and power as low as possible. The robot is free in an emergency, so that the worker can free himself in an emergency. The linear axis is controlled via two speed sensors and two brakes stop the axis in an emergency.

The shape and the structure of the robot were built up with no sharp edges and no clamping positions.

## 6 SUMMARY

Finally it shows that the robot system, consisting on robot and gripper, is capable to handle mid to upper sized heavy electronic consumer goods. Concepts on the safety of the linear axis have to be developed and partly installed. Afterwards some additional safety measurements have to be done in the further work regarding the robot and the gripper and also some gripping tests have to be carried out with more weight. Finally the cycle time has to be measured and the potentials of the human-robot-collaboration and the division of the work to human and robot should be carved out.

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# Singularity Analysis for a 6 DOF Family of Robots

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**Abstract**

Path planning for serial 6 degree of freedom (DOF) robot based systems is challenging due to their kinematic structure, the behaviour of robot based on the configuration, and singularity conditions. Understanding the singularity conditions and zones is critical for both single robot applications, and robot cells. Visual representations of singularity zones will help process designers develop valid travel paths and layout designs. MATLAB tools are employed to represent the singularity zones using fundamental kinematic equations. The target application for this research is the FANUC family of serial 6 DOF robots, and the identified singularity regions are plotted in 2D and 3D Cartesian space.

**Keywords:**

FANUC Serial 6 DOF robot; Singularities; Analytical method; Geometric representation

## 1 INTRODUCTION TO ROBOTIC PATH PLANNING ISSUES

Path planning for serial 6 degree of freedom (DOF) robot based systems is challenging due to their kinematic structures, the robot behavior due to the robot's configuration, and singularity conditions. The American National Standard for Industrial Robots and Robot Systems — Safety Requirements (ANSI/RIA R15.06-1999) defines a singularity as "a condition caused by the collinear alignment of two or more robot axes resulting in unpredictable robot motion and velocities." [1] Understanding the singularity conditions and zones is critical for both single robot applications, and robot cells. Research in this area expanded in the 1980's, as researchers were developing control algorithms [2 – 5]. A visual representation of these zones will help process designers develop valid travel paths in a timely fashion. Additionally, designers will be able to develop travel paths in regions that are insensitive to singularities when modifications due to (i) in field adjustment, (ii) new product changes, or (iii) modifications due to a new kinematic structure are required. It is known that when utilizing standard industrial serial DOF robots, the alignment of joint 5 must not be collinear with joints 4 and 6. The impact of the other joints on a singularity condition is not as clear cut, but the other joints and their physical configurations impact the singularity regions. These regions need to be identified both analytically, and graphically. Although the determinate of the Jacobian matrix can be numerically resolved for a desired point (position and orientation) to determine whether it is equal to 0 or not, to identify a singularity region without performing a multiple point by point check throughout the workspace or along a given travel path requires a different approach. The target application for this research is the FANUC family of serial 6 DOF robots. A virtual design of experiments (DOE) approach is taken to identify joint parameter interactions. Selected results including the link lengths, offsets, and joint angles are presented and the identified singularity regions are plotted in Cartesian space using MATLAB tools.

The goal of this research is to provide a foundation for representing singularity regions geometrically for a robot, and a robotic cell. These defined problematic regions can be utilized in layout designs, and optimizing the travel paths. Alternatives for a new product, cell configuration, or modification to the base robotic structure can be readily anticipated and changes evaluated.

## 2 REPRESENTATION OF SINGULARITIES

### 2.1 Jacobian Analysis

Per ANSI/RIA R15.06-1999, a singularity occurs when two or more robot joints are pointing in the same direction. This means that a position has multiple solutions, which causes problem for motion in certain directions. These are robot positions that are referred to as singularities or a degenerate condition. Examples of singular configurations for a serial manipulator with $n \leq 6$ revolute joints occur when:

- Two joints in a concurrent 3-joint spherical wrist assembly are collinear, so that instantaneous rotation is only possible about axes in a plane through the wrist centre—a wrist singularity
- Three joints are coplanar and parallel, so that the three joints instantaneously permit only rotation about one axis and translation perpendicular to the common plane—an elbow singularity. [6]

The Jacobian matrix is calculated for the standard 6 DOF family of robots with all joints being rotational joints. This type of kinematic structure consists a 3-DOF forearm with a 3-DOF spherical wrist. The Jacobian matrix has been calculated for the standard Fanuc kinematic structure. The selected Fanuc robots for this research are: ARCMATE100, ARCMATE 120, ARC MATE 120IL, M6I, M-16IL, M710I, S6, S400, S420FD, FANUC_S430IW, and the S500. Based on the Fanuc 6R robot kinematic similarities, the general kinematic structure is generated and presented with its Denavit–Hartenberg (D-H) parameters can be expressed as shown in Figure 1 [7]. The Jacobian (a $6\times 6$ matrix) for the Fanuc kinematic structure needs to be calculated. This robot is in the singular position if and only if the equation (1) is true.

$$\det(J) = 0 \tag{1}$$

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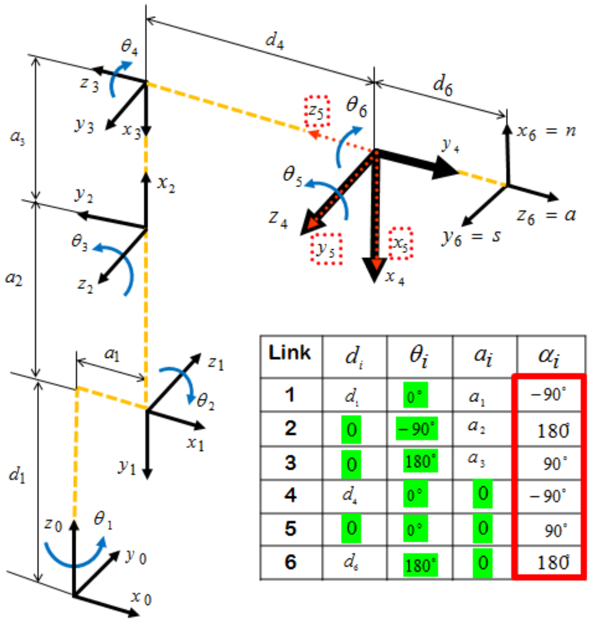



| Link | $d_i$ | $\theta_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $d_1$ | $0^\circ$ | $a_1$ | $-90^\circ$ |
| 2 | 0 | $-90^\circ$ | $a_2$ | $180^\circ$ |
| 3 | 0 | $180^\circ$ | $a_3$ | $90^\circ$ |
| 4 | $d_4$ | $0^\circ$ | 0 | $-90^\circ$ |
| 5 | 0 | $0^\circ$ | 0 | $90^\circ$ |
| 6 | $d_6$ | $180^\circ$ | 0 | $180^\circ$ |

Figure 1: Fanuc 6R family kinematic structure.

In order to simplify the singularity analysis, the Jacobian matrix $J$ can be divided into four blocks of 3x3 matrices.

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \tag{2}$$

The equation (3) represents a relationship between the joint rates and end-effector velocities of Fanuc model, and can be written as:

$$\dot{X}_E = J_E \dot{\theta} \tag{3}$$

The end-effector center $E$ is presented with the position vector $p_E$ , while the center of the spherical wrist $W$ is presented with vector $p_W$ , (Figure 2).

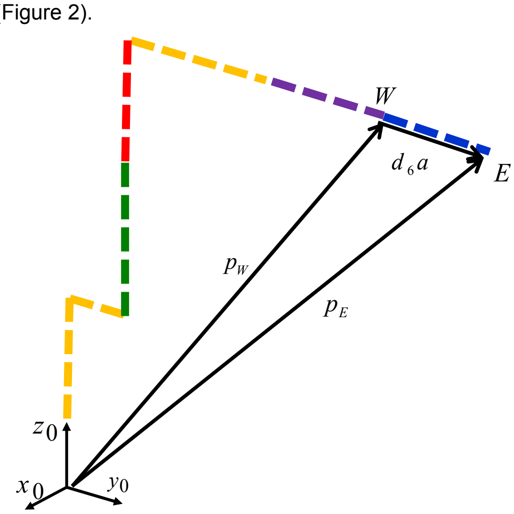



Figure 2: Position vector $p_W$ for spherical wrist robots.

If the velocity reference point is selected at the center of the wrist, then the relationship between the joint rates and the velocity of the wrist becomes:

$$\dot{X}_W = J_W \dot{\theta} \tag{4}$$

Referring to Vassilios D. Tourassis, et al., [8] and Fan-Tien Cheng, et al., [9], the Jacobian matrix $J_W$ will have the block triangular form:

$$J_W = \begin{bmatrix} J_{11} & 0_{3\times3} \\ J_{21} & J_{22} \end{bmatrix} \tag{5}$$

The Jacobian matrix for the general Fanuc model has been calculated using the Recursive Newton-Euler method.

From to Orin, et al., [10] the determinant of Jacobian is independent of the velocity reference point selected. From this conclusion the following equation can be written:

$$\det(J_W) = \det(J_E) \tag{6}$$

Manipulating equations (5) and (6) generates:

$$\det(J_W) = \det(J_{11})\det(J_{22}) \tag{7}$$

From the equations (1) and (7), the condition of singularity of the general Fanuc 6Rmodel can be decoupled into two determinates:

$$\det(J_{11}) = 0 \text{ and } \det(J_{22}) = 0 \tag{8}$$

The forearm singularities can be identified by checking the determinant of the matrix $J_{11}$. This produced two conditions, for forearm singularities. One is for boundary singularities, equation (9):

$$C_b = a_3 \sin(\theta_3) + d_4 \cos(\theta_3) = 0 \tag{9}$$

and the other one isfor the interior singularities, equation (10):

$$C_i = -a_1 - a_2 \cos(\theta_2) - a_3 \cos(\theta_2 - \theta_3) + d_4 \sin(\theta_2 - \theta_3) = 0 \tag{10}$$

The wrist singularities can be identified by checking the determinant of the matrix $J_{22}$ . See equation (11).

$$\det(J_{22}) = -\sin(\theta_5) = 0 \tag{11}$$

This is true when $\theta_5 = 0$ , or $\theta_5 = 180^\circ$ , which physically means that joints 4 and 6 are aligned.

### 2.2 Graphical Approach

The equations for the graphical representation of the boundary and interior singularity conditions for the Fanuc family have been generated from equations (10) and (11) by solving them for $\theta_2$ and $\theta_3$ , which are presented in equations (12) and (13) .

$$\theta_2 = a\tan 2\left(\frac{-a_1 + a_2 + a_3\cos\theta_3 + d_4\sin\theta_3}{a_3\sin\theta_3 - d_4\cos\theta_3}\right) \tag{12}$$

$$\theta_3 = -a\tan 2\left(\frac{d_4}{a_3}\right) \quad (13)$$

Using MATLAB tools, for an incremental value of 10 for $\theta_4$, $\theta_5$, and $\theta_6$, at $\theta_1 = 0°$, *a* singularity region point set is derived for an ARC MATE 120i, where:

| $a_1$ | $a_2$ | $a_3$ | $d_1$ | $d_4$ | $d_6$ |
|---|---|---|---|---|---|
| 305 | 800 | **-75** | 700 | **-813** | **-100** |

This is illustrated in Figures 3 and 4.

From point set data, a heuristic is developed for the ellipisoid representation of the singularity region, where the center of the ellipsoid coordinates is:

$$X_{ellipsoid} = X_{\min} + \frac{1}{2}(X_{\max} - X_{\min}) \quad (14)$$

$$Y_{ellipsoid} = Y_{\min} + \frac{1}{2}(Y_{\max} - Y_{\min}) \quad (15)$$

$$Z_{ellipsoid} = Z_{\min} + \frac{1}{2}(Z_{\max} - Z_{\min}) \quad (16)$$

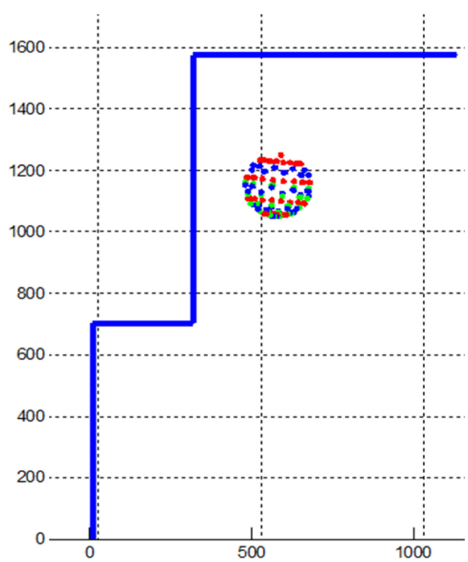


Figure 3: Ellipsoid shape generated for multiple end effector orientations (ARC MATE 120iL).

To represent a complete singularity region $\theta_1$ must be incremented between -180° to 180°. Again, an incremental value of 10 is utilized. The complete singularity region for the ARC MATE 120iL, which is essentially a torus at *z* = 1155.7, *sweep radius* = 565.6 external ellipse major axis $a_{xz}$ = 98.06, and the minor axis $b_{xz}$ = 97 and minor axis $b_{xy}$ = 98.2 which is illustrated in Figure 5.

Visualization of the boundary and interior singularity conditions has been done for selected Fanuc family robots, as shown in Table 1. It is evident that the *Z* height, the sweep radius, and singularity zone ellipse base dimension values are impacted by the base robot configuration.

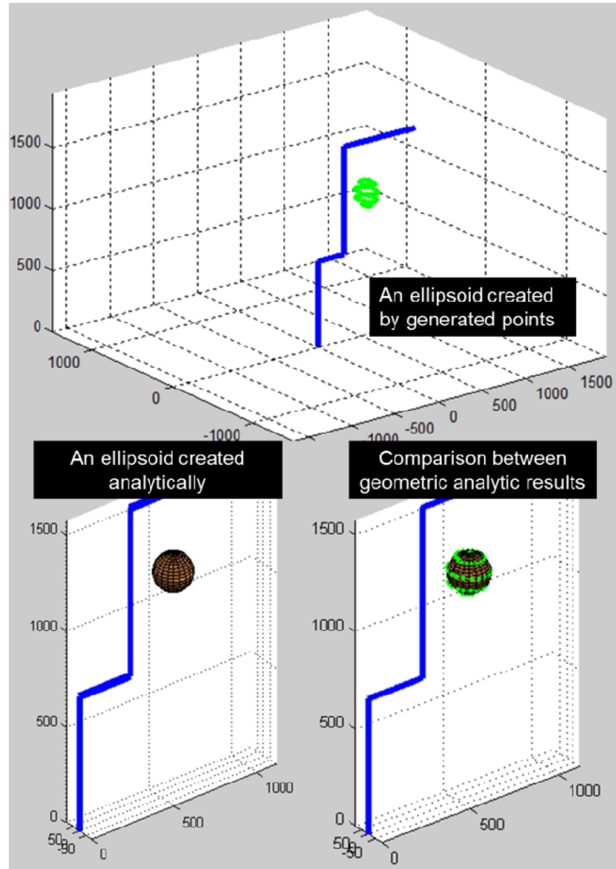



Figure 4: A comparison of the analytical and geometric singularity zones for one position (ARC MATE 120iL).

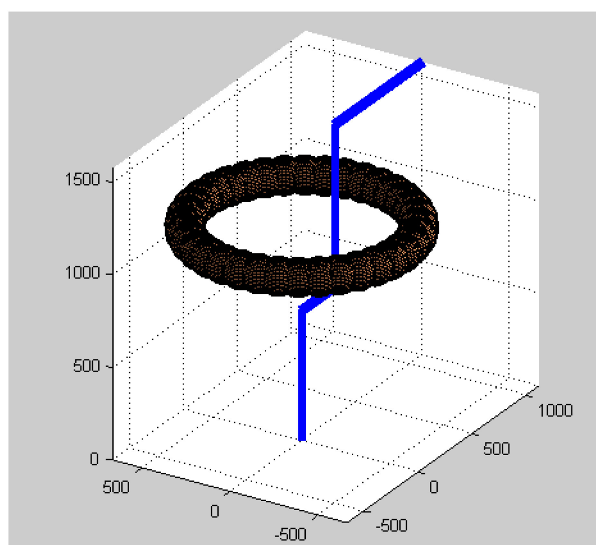


Figure 5: A complete singularity region for an ARC MATE 120iL.

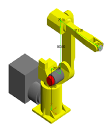
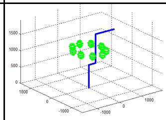
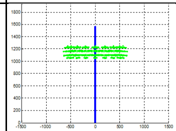
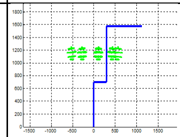
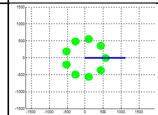
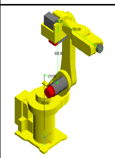
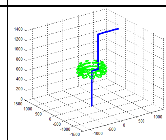
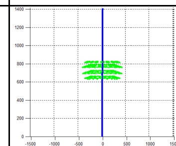
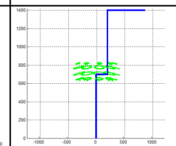
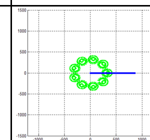
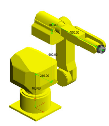
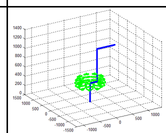
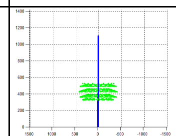
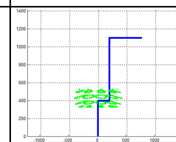
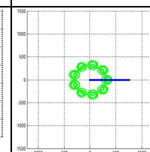
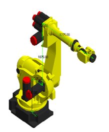
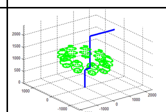
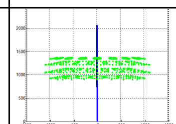
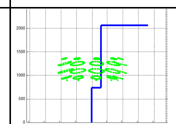
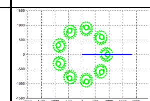
| FANUC robots | CAD Model | $a_1$ | $a_2$ | $a_3$ | $d_1$ | $d_4$ | $d_6$ | Singularity space | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Isometric view | Front view | Side view | Top view |
| ARC MATE 120iL |  | 305 | 800 | **-75** | 700 | **-813** | **-100** |  |  |  |  |
| M6i |  | 210 | 600 | **-100** | 700 | **-550** | **-100** |  |  |  |  |
| S6 |  | 210 | 600 | **-100** | 400 | **-550** | **-100** |  |  |  |  |
| S430iW |  | 305 | 1075 | **-250** | 740 | **-1275** | **-240** |  |  |  |  |

Table 1: Graphical representation of the singularity spaces for the Fanuc family 6R robots where the analysis increment is 10° throughout.

## 3 EXPLORATION OF THE EFFECTS OF LINK LENGTHS ON THE SINGULARITY REGION

Using the ARC MATE 120iL as a base, a series of virtual experiments are conducted to evaluate the impact of the joint lengths on the singularity regions. For Figures 6 the standard value for $a_1$ (305 mm) is shown in blue. In Figure 6, the values $a_1$ are incremented by 200 mm (green), which increases the *z* height of the region, and decreases the torus sweep radius in a non-linear relationship (Figure 7). The singularity cross section region remains constant. Decreasing $a_1$ shifts the singularity zone down, but the torus sweep radius is larger at *z* = 205, and then starts to decrease. As a different relationship was observed, decrements of 100 mm for $a_1$ are employed for Figure 8.

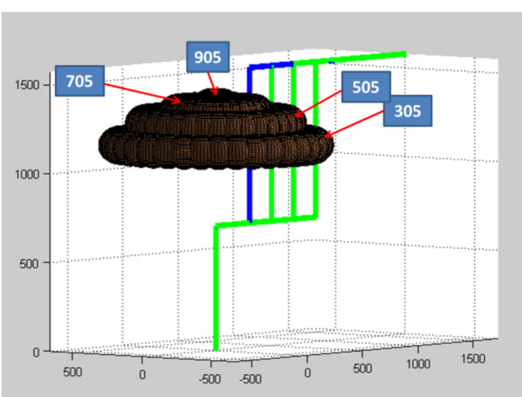



Figure 6: Increasing values for $a_1$ (305 mm – 905 mm).

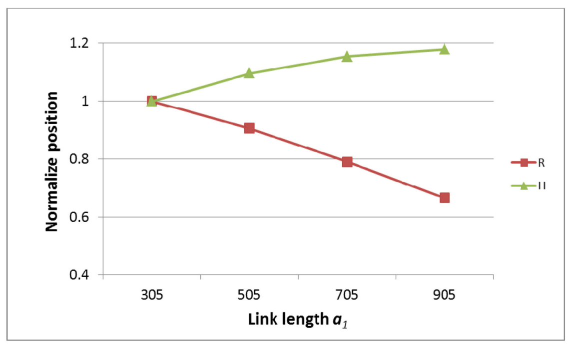



Figure 7: Relationship Increasing values for $a_1$.

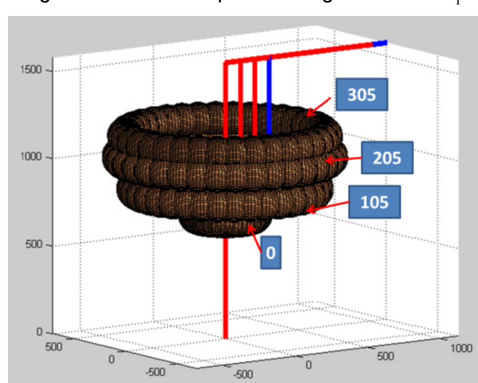



Figure 8: Decreasing values for $a_1$ (305 mm – 0 mm).

The $a_2$ link base value is 800 mm (blue geometry). This value is decremented by 100 mm (green geometry), which increases the *z* height of the region, and decreases the torus sweep radius (Figure 9). The opposite occurs when increasing link (Figure 10). As with $a_1$ the rate of change for the singularity region is different when incrementing and decrementing the values from the nominal value. Figure 11 illustrates modifying $a_3$ from -75 mm (base value) to +75, at 25 mm increments.

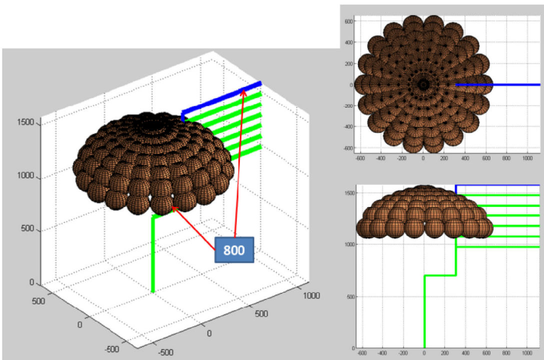



Figure 9: Decreasing values for $a_2$ (800 mm – 200 mm).

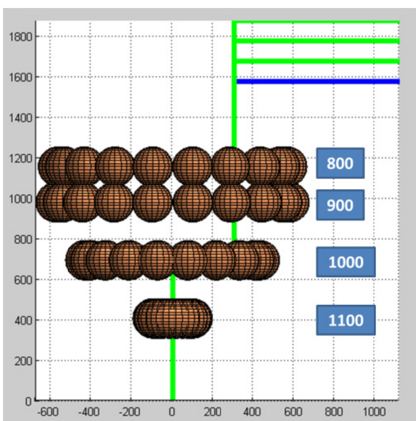



Figure 10: Various values for $a_2$ (1100 mm – 800 mm).

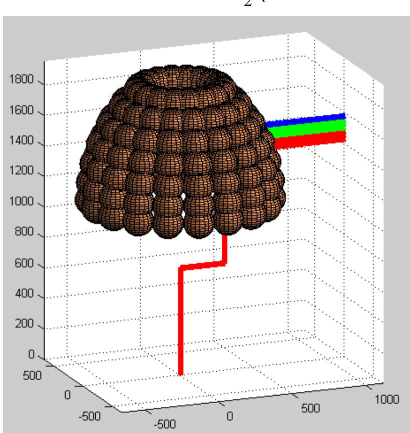


Figure 11: Various values for $a_3$ (-75 mm – 75 mm).

Changing the values of $d_4$ and $d_6$ also generated interesting results. The base value for $d_4$ is -813 mm. changing this value from -813 to 0 introduced a reciprocating type of pattern; hence, the two sets of pictures for Figure 12 for clarity. The singularity torus cross section is impacted by $d_6$ , which is shown in Figure 13.

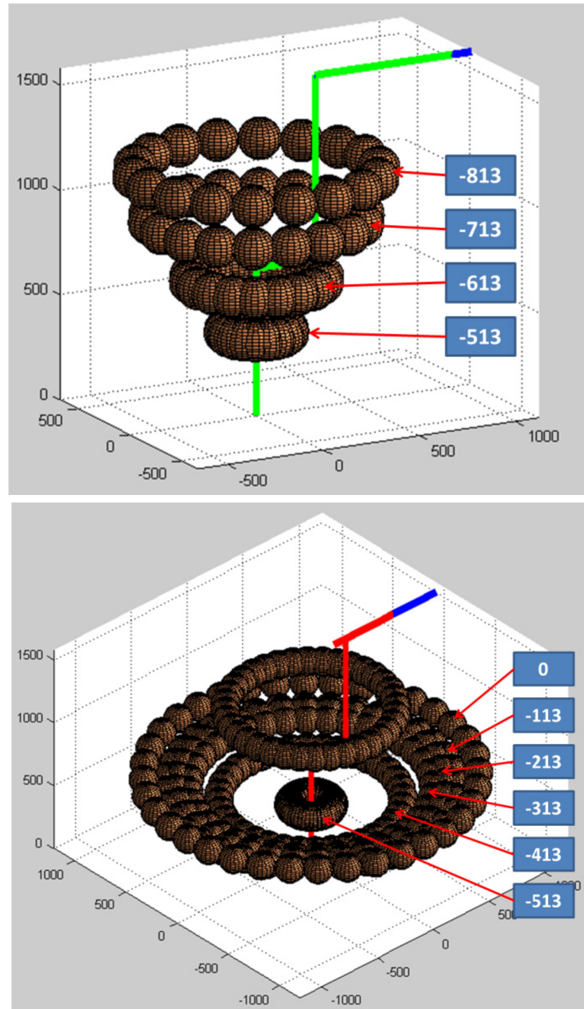



Figure 12: Various values for $d_4$ (-813 mm – 0 mm).

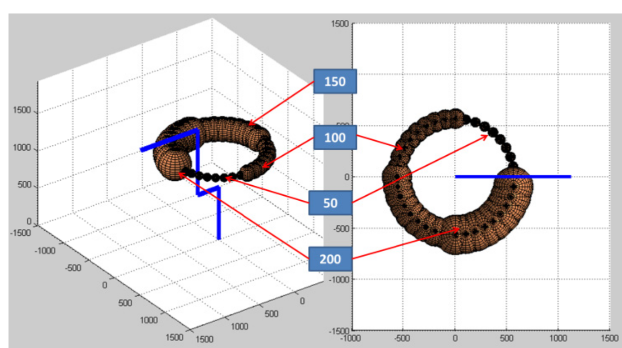



Figure 13: Selected values for $d_6$ (50 mm – 200 mm).

After modifying the individual link lengths, a Design of Experiments (DOE) approach is taken to assess the impact of changing multiple parameters on the singularity region. The first virtual experiment explored changing $a_1$ and $a_2$. Next four levels are chosen (Table 3) for the analysis, and a selected set of results in presented in this work (Table 3).

| $a_1$ | $a_2$ | **Colour** |
|---|---|---|
| 105 | 100 | magenta |
| 105 | 1100 | yellow |
| 305 | 800 | blue |
| 905 | 100 | green |
| 905 | 1100 | red |

Table 2: Two parameters that are simultaneously changed, and the associated link colours for Figure 14.

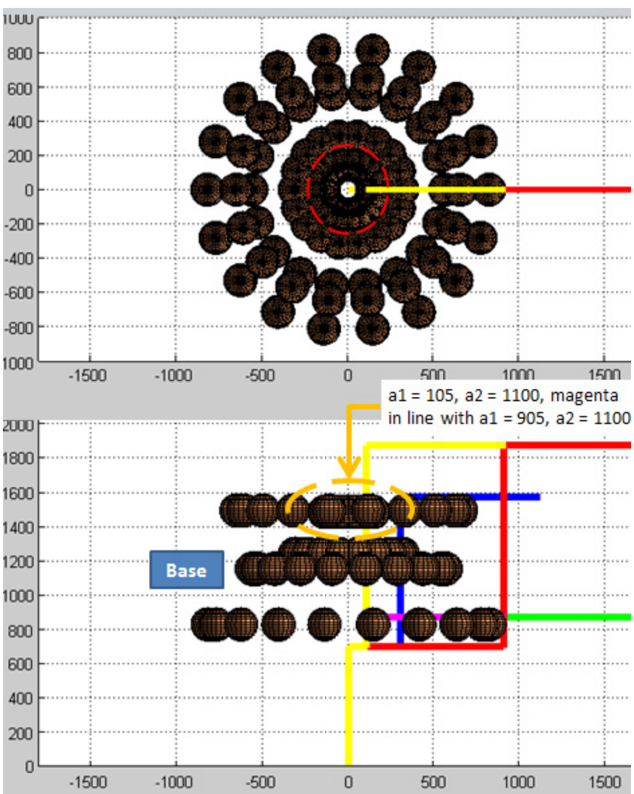



Figure 14: Singularity zones for set ups presented in Table 2.

| $a_1$ | $a_2$ | $a_3$ | $d_4$ |
|---|---|---|---|
| 105 | 100 | -300 | -813 |
| 305 | 800 | -75 | -400 |
| 905 | 1100 | 75 | 0 |

Table 3: DOE parameters and their values for the experiments.

## 4 SUMMARY

Path planning for serial 6 DOF robot based systems is challenging, and being able to visualize the singularity zones is critical both for designing functional travel paths for standard 6 DOF robots, and potential robot reconfigurations / structural modifications. Using fundamental kinematic equations and MATLAB tools, singularity zones are visualized for basic FANUC family robots, and variations of their link lengths. This foundational work will be extended to include other robot families and type of joints. This will then be incorporated as a robot selection, or robot design tool.

| **Configuration** | $a_1$ | $a_2$ | $a_3$ | $d_4$ |
|---|---|---|---|---|
| 1 | 305 | 800 | -75 | -813 |
| 2 | 105 | 100 | -300 | -400 |
| 3 | 905 | 100 | -75 | -400 |
| 4 | 105 | 100 | 75 | -400 |
| 5 | 905 | 1100 | 75 | -400 |
| 6 | 905 | 1100 | -300 | 0 |

Table 4: Selected DOE experiments.

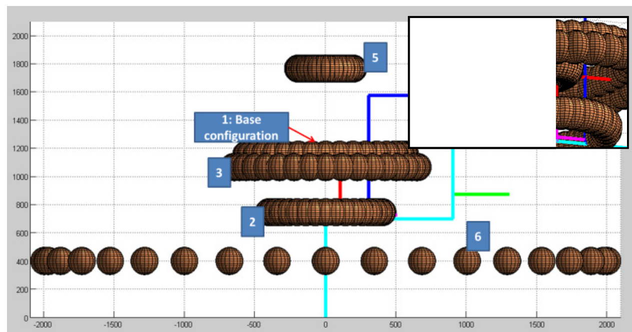



Figure 15: Singularity zones for set ups presented in Table 4.

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# Effective Work Region Visualization for Serial 6 DOF Robots

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**Abstract**

Optimal serial 6 degree of freedom (DOF) robot path planning has challenges due to the kinematic structures, singularity conditions, and the practical reach limits due to the a path-fixture-end effector orientation and design-robot structure combination. Previous research has been done to define and visualize the functional reach limits for a robot-end effector orientation-end effector tool geometry set. This is expanded and combined with singularity region analyses to be able to visualize the total effective travel path regions for a target application (i.e., FANUC, ABB, or Comau robot families) using the MATLAB toolbox. Visualization tools that represent both the functional work region or work window and singularity regions are presented. This research will provide designers the ability to assess a wide range of industrial robot configurations comprehensively at the design or redesign stages as the valid bounded region defined in this work can be employed for subsequent downstream optimization related to velocity and acceleration control.

**Keywords:**

FANUC Serial 6 DOF robot; Singularity visualization; Workspace; Work window

## 1 INTRODUCTION

Robotic systems are a core element for reconfigurable manufacturing approaches. Altering a base configuration introduces new processing opportunities [1], but changing a structure changes the operating conditions. The 'boundary of space' model representing all possible positions which may be occupied by a mechanism during its normal range of motion (for all positions and orientations) is called the work envelope. In the robotic domain, it is also known as the robot operating envelope or workspace [2]. Several researchers have investigated workspace boundaries for different degrees of freedom (DOF), joint types and kinematic structures utilizing many approaches [3-6].

A recent example utilizes a reconfigurable modeling approach, where the 2D and 3D boundary workspace is created by using a method identified as the Filtering Boundary Points (FBP) algorithm, [7]. In Djuric and Urbanic [8], the authors first defined the work window as the functional subset of the work space. Previous research investigations were on developing Jacobian by using different methods [9]. These methods are compared in terms of their computational efficiency since the Jacobian must be computed in real time for control. Using three different methods for calculating Jacobian of 6 DOF robots with rotary of sliding joints are presented by Fu et al. [10] and applied on the PUMA robot. By employing symbolic reduction techniques in conjunction with the separation of the resultant equations into on-line, temporary variables and off-line constraints, efficient formulations of the Jacobian, inverse Jacobian, and inverse Jacobian multiplied by a vector have been developed by Leahy et al. [11]. The Jacobian can be obtained by a simple methodology, as explained in reference [12], and studies related to the PUMA robot singularities have been analyzed [13-15]. An important step for the robot singularity analysis is task decoupling. This concept has been known since Pieper's pioneering work, [16] and a complete analysis of task decoupling has been done [17]. The structural synthesis and the singularity analysis of six different families of orthogonal anthropomorphic 6R robotic manipulators have also been presented [18]. The kinematics singularities of each family were analyzed and interpreted both algebraically and geometrically. The singular configurations of 6R robots with spherical wrist in general and the KUKA KR-15/2 industrial robot in particular, are analytically described and classified by Hayes et al. [19]. The symbolic inversion of the Jacobian matrix for the robots with spherical wrist has also been investigated and the examples were performed on a PUMA, Stanford and 6R joints coplanar robot [20]. Much fundamental work has been done for understanding and representing singularities. This can be expanded upon, and represented graphically. Denoting this information, along with the function reach regions, described next, would allow designers to select the total effective travel path regions for the target application, and provide a basis for subsequent downstream optimization related to velocity and acceleration control.

## 2 WORK SPACE OVERVIEW

For the workspace calculation, the first three joints are used. By varying their joint limits from minimum to maximum, the complete 3-D reachable workspace is described, and is shown in Figure 1.

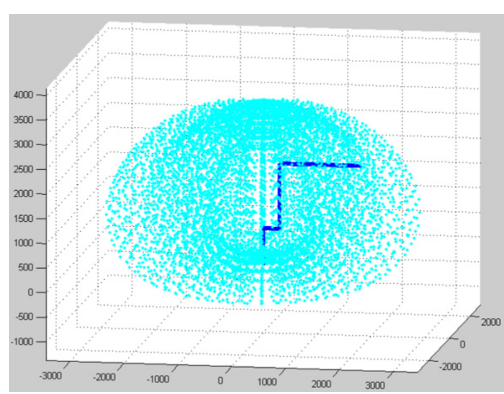


Figure 1: Point set representing 3D Workspace for a Linked configuration for a FANUC S430IF.

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Most of the 6R industrial robots have Joint 2 and Joint 3 linked. This condition is expressed with equation (1).

$$(\theta_2+\theta_3)\geq J_{23LIMIT\_min}\wedge(\theta_2+\theta_3)\leq J_{23LIMIT\_max} \tag{1}$$

Where $J_{23}$ is the minimum and maximum joint 2 and 3 linked limits, as defined by the robot manufacturer

This property will limit the workspace and make a change in the workspace shape, as shown in Figure 2.

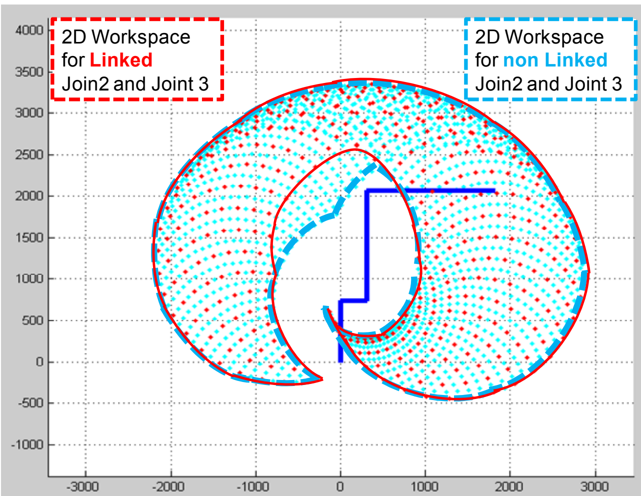



Figure 2: 2D Workspace for a Linked and non-Linked Joint 2 and 3.

## 3 WORK WINDOW ALGORITHM

The work window is defined as the valid functional space for a configuration to allow a kinematic structure (robot, machine tool, etc.) to follow a path for a set of conditions relating to the system configuration, , fixture location, desired end-effector orientation, and so forth [8]. A serial link manipulator is a series of links, which connects the end-effector to the base, with each link connected to the next by an actuated joint. The selected FANUC 6R robot family is selected to illustrate this methodology which kinematic structure and D-H parameters, [21], are shown in Figure 4.

A kinematic synthesis, where $\theta_4$ and $\theta_6$ fixed, is performed by Urbanic and Gudla [22]. $\theta_2$, $\theta_3$, $\theta_5$ are the key rotation angles being analyzed, and $\theta_1$, $\theta_4$, $\theta_6$ remain constant. $\theta_1$ is fixed for the two dimensional (2D) robot-tool-orientation solution, but can be rotated to provide the 3D solution. This approach essentially reduces the robot into a 4 bar linkage. However, disjoint functional work space regions will occur for specific robot structure-end effector orientations due to the $\theta_5$ joint limits. For a range of end effector orientations, the $\theta_{2max}$ limit cannot be reached, which essentially partitions the reachable regions. In Figure 3, the work space (phantom line), and the reachable boundaries are illustrated for an ABB IRB 140 robot, for the end effector pointing up and perpendicular to the ground. It can be seen that although the problem complexity has been reduced by constraining the system, the functional work space region is not intuitive to define, and with multiple end effector orientations, can be challenging to represent the total effective travel path regions. Consequently, analytical methods that complement the geometric approach have been developed.

If a coordinate frame is attached to each link, the relationship between two links can be described with a homogeneous transformation matrix using D-H rules, and they are named ${}^{i-1}A_i$, where $i$ is number of joints.

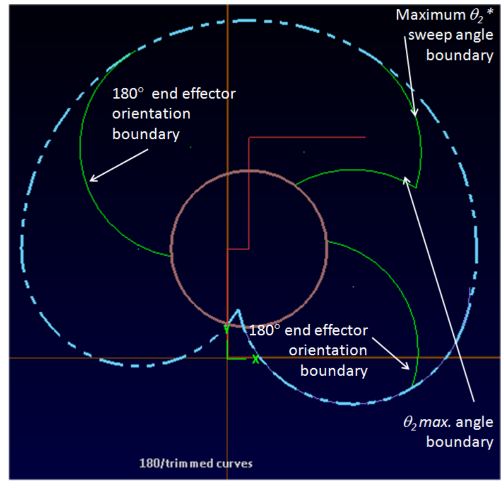


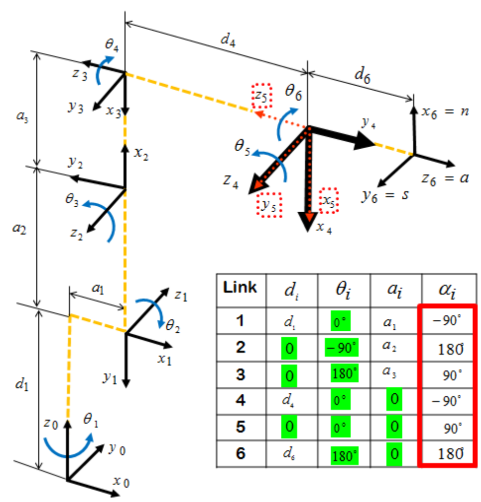

Figure 3: 2D disjoint functional work windows for an ABB IRB robot, for $\phi$ = 180° end effector orientation [22].

$${}^{i-1}A_i=\begin{bmatrix}\cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & a_i\cos\theta_i\\ \sin\theta_i & \cos\alpha_i\cos\theta_i & -\sin\alpha_i\cos\theta_i & a_i\sin\theta_i\\ 0 & \sin\alpha_i & \cos\alpha_i & d_i\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{2}$$

The robot can now be kinematically modelled by using the link transforms:

$${}^0A_n={}^0A_1\,{}^1A_2\,{}^2A_3\,{}^3\ldots{}^{n-1}A_n \tag{3}$$

Where ${}^0A_n$ is the pose of the end-effector relative to base; ${}^{i-1}A_i$ is the link transform for the $i^{th}$ joint; and $n$ is the number of links.




| Link | $d_i$ | $\theta_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $d_1$ | 0° | $a_1$ | −90° |
| 2 | 0 | −90° | $a_2$ | 180° |
| 3 | 0 | 180° | $a_3$ | 90° |
| 4 | $d_4$ | 0° | 0 | −90° |
| 5 | 0 | 0° | 0 | 90° |
| 6 | $d_6$ | 180° | 0 | 180° |

Figure 4: FANUC 6R family kinematic structure and D-H parameters.

For the FANUC 6R robot family, six homogeneous transformation matrices have been developed using Maple 16 symbolic manipulation software. The pose matrix of the end-effector relative to base is presented in equation (4).

$$ {}^{0}A_6 = \begin{bmatrix} n_x & s_x & a_x & p_x \\ n_y & s_y & a_y & p_y \\ n_z & s_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

The end-effector orientation is defined with the rotation matrix in equation (5).

$$ {}^{0}R_6 = \begin{bmatrix} n_x & s_x & a_x \\ n_y & s_y & a_y \\ n_z & s_z & a_z \end{bmatrix} \tag{5} $$

The orientation of the end-effector, relative to the robot base frame, is defined with the three vectors: $n$, $s$, and $a$. For the end-effector approach vector pointing down and up (Figure 5), the rotational matrix is given with equation (6).

$$ {}^{0}R_6 = \begin{bmatrix} \pm 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & \mp 1 \end{bmatrix} \tag{6} $$

The calculation of the 2D end-effector orientation is dependent on the three joint angles: Joint 2, Joint 3 and Joint 5. The formula for Joint 5 is generated by assigning initial values for the Joint 1, Joint 4 and Joint 6 in the forward kinematic solution. The rotational matrix in that case is calculated and shown in equation (7).

$$ {}^{0}R_6 = \begin{bmatrix} -\cos(\theta_2-\theta_3)\cos\theta_5 - \sin(\theta_2-\theta_3)\sin\theta_5 & 0 & -\cos(\theta_2-\theta_3)\sin\theta_5 + \sin(\theta_2-\theta_3)\cos\theta_5 \\ 0 & -1 & 0 \\ -\cos(\theta_2-\theta_3)\sin\theta_5 + \sin(\theta_2-\theta_3)\cos\theta_5 & 0 & \cos(\theta_2-\theta_3)\cos\theta_5 + \sin(\theta_2-\theta_3)\sin\theta_5 \end{bmatrix} \tag{7} $$

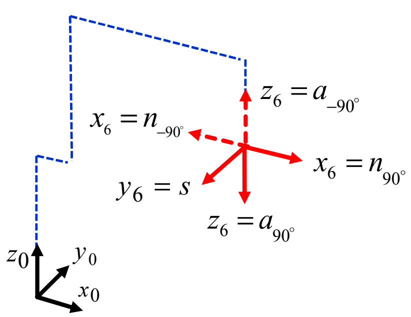



Figure 5: Relation between end-effector and base frames for the ABB 6R robot family.

By combining equation (6) and (7) the formula for the Joint 5 angle is generated.

$$ \theta_5 = a\tan 2\left( \frac{\sqrt{1 \pm \cos^2(\theta_2 - \theta_3)}}{\mp \cos(\theta_2 - \theta_3)} \right) \tag{8} $$

To be able to generate complete work window, the Joint 2 and Joint 3 angles must vary between their given limits for the desired increment value $\Delta$ and using the forward kinematic solution to generate the solution for Joint 5. The work window for the FANUC S430if robot with approach vector pointing normal (down or up) to the floor is given in Figure 6.

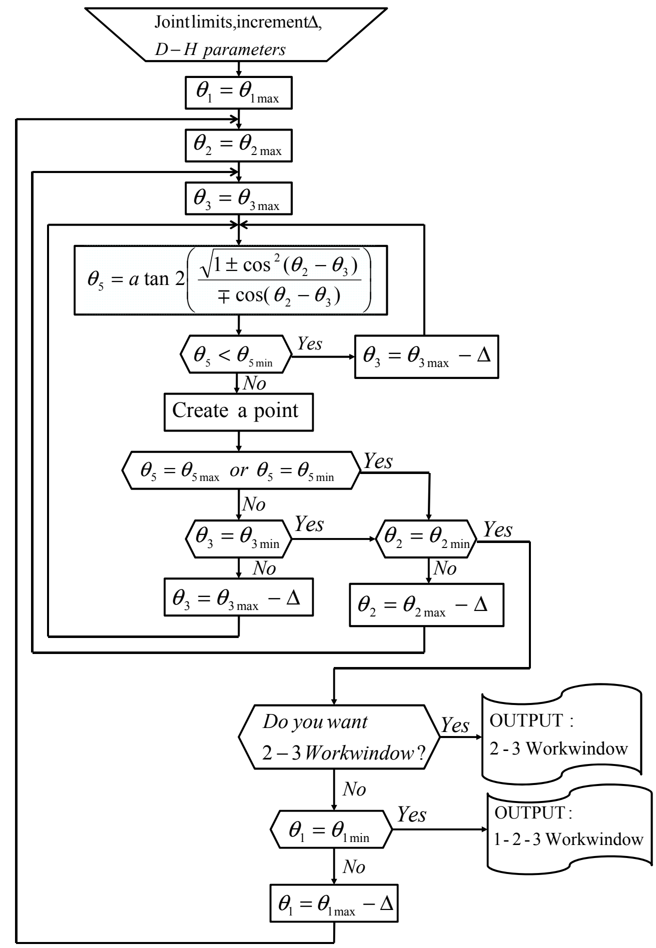



Figure 6: Work window generation algorithm (adapted from [8]).

Sample work window sets in combination with the work space are presented in Figures 7 and 8 for an ARC MATE 120iL, where the robot parameters are:

| $a_1$ | $a_2$ | $a_3$ | $d_1$ | $d_4$ | $d_6$ |
|---|---|---|---|---|---|
| 305 | 800 | -75 | 700 | -813 | -100 |

## 4 REPRESENTATION OF SINGULARITIES

### 4.1 Introduction to the Jacobian

Per ANSI/RIA R15.06-1999, a singularity occurs when two or more robot joints are pointing in the same direction. This means that a position has multiple solutions, which causes problem for motion in certain directions. These are robot positions that are referred to as singularities or degeneracy. The Jacobian matrix has been calculated for the standard 6DOF family of robots with all rotational joints. This type of kinematic structure consists of a 3-DOF forearm with a 3-DOF spherical wrist. In this case last three joints intersect in one point, i.e. the Pieper condition is satisfied (Figure 9).

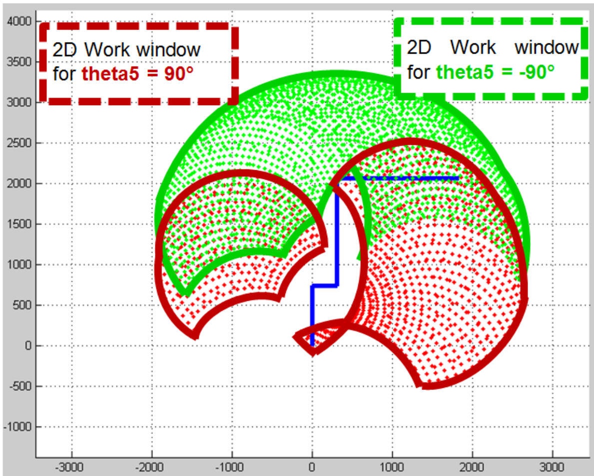



Figure 7: Work window for theta 5 = ±90°.

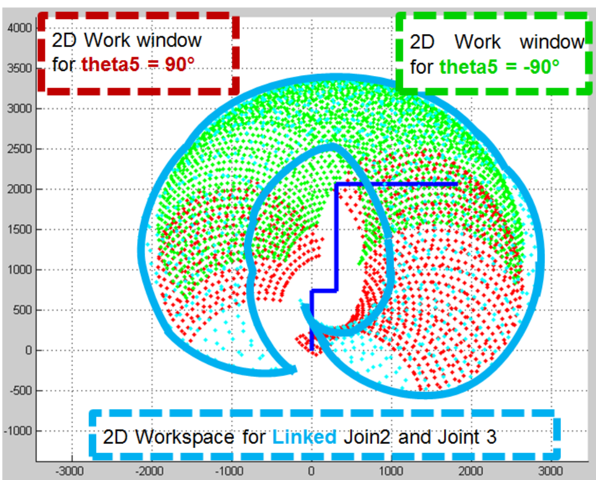
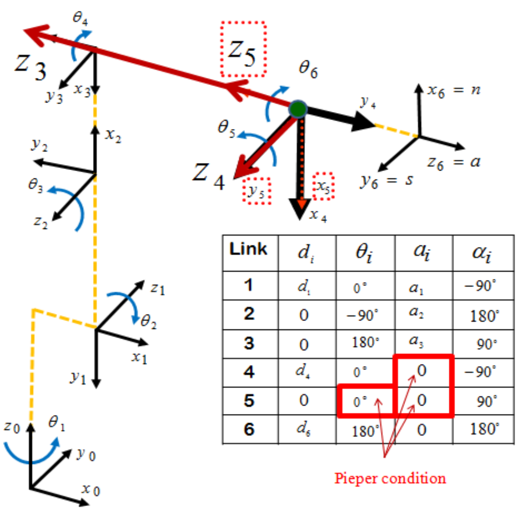



Figure 8: Work space and bounded regions based on end effector orientation theta 5 = ±90°.




| Link | $d_i$ | $\theta_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $d_1$ | 0° | $a_1$ | −90° |
| 2 | 0 | −90° | $a_2$ | 180° |
| 3 | 0 | 180° | $a_3$ | 90° |
| 4 | $d_4$ | 0° | 0 | −90° |
| 5 | 0 | 0° | 0 | 90° |
| 6 | $d_6$ | 180° | 0 | 180° |

Figure 9: Graphical presentation of the Pieper condition.

The Jacobian matrix has been calculated for the standard FANUC kinematic structure. The selected FANUC robots are: ARCMATE100, ARCMATE 120, ARC MATE 120IL, M6I, M-16IL, M710I, S6, S400, S420FD, FANUC_S430IW, S500. According to the FANUC 6R robot kinematic similarities, the general kinematic structure is generated and presented with its D-H parameters in Figure 8.

The Jacobian (a $6 \times 6$ matrix) for the FANUC kinematic structure needs to be calculated. This robot is in the singular position if and only if the equation (9) is true.

$$\det(J) = 0 \tag{9}$$

In order to simplify the singularity analysis, the Jacobian matrix $J$ can be divided into four blocks of 3 x 3 matrices.

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \tag{10}$$

The equation (4) represents a relationship between the joint rates and end-effector velocities of FANUC model, and can be shortly written as:

$$\dot{X}_E = J_E \dot{\theta} \tag{11}$$

The end-effector center $E$ is presented with position vector $p_E$, while the center of the spherical wrist $W$ is presented with vector $p_W$, (Figure 10).

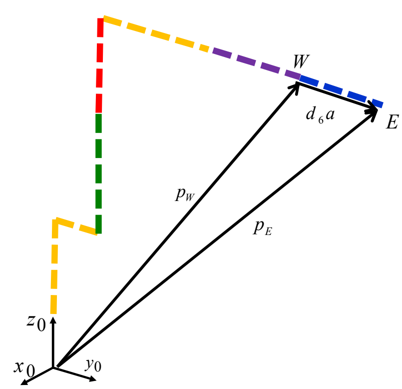



Figure 10: Position vector $p_W$ for spherical wrist robots.

If the velocity reference point is selected at the center of the wrist, then the relationship between the joint rates and the velocity of the wrist become:

$$\dot{X}_W = J_W \dot{\theta} \tag{12}$$

Referring to [17], the Jacobian matrix $J_W$ will have the block triangular form:

$$J_W = \begin{bmatrix} J_{11} & 0_{3\times3} \\ J_{21} & J_{22} \end{bmatrix} \tag{13}$$

The Jacobian matrix for the general FANUC model has been calculated using the Recursive Newton-Euler method.

Referring to [9], the determinant of Jacobian is independent of the velocity reference point selected. From this conclusion we can write equation (14):

$$\det(J_W) = \det(J_E) \tag{14}$$

From the equations (13) and (14) we have:

$$\det(J_W) = \det(J_{11})\det(J_{22}) \tag{15}$$

From the equations (9) and (15), the condition of singularity of the general FANUC 6Rmodel can be decoupled into two determinates:

$$\det(J_{11}) = 0 \text{ and } \det(J_{22}) = 0 \tag{16}$$

The forearm singularities can be identified by checking the determinant of the matrix $J_{11}$. This produced two conditions, for forearm singularities. One is boundary singularities, equation (17):

$$C_b = a_3\sin(\theta_3) + d_4\cos(\theta_3) = 0 \tag{17}$$

and the other one is the interior singularity, equation (18),

$$C_i = -a_1 - a_2\cos(\theta_2) - a_3\cos(\theta_2 - \theta_3) + d_4\sin(\theta_2 - \theta_3) = 0 \tag{18}$$

The wrist singularities can be identified by checking the determinant of the matrix $J_{22}$. See equation (19).

$$\det(J_{22}) = -\sin(\theta_5) = 0 \tag{19}$$

This is true when $\theta_5 = 0$, or $\theta_5 = 180^\circ$. Physically, this means that joints 4 and 6 are aligned.

### 4.2 Graphical Approach

The equations for the graphical representation of the boundary and interior singularity conditions for the FANUC family has been generated from equations (10) and (11) by solving them for $\theta_2$ and $\theta_3$. See equations (12) and (13).

$$\theta_2 = a\tan 2\left(\frac{-a_1 + a_2 + a_3\cos\theta_3 + d_4\sin\theta_3}{a_3\sin\theta_3 - d_4\cos\theta_3}\right) \tag{20}$$

$$\theta_3 = -a\tan 2\left(\frac{d_4}{a_3}\right) \tag{21}$$

## 5 RESULTS

### 5.1 Case Studies

To illustrate this work, different robot families and configurations were assessed. For the FANUC 430IF robot the workspace, work window for $\theta_5$ = 90°, and the singularity space is illustrated in Figure 11, where the singularity region is the torus. To compare to different robots families, and to determine a common region, the FANUC S430IF robot is overlaid with an ABB 2400-10, as shown in Figures 12 and 13. The main difference between the ABB family and the FANUC family relates to the physical structure of the second twist angle. For the ABB family $\alpha_2$ = 0°, and for the FANUC family, $\alpha_2$ = 180°. This configuration difference is parameterized within these methodologies, leading to quick results generation.

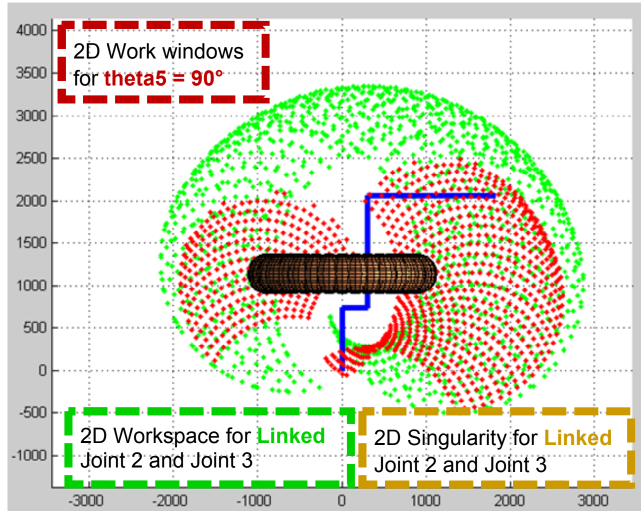



Figure 11: Work space, work window for $\theta_5$ = 90°, and singularity space for the FANUC S430IF robot.

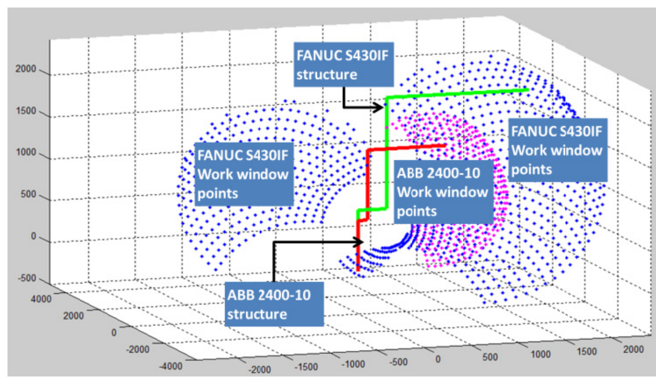



Figure 12: Work window for $\theta_5$ = 90° for the FANUC S430IF robot and ABB 2400-10.

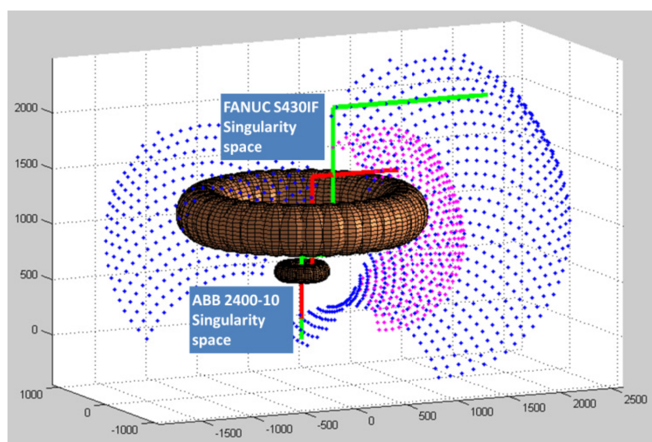



Figure 13: Work window for $\theta_5$ = 90° and singularity space for the FANUC S430IF robot and ABB 2400-10.

## 6 SUMMARY

Determining the total effective travel path regions for target applications utilizing 6 DOF robots is challenging as there are structure differences between robot families as well as the individual robots. However, prior to optimizing travel approaches, velocity, and acceleration control, or other optimization criteria, the designers need to know whether any given point can be reached for a robot-end effector orientation-end effector tool geometry set. This needs to be combined with singularity region analyses to be able to visualize the operative travel path regions. The singularity impact factors are not clearly defined except for the rule relating to the avoidance of collinear conditions for the last three joints, and visualizing the singularity regions has been done. The functional space or work window has been defined both geometrically and analytically. The work and singularity spaces are related to the kinematic structure, which is static. The work window is related to both the application and structure, and is dynamic and can include disjoint regions, which increases the visualization complexity. Using the presented methodologies, these issues have been overcome. The future work will include expanding on the 3D visualizations of the work window for various robotic structures which can be used to design / redesign complex robotic cells.

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# A Stepped Conveyor Singulator Design for Reconfigurable Assembly

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**Abstract**
Part singulation and feeding is an integral part of the automated assembly process. This paper presents a singulator designed for part feeding in dynamic manufacturing environments characterised by frequent product changeovers, where conventional, part specific singulators are not effective. The presented singulator design is intended for use in a reconfigurable assembly system. The important design considerations during the development of the singulator are discussed. The stepped conveyor singulator exhibits flexibility, since in a given configuration allows the singulation of a family of parts with similar envelopes, and reconfigurability, since it can be configured for the singulation of families of parts with different envelopes.

**Keywords:**
Assembly; reconfiguration; part feeding

## 1 INTRODUCTION

Niche markets are characterised by high product variety and low production volumes. For niche markets the utilization of traditional automation systems, designed for a narrowly defined part family, would be too low to be economically feasible. To achieve cost effective automation for niche markets, the assembly system must be able to handle more widely ranged product families. The Reconfigurable Manufacturing System (RMS) paradigm holds promise for the automation of assembly processes for niche markets since RMSs are designed to handle different product families through rapid reconfiguration.

A key function in many automated assembly processes is the automatic feeding of parts. Automated part singulators (or sometimes referred to as *feeders*) have to separate parts, from bulk storage of randomly orientated parts, and present them individually to a manipulation or fixturing device. The layout of the experimental RMS at the Automation Laboratory of Stellenbosch University is shown in Figure 1. An automated spot-welding process for electrical circuit breaker sub-assemblies is implemented by the RMS. The RMS includes a feeding subsystem (containing singulators and a pick-‘n-place robot) and a welding subsystem (containing a Cartesian welding robot). The product sub-assemblies are transported by a conveyor, while the sub-assemblies are held in fixtures which are mounted on the conveyor pallets. The pallets for various products are stored in a pallet magazine.

The feeding subsystem is schematically shown in Figure 2. Its operation is as follows: An operator loads parts from bulk bins into the singulation units' (SUs) input bins. Each SU takes parts from its input bin and presents them one-by-one for collection to a six degree-of-freedom pick-‘n-place robot. When the transport system has positioned a pallet (carrying a fixture) at the feeding station, the cell controller instructs the robot to pick up parts from the correct SUs and place them in the fixture. When all the parts have been placed, the feeder controller informs the cell controller and the pallet is moved to the next station in the cell.

Conventionally, automated part singulators are specialized, dedicated machines designed with a particular part in mind. For niche markets, where the introduction of, or the changeover between, part families occur frequently, conventional singulators are not feasible [1]. Modern manufacturing processes require feeders that can easily be reconfigured for subsequent or future production runs [2]. Adhering to the objectives of RMSs, their singulators have to be able to feed a range of parts with minimal ramp-up time and reconfiguration effort.

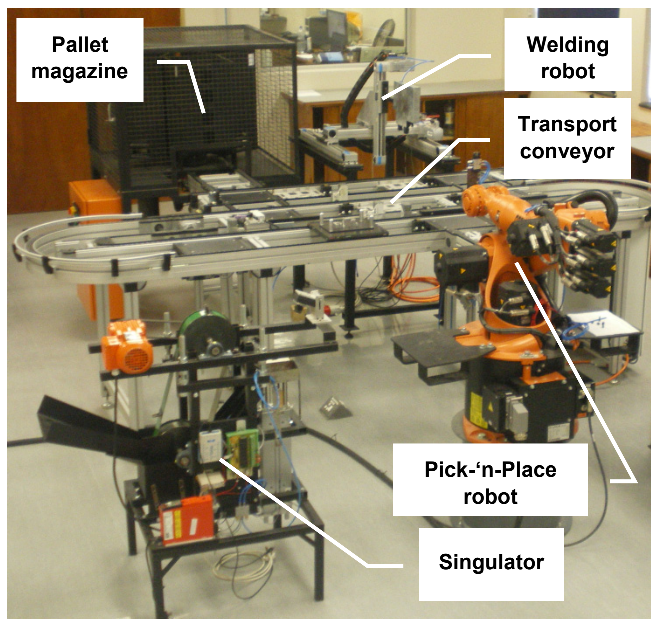


Figure 1: The experimental RMS at Stellenbosch University.

Many current singulators that are designed to feed several different parts, are called flexible feeders. It is thus important to clarify the meaning of flexibility and reconfigurability when referring to singulators. Wiendahl, et al. [3] explain that flexibility generally refers to fixed configuration and capability, where reconfigurability refers to changeable configuration and capability. In other words, flexible singulators are designed to feed a range of parts without changing the configuration. By adding reconfigurability to the singulator, possible changes in configuration may allow the feeding of a wider range of parts (even parts that were not considered during the design of the machine). In practice, reconfigurable singulators should ideally maintain some flexibility.

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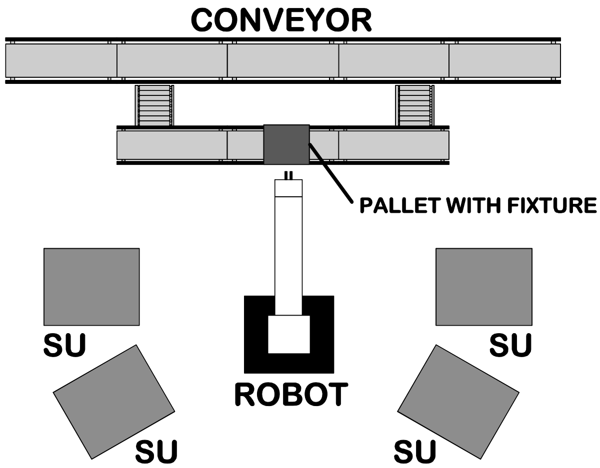


Figure 2: Layout of the experimental RMS.

A great deal of research has been conducted into the design and implementation of part feeders in the last few decades (e.g. [1], [2], [4] and [5]). Part feeders can be divided into two categories: non-vision based and vision based feeders [1]. With non-vision based, the feeding and orientating of parts is done by means of simple sensors and reconfigurable mechanical escapements. Vision based feeders make use of a vision system to control the feeding and determine the orientation of parts [1].

Non-vision based singulators are simple, inexpensive solutions for the singulation of geometrically simple parts [6]. However, the fixed design of non-vision based singulators restricts the variety of parts which can be singulated. The reconfiguration of such singulators may involve the replacement or alteration of orientation mechanisms and the relocation of position sensors. These reconfigurations will also have to be accompanied by online testing, performed by a skilled and experienced operator, to ensure desired performance – a process which increases ramp-up time. Vision based singulators offer more flexibility with regards to part orientation and can thus singulate a wider family of parts. This increased flexibility comes with a cost – reconfiguration requires calibration and training of the vision system (which can often be done offline) and a multi-degree-of-freedom articulated robot is often required to utilize the flexibility of the feeder. The computation time and control complexity of the vision system and the robot also increase with an increase in geometrical part complexity [6].

The most common singulator concepts are based on vibratory bowls. Conventional vibratory bowl singulators have become an integral part of assembly processes for mass production, but are infeasible for use in batch production [2]. This is due to their lack in flexibility – changeovers between parts require long ramp-up times. The singulators are not only limited by part shape, but also part weight and size [7]. Maher [2] describes research into automated, flexible vibratory bowl singulators.

This paper describes the design and evaluation of a reconfigurable singulator, based on the stepped conveyor concept. The specifications, with consideration of the properties RMSs, are discussed first and the concept is then explained. Finally, key aspects of the design are evaluated and discussed.

## 2 DESIGN REQUIREMENTS

Boothroyd, et al. [8] compiled a set of performance requirements for singulators, of which the following are relevant to the development of the stepped conveyor singulator:

- The restricted feed rate of the singulator should not vary widely.
- The mean unrestricted feed rate must not fall below the output rate of the machine being fed.
- The singulator must be designed to eliminate the possibility of parts jamming in its orienting devices.
- The singulator must ensure minimal damage to the parts being singulated.
- The singulator must operate as quietly as possible.

Beyond these requirements, the following set of design requirements was developed according to the specific needs of the RMSs:

*Reconfigurability*

The singulator had to be reconfigurable, i.e. the components of the singulator had to be modular so that they can easily be interchanged to allow for the singulation of new parts. The singulation process may not be part-specific, i.e. the design may not be dedicated to a single part.

*Flexibility*

The singulator design had to exhibit some flexibility. The singulation process had to be part-size specific, rather than part-shape specific – this would allow the singulation of parts of similar size without having to reconfigure the singulator. The position of key singulator components should be adjustable to allow for the refinement of the singulation process.

*Part Presentation & Rejection*

The experimental feeder subsystem (Figure 1) requires the singulator to present the parts to a pick-‘n-place robot. To allow for manipulation by the robot, the presented part must be in a collectable orientation and pick-up position must allow for unobstructed access by the robot. Parts which are observed to be in an uncollectable orientation must be rejected, thus clearing the presentation platform.

*Batch Volume*

The parts which are to be singulated are stored in bulk containers holding one hundred individual parts in the experimental RMS. The singulator design thus had to be capable of handling between 20 and 120 parts during the singulation process.

*Throughput*

The singulator must be capable to present a collectable part every three seconds to match the cycle times of the other systems. Parts which were detected in an uncollectable pose had to be rejected.

## 3 CONCEPT DESIGN

The singulator design presented here (Figure 3) is based on the “stepped-conveyor” concept. The preliminary concept design was performed by Poletti [9] and the further design refinements and testing was done by Kruger [10].

Figure 4 illustrates the operation of the singulator. The parts to be singulated are located in the input bin – the position is indicated in Figure 4 by a red, dashed line. The conveyor pulleys are driven in the clockwise direction, causing the conveyor steps to move through the input bin. The steps then scoop individual parts – these parts are carried along the path indicated in Figure 4 with red arrows. The parts are carried up by the steps to the top conveyor pulley, from where they drop into the gateway mechanism. The gateway mechanism channels the parts either onto the presentation platform or into a rejection chute. The singulator is fitted with a camera to detect and inspect parts on the presentation platform. According to the result of the optical inspection, the parts can be presented for collection or rejected, by the upward or downward motion of the guided cylinder (illustrated with a bi-directional arrow in Figure 4).

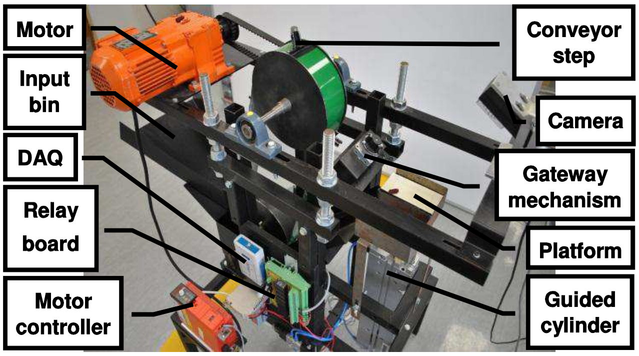



Figure 3: The stepped-conveyor singulator.

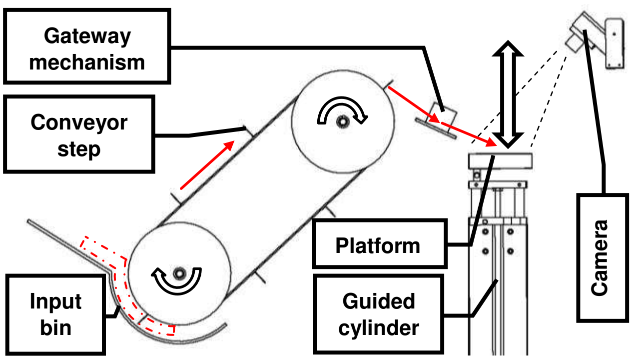



Figure 4: The operation of the singulator.

When in operation, the camera continuously checks the presentation platform for the presence of a part. When a part is detected, the camera signals the controller to change the direction of the gateway mechanism (so that parts are channeled to the rejection chute) and performs an inspection to determine whether the part is in a collectable pose. If the part cannot be picked up by the robot, or if multiple parts are present, the platform is lowered and the part(s) are rejected back to the input bin. This rejection is done by lowering the presentation platform (as described in Section 4.4), where a stationary pin tilts the hinged platform, causing the part to fall down the rejection chute. The platform is then returned to the middle position and the singulation process is continued. In the case of a collectable part, the camera sends the pickup coordinates to the controller and the presentation platform is lifted for the pickup action of the robot, as discussed in Section 4.4. After the part has been picked up, the platform is lowered to the middle position and singulation can resume.

The actuators and sensors used are as follows: the upper pulley of the SU's conveyor is driven continuously by an AC motor through a toothed belt. The gateway mechanism uses a pneumatic swivel unit – this actuator causes the rotation of a deflector plate. The motion of the presentation platform is provided by a guided linear pneumatic cylinder. The position of the platform is monitored by using two proximity switches – one for the *home* position (the position of the platform when awaiting parts from the conveyor) and one for the *rejection* position (the position of the platform when a part is rejected). The camera used in the work described here is a DVT Legend 530 camera with an Ethernet interface to the PC controller.

The actuators of the singulation unit are controlled via the digital outputs of an Eagle µDAQ-lite (data acquisition) device (commonly referred to as a DAQ), connected to a PC. The 5 V digital outputs of this device are used to switch the relays of an Eagle relay board, to which the 24 V actuator inputs are connected. The digital outputs of the DAQ device control the motor, the direction of the gateway mechanism and the motion of the guided cylinder. The digital inputs of the DAQ device are used to read the status of the proximity switches, thus monitoring the position of the guided cylinder.

## 4 DEVELOPMENT AND TESTING

This section describes various important design considerations encountered during the development and testing of the stepped-conveyor singulator.

### 4.1 Step Design

The design of the conveyor steps greatly influences the performance of the singulator. The throughput rate of the singulator largely depends on the ability of the steps to scoop a single part from the input bin. The design of the steps must avoid scooping multiple parts, but still provide the greatest chance for scooping one part with each conveyor cycle. The design must also strive not to be part-specific, as this would directly decrease the flexibility of the singulator. Figure 5 shows a conveyor step holding two parts with similar envelopes.

Initially flat steps were tested in the development, but this shape was found to be inefficient: if the steps are narrow enough that not more than one part is picked up, then the part often falls off the step. The step shape shown in Figure 4 was arrived at through trial and error. The rounded leading edges were found to be necessary to avoid damaging the parts when the step moved through the input bin.

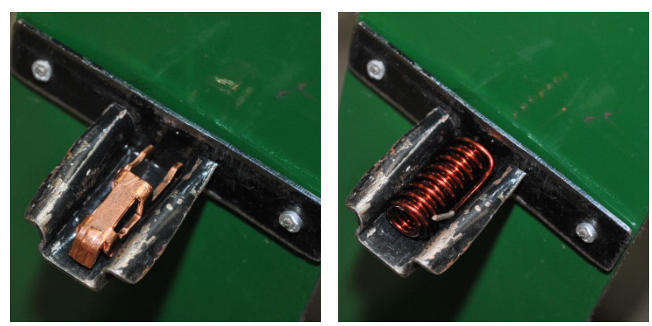


Figure 5: The conveyor step holding two similarly sized sub-assembly parts.

### 4.2 Input Bin Design

The design and manufacture of the input bin is very important, as unpredictability of the pickup action from the input bin reduces the consistency, and thus the throughput rate, of the singulator. The bin must be made to closely follow the circular path of the conveyor steps, to avoid jamming of parts in the bin. Jamming becomes a serious problem if the parts to be singulated are delicate or subject to tight tolerances.

### 4.3 Part Inspection

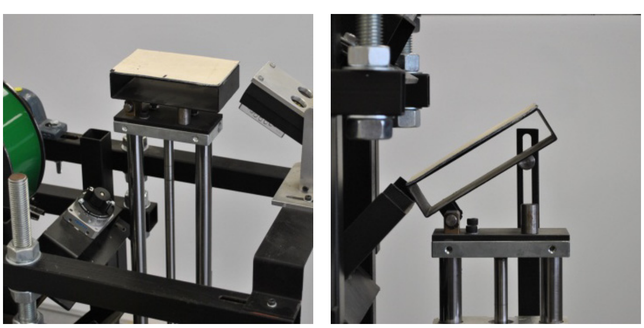
As shown in Figure 3, in the current configuration the camera's view direction is not perpendicular to the presentation platform so that the platform can be lifted above the camera's height, thereby providing maximum access to the robot that has to pick up the part. This location of the camera does not allow an optimal inspection setup. It adds complexity to the identification and location of parts, since part features may be obscured, depending on the angular orientation of the part. It also causes longer calibration times during reconfiguration since the coordinate transform must also compensate for the angle of the platform. Reliable machine vision inspection also requires consistent lighting – this is usually achieved by housing the camera inside a box.

To address the two above-mentioned concerns would require the addition of further actuators or mechanisms to the singulation unit. The camera location problem can be solved by either moving the camera out of the way when a part is to be presented, or by installing a mechanism which moves mirrors during inspection and presentation. The lighting issue must be resolved by enclosing the camera and the platform, but the enclosure must be able to open to allow for the presentation of a part to the robot.

### 4.4 Presentation and Rejection Mechanism

The use of a guided cylinder for the presentation and rejection mechanism has various advantages. The attachment of the presentation platform by means of a hinge allows the presentation and rejection actions to be performed by the same actuator (this is shown in Figure 6). During presentation of the part to the robot, the guided cylinder moves upward, lifting the platform to a level above the camera and the frame of the singulator (as is shown in Figure 7). The platform position allows for access by the robot gripper, from any angle, without interference. Parts can thus be picked up from any side, as well as from above.

The disadvantage of using a guided cylinder is the cost – a guided cylinder with the necessary stroke is quite expensive. In the current design configuration, the guided cylinder also means that another mechanism must be added to allow for the camera to inspect from directly above the platform (as discussed in Section 4.3). Even though the guided cylinder concept allows for rapid rejection, the speed of presentation is limited since excessive deceleration at the top cylinder position may cause the part on the platform to move. The use of a proportional pneumatic valve and a proximity switch near the top position can circumvent this problem, but adds extra cost.



(a) (b)

Figure 6: The position of the platform during (a) part presentation and (b) part rejection.

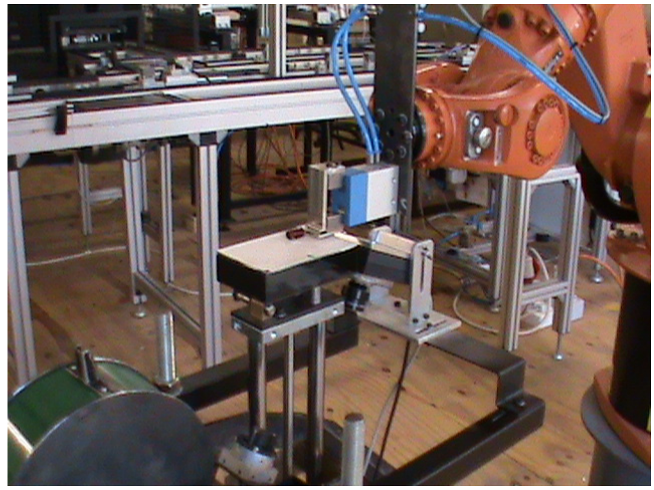


Figure 7: A part being picked up from the singulator by the robot.

### 4.5 Singulation Process

It was noticed that the success rate of the singulation process is dependent on the speed of the conveyor. At lower speeds, the conveyor steps tend to pick up multiple parts more frequently. At higher conveyor speeds, the steps tend to not pick up any parts as they move through the input bin. It was also noticed that the success rate of singulation was also dependent on the amount of parts present in the input bin.

To obtain an optimized singulation process, testing must be done on the machine with changes in the conveyor speed and part amount parameters.

### 4.6 Reconfigurability and Flexibility

Several design features were added to improve the reconfigurability of the singulator, i.e. to enable the singulator to singulate a range of parts requiring only quick and simple alterations: The singulator was designed to be vision-based – the use of an optical inspection greatly increases the range of parts which can be singulated. The inspections can be set up offline and be imported by the singulator's camera. Regarding flexibility, the steps of the conveyor are designed to be part envelope specific and not part-shape specific – this means that parts of similar outer dimensions can be singulated with the same steps. When parts of different outer dimensions are introduced, the singulator must be reconfigured by replacing the conveyor belt with one fitted with appropriately shaped steps. In some cases, the input bin (or inserts inside the bin) may also have to be replaced. The positions of the key components of the singulator are adjustable to allow for the changeover to a new part. The gateway mechanism and the presentation platform are not part-specific.

## 5 CONCLUSION

This paper describes the development of a stepped conveyor singulator for reconfigurable assembly processes. As opposed to conventional, dedicated singulators, the stepped-conveyor singulator was developed with a changeable configuration and capability. The developed singulator was used to feed individual sub-assembly parts to a pick-‘n-place robot in the experimental reconfigurable manufacturing system at Stellenbosch University.

The design requirements included flexibility (to allow for the singulation of similarly sized parts in a given configuration) and reconfigurability (to allow for the singulation of parts with different envelopes).

The important design considerations, identified through the development and testing process, include the shapes of the conveyor steps and input bin, the setup of the part inspection, the rejection and presentation mechanism, and the reconfigurability and flexibility aspects.

The stepped conveyor singulator presented here is an alternative concept to conventional singulators used in traditional manufacturing environments. The reconfigurability and flexibility characteristics of the design contribute towards the development of singulators suitable for reconfigurable manufacturing systems. The design allows for singulation that is part envelope specific rather than part specific. The hardware components of the singulator are all designed to be adjustable and interchangeable to allow for changes in the configuration and capability of the singulator.

For this singulator design to be feasible, it must be able to achieve a throughput rate competitive to that of conventional singulators. Future work will thus include comprehensive throughput testing of the singulator. The testing will include throughput rates for different parts and singulator configurations.

## 6 ACKNOWLEDGMENTS

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# Systematic Development of Mobile AR-Applications Supporting Production Planning

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**Abstract**
Tablet-PCs and Smartphones are starting to be established in the field of production engineering as planning and communication devices. Today's available mobile Augmented Reality (AR) tools are often results of technology driven development processes or adaptions of traditional desktop based systems. In contrary, the approach presented in this paper is introducing a systematic development process for mobile AR-applications. By using mobile AR-applications, established workflows should not be substituted, but systematically extend by new functionalities and interactive means. The approach focuses on two main areas: the user's needs and the capabilities offered by tablet-PCs.

**Keywords:**
Production Planning; Tablet-PC; Mobile Applications

## 1 INTRODUCTION

Augmented Reality (AR) is an emerging technology [1]. Several years ago it was mainly used within the research area, but AR technology made its way in the professional sector and consumer sector. The reasons why users are adapting this technology are because of the intuitive use and possibility to use it with common hardware devices. Especially in the professional, industrial field potentials are not comprehensively identified and exploited [2]. Most AR applications are not initiated on user or demand driven basis. The tendency is a technology driven development of applications for special sets of problems or demands. They are results of technology driven development processes and mostly spin-offs and adaptions from well-accepted traditional desktop based systems. As a result, there is no continuous and integrated support within production planning of mobile applications. To use these idle potentials, it is necessary to develop applications that are applicable and thus guarantee both the usability and utility. Therefore, a systematic development approach of mobile AR-applications supporting production planning is here presented in order to close the existing gaps.

## 2 STATE OF THE ART

### 2.1 Collaborative Production Planning Process

Collaborative design processes are beneficial for the development of complex systems by sharing experience and knowledge between several co-designers [3]. Implementing collaborative processes in the concept development phase involving various production planners is furthermore important, because early decisions contribute largely to the cost and manufacturability of products [4]. Production planning in this sense is an approach that requires a high level of collaboration between all stakeholders. Due to the fact that multiple domains and planning participants are typically involved, comprehensive and efficient communication is leading to decreased project durations, improved planning quality and reduced effort during planning projects [5]. Thereby, the influence between product development and production planning needs to be considered as one aspect demanding collaboration. By sequential development of product and production optimal solutions cannot be achieved, because relevant planning constraints are not exchanged between product designers and production planners [6].

In the range of production planning industrial companies are using software tools to achieve improvements of planning quality and reduction of planning time [7]. However, these software tools often lack in support of whole planning teams, involving several experts. Long training periods are necessary to operate the software tools, the involvement of stakeholders from various domains is not granted [8]. Nevertheless a user centered planning approach requires direct collaboration between planning participants and support by software tools on such co-creative way [9]. Communication between planning participants is the key element on which decision making is conducted. Therefore, human-computer interaction must be available in front to allow investigation of current planning status by all planning participants [10].

### 2.2 Augmented Reality Technology

Different definitions regarding Augmented Reality (AR) are having one common base: They define AR as an overlay of reality with computer generated information [11]. By the majority, also a real time exchange of information is required and an emphasis on interaction is given without a limitation of a specific sense like touch or smell. Furthermore, depending on the application area and purpose of use, different extensions can be added to define AR [12-13].

In recent years, there have been great advancements in the AR area which are mainly due to the developments and changes in the area of information and communications technology (ICT) [14]. In the starting time, AR technology has been mainly used in the research area, while today the private sector is using this technology as well. The biggest advantage of AR, in comparison to other Virtual Reality systems, can be seen in the common hardware that can be used and intuitively handled. Years ago the costs of developing hardware and software to support and use AR were much higher and accordingly the circle of users was very small. Nowadays, the hardware requirements to use AR in the private sector are low. Handheld off-the-shelf devices like smartphones and tablets are sufficient for private use. As for software, several mobile device applications are available as open-source and free platforms [14].

But, especially for the industrial use, explicit requirements have to be fulfilled like, for instance, the accuracy of overlaying objects as well as the processing capability to handle time necessary for computing [15]. Since the focus of this research is on a systematic development of mobile AR-applications, only tablet-PCs as hardware device that support mobility are considered further.

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### 2.3 AR Approaches for Factory Planning

AR technology is used in many different areas and has in general a very broad field of potential application. It goes from military use to medical and industrial applications towards the private and commercial sector for entertainment and gaming [13]. Within industrial companies, AR has many different application areas and ways to support. It reaches from early planning phases like design, production planning and assembly over later phases of lifecycles like service and maintenance, and logistics [15-16].

But especially within the factory planning process, AR has the advantage to enhance the collaboration and discussion between different operators without complicating the planning process. As a result, the main field of industrial AR applications is product design and factory planning. Several factory planning applications were in use to tackle specific sets of problems [17]. The successful adaption of these applications by the users is in two columns: Most applications never leave the prototyping state due to lack of maturity [14]. The maturity results from a mismatch between technological circumstances and real industrial demand [15]. On the other side, successful applications in use show the usability and utility of systematic planned AR-tools.

Especially, for factory layout planning tasks AR is beneficial. First, Virtual Reality (VR) based planning and simulation systems and tools were in use for factory planning and material flow planning. But, the overhead of complex modeling of already existing factory objects and environment due to rebuilding every real object in its 3D virtual object is not in proportion to the benefits. As soon as anything changes within the real environment, a reconstruction of the 3D scenery has to follow. Therefore, AR seems to close the gap between the disadvantages of VR based factory planning tools and industrial demands [14].

## 3 FRAMEWORK

### 3.1 Concept Idea

The mobile AR-prototypes and software tools supporting industrial production planning, which have already been developed throughout the scientific community, but also by international software companies, are each representing solutions for a very specific task. In most cases they are able to support a narrow bandwidth of derivations from the initially set problem definition. Nevertheless, todays mobile AR-prototypes are tailored to dedicated problems within encapsulated projects. A flexible mobile AR-solution which suits various challenges in the scope of production planning is not available yet. In addition to that, today´s mobile AR-prototypes are often results of technology driven development processes or adaptions of traditional desktop based systems. Hence, the full range of capabilities that tablet-PCs can offer are not completely considered and therefore potential benefits are not exploited, yet.

The approach presented in this paper will introduce a systematic development process for mobile AR-applications to overcome the existing drawbacks. Mobile AR-applications should not substitute desktop PC systems, but extend existing workflows by new aspects and interactive means. Therefore, mobile AR-applications must use the special capabilities tablet-PCs offer and enhance everyday-tasks of production planers by innovative means which are not feasible with desktop PCs and laptops. This includes the usage of innovate and intuitive interaction means as also the capability of self-registration in real environments, for example. To achieve a target driven development of applications, the approach considers two main areas: the user's needs and the capabilities offered by tablet-PCs. As shown in Figure 1, it is not sufficient to map tablet components like display or sensors directly to gaps in the problem field, which can be the missing capability to visualise digital information and real constraints at once. Ad-hoc developments with the purpose of closing a specific gap have been successfully completed. But, these developments have no basic structure. Because of this, a successful implementation cannot be guaranteed nor can the quality of provided support be assessed. Instead of this, the tablet-PC components need to be assembled and tablet features need to be derived. For instance, the functional interaction of a camera, position sensors, and CPU is leading towards the registration feature that needs to be available for the position tracking of AR applications. In general, the list of features is describing the capabilities of a tablet-PC in a more user-focused way than the product data sheet.

This level of description is still not sufficient to directly cover gaps within the problem field. Therefore, the problem field, which is production planning in this case, needs to be laid out in detail. The processes and methods that should be supported need to be analysed. One example for a key demand is the need to compare current digital planning status with already existing workshop constraints. But other gaps can be identified as well. After identifying the gaps, functions must be developed which can grant support for the gaps. A typical function would be to overlay real images with digital images, as it is a key feature provided by AR-systems. At this level, bridging between tablet features and required functions is possible (Figure 1).

The idea outlined above is the fundament, on which the development framework will be based. Further, the steps will be explained in detail and a proposal will be given to make the development of AR-applications feasible.

**Systematic App development**

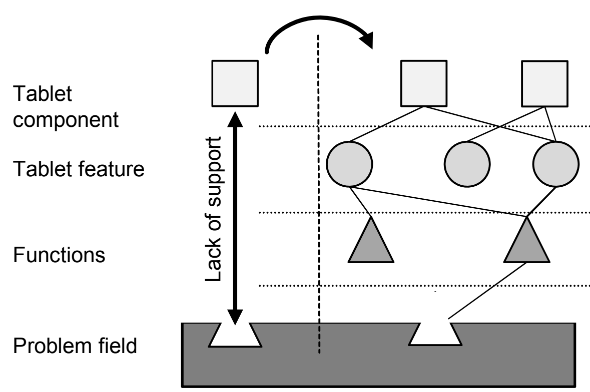


Figure 1: Structured Development Approach for mobile Applications in production planning.

### 3.2 Development Framework

Developing mobile AR-applications should focus on the user and support users during the execution of daily work tasks. Therefore, new methods and processes have to be established. Also a new technology will be introduced. But the usage of new technology should not be sheer self-purpose. Methods should be integrated into existing workflows to attract the user´s acceptance and to provide real support instead of creating new problems. Against this backdrop, it is crucial to know users' needs prior to the development of AR-applications. To identify the expected functionality of AR-applications, the mobile application concept is subdivided into the two sections dealing with 'Cognitive Aspects' and 'Functional Aspects' (Figure 2).

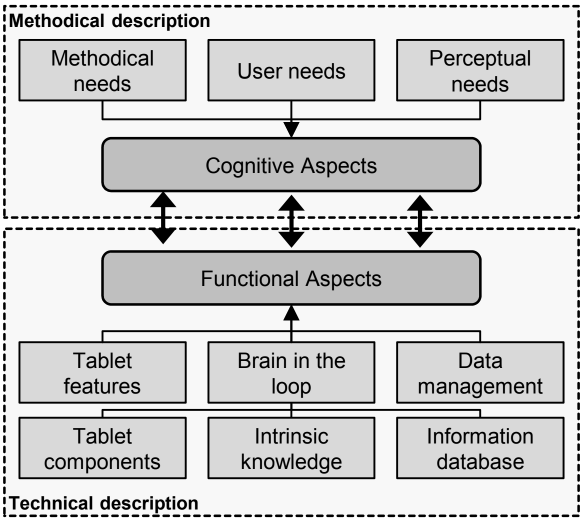


Figure 2: Mobile application concept.

Cognitive aspects are directly related to the needs, occurring from methodical gaps and the workflow the user is embedded in (e.g. the factory planning process). Due to the above mentioned circumstances, the mobile application concept has to follow a number of requirements and constraints in order to enhance production planers workflow. Perceptual needs complete the cognitive aspect as the perception of information visualised differs from user-group to user-group. Depending on the personal objectives and professional experience other information will be taken into account, while different visualisation forms and styles will be beneficial. For instance, logistic specialists are focusing other details during factory layout planning than process planers.

On the other hand, functional aspects are related to the technical description of the mobile AR-application. In our sense, this means not only the components of tablet-PCs, but also the features that are created by proper combination. An information database and data management must be considered during the development of AR-applications. They need to be integrated into the mobile application to allow users a case sensitive access to information, which means that for each situation and user group the proper information (and only the proper information) is provided. The integration of users' experience and know-how represented as the intrinsic knowledge is completing the functional aspects. Knowledge should not be integrated by a formalised procedure, but the application should foster the involvement of users' experience in a target driven way.

### 3.3 Cognitive Aspects during collaborative Production Planning

In this section, the already introduced cognitive aspects will be discussed in detail. Users' demands are the fundamentals to achieve a target driven AR-application development process. In order to specify the development framework, the problem field of production planning will be limited.

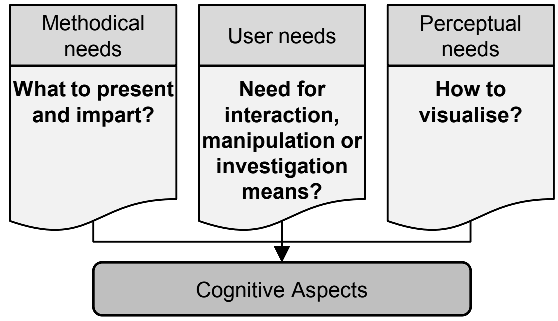


Figure 3: Key questions regarding the Cognitive Aspects.

Methodical needs are directly aligned to the subject, which is in focus of the AR-application. They arise out of the production planning methods which will be supported by the AR-application. For production planers it is, for instance, crucial to facilitate the planning process on the interface between virtual planning status and real environment constraints. A key objective is making the comparison between planed digital objects and existing real ones seamless. Out of this task, methodical needs are identified as for example providing a planned layout proposal enriched by architectural details. Methodical needs can not only be identified at final comparisons. Also during the whole PDCA-process (Plan-Do-Check-Act) of production planning a missing support can be identified. The output of this analysis is the identification of the relevant information that needs to be integrated into the AR-application (Figure 3).

Perceptual needs are partially linked to the considered information. Knowing which information is relevant is not enough to develop AR-applications; a visualisation concept is required to give users a sufficient understanding of information's content (Figure 3). Thereby the context which obtains the information is influencing the way of visualisation as well as the addressed specific user group. For instance a security area at the shop floor can be displayed by a red, highlighted circle or a simple overlaid text, depending on the focus of the users. The main issue is to visualise all required information in a beneficial way, but no unnecessary, unused information.

Beyond that, user needs are based on the analysis and optimisation means within AR-application which have to be provided. It is important to know whether users have to interact with information and manipulate them or if they are just observing a situation. Depending on the required level of bi-directional communication between user and AR-application different cognitive tasks need to be integrated into the application to enhance users' methods. This categorization cannot substitute the analysis of dedicated production planning methods according to the demand for AR support. It is more a general approach how to decompose production planers methods and investigate which functions are necessary to enhance specific processes.

### 3.4 Functional Aspects in the Scope of Collaborative Production Planning

In addition to cognitive aspects representing user demands, also technical constraints need to be discussed when developing a mobile AR-application supporting production planning. The application and the objective functionality must be feasible to achieve proper utility. Within this approach the discussion among functional aspects subdivided into three major fields as followed (Figure 4).

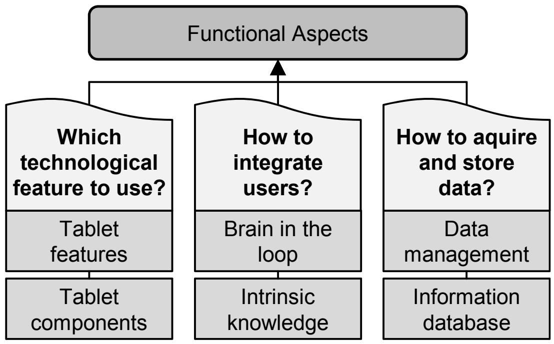


Figure 4: Key questions regarding the Functional Aspects.

*Tablet Features and Tablet Components*

After identifying production planers needs, ways to fulfil them by mobile AR-applications have to be outlined. Even if the development process is user driven, the capabilities of tablet-PCs have to be considered to make applications usable and reliable. Therefore, the in chapter 3.1 defined tablet features will be used. A wide range of potential features are available which need to be identified for respective development activities; here some typical ones will be highlighted.

Displaying digital information is a core feature of tablet-PCs. By using high-resolution displays and matured CPUs the presentation of virtual images is standard. This allows the mobile representation of 3D-CAD data for example. When addressing position sensors and cameras in addition, the superposition of virtual and real images is possible.

Another feature incorporating position sensors and touch sensitive displays for instance is intuitive and innovative interaction with the tablet-PC. By enabling such new ways of interaction, metaphors beyond 2D GUI can be addressed. This allows the extension of data manipulation within new and yet not completely explored ways.

The integration of tablet-PC's, Wi-Fi-connector, and mobile data communication to enable features opens additional options. By accessing web-based databases information can be provided in a context sensitive and position aware way.

*Brain in the Loop and Intrinsic Knowledge*

The users itself is one key element of AR-applications who is sometimes neglected by developers. On the one hand, intuitive interaction means need to be implemented. They should allow user-content interaction, user-application interaction, and user-user interaction in the way users expect. On the other hand, AR-applications should allow and foster the integration of users' experience and intrinsic knowledge to the problem solving process.

The way users' interact with the content of the AR-application has to be oriented on users' demands and experience. But also technological and software-based aspects need to be considered. Here, not only the interaction metaphor has to be developed, but also the level of detail, the granularity, and the users' rights need to be mentioned. The presentation of information needs to be case sensitive and user sensitive, to achieve a user centred application. The development of interaction means between user and the application on the tablet-PC can be understood as development of the user interface. In a final step, the interaction among different users needs to be analysed. Within production planning, cooperative processes and team based decision making is well established. The support of multi-domain planning teams with several stakeholders aiming at dedicated sub-objectives by mobile AR-applications needs to be extended. The mobile AR-application must be designed in a way that communication between users is enabled and information exchange is facilitated. Only by addressing whole planning teams and their interconnection, penetration of established production planning methods can be achieved.

The second aspect when considering production planers as key element of the AR-application system is the involvement of their experience and intrinsic knowledge into the planning process. Knowledge management approaches try to formalise such know-how and make personal experience available for other planning participants. For most AR-applications such an attempt will be too complex. Therefore, we propose to include intrinsic expert knowledge by communication and presentation capabilities within mobile AR-applications. This requires appropriate functionalities to share points of view, introduce problem descriptions to other participants and compare competing solutions. Such collaborative means of communication will make mobile AR-applications interesting for planning teams and allow integration into established workflows.

*Data Management and Information Database*

The functional aspect of information and data management should not be confused with cognitive aspects. While cognitive aspects are focusing on the content and scope of information, the functional aspect is related to the source and representation of information and data. The main challenge is to investigate which data can be used from CAx-systems and how missing information can be acquired and stored in a proper way. One future aim is to allow a seamless integration into PLM/PDM systems to access existing 3D-CAD models for instance. Other existing sources of information and data-bases within an industrial company could be addressed as well. Nevertheless, additional information might be necessary. Therefore, the process of data acquisition and related storage options have to be adjusted.

### 3.5 Typical Deployment of the Development Framework

An AR-application in the range of production engineering will be designed and implemented to validate the development framework. The definition of the problem field will be discussed and functions will be derived to close identified gaps. The implementation of the idea by a mobile AR-application is not object of this paper and will be conducted upcoming.

Within production planning, the product review process described in collaborative engineering approaches is identified a sub-process that will benefit from mobile AR-applications. This is caused by methodical gaps and cognitive aspects which are required, but not covered yet. The key issue is the lack of support to compare newly designed digital product models and already existing production environment elements for which no digital model is available. Production planers need to investigate if new designed or adapted components fit to existing manufacturing processes, machines and devices. If they could compare new components with the existing production environment elements, they could discuss and rate compatibility and explore adaptation demands on the shop-floor prior the finalisation of the product design process. Vice versa could such comparison influence product designers and lead to changes on the product itself. Based on this idea, the cognitive aspects were identified as following (Figure 5).

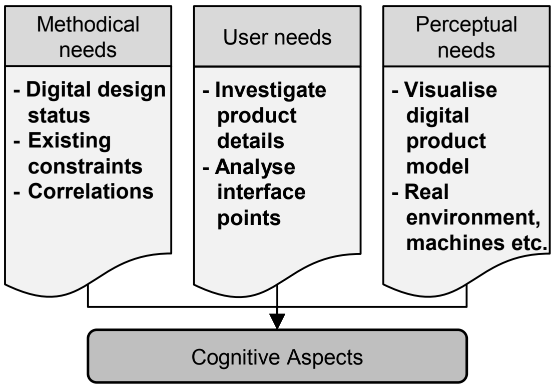


Figure 5: Cognitive Aspects use-case.

The functional aspects have been outlined in addition to the problem field and the identified cognitive aspects. In general, an AR-application is proposed to overlay existing production environment elements and manufacturing equipment with virtual product and part models. The AR-application should further enhance communication capabilities among different stakeholders during the concurrent engineering product review. Recording the identified problems, but also solutions during a collaborative session is completing the catalogue of technical functionality. The core functional aspects are summarised in Figure 6.

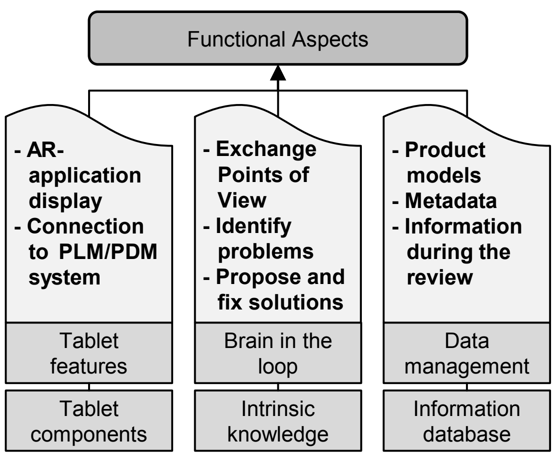


Figure 6: Functional Aspects use-case.

To map the cognitive aspects and the functional aspects tablet features and functions need to be merged to achieve solutions for the identified gaps in the problem field. Therefore, a list of core tasks which can be provided by mobile AR applications is proposed:

- Visual search
- Navigation/way finding
- Manipulation of digital content
- Situation awareness
- Knowledge/Information visualization
- Enriching real environment by metadata
- Collaboration

This list will serve as a cornerstone for further implementation of the concept idea into an AR-application. By doing this, the development framework itself will be evaluated accordingly.

## 4 CONCLUSION AND FUTURE OUTLOOK

The introduced approach aims at the target driven development of mobile AR-application supporting production planning starting from users' point of view. This fundamental consideration should increase the utility of upcoming AR-applications and ease the integration of new tools into existing workflows by enhancing engineering process instead of creating new ones. The concept idea is already partly evaluated by identifying concurrent engineering as potential field of application. The evaluation will be continued by the development of a detailed AR-application architecture and its implementation into a working prototype. Therefore, the concurrent engineering review-process has to be enhanced and methods will be developed to integrate the concept idea into the workflow of production planers and product designers.

## 5 ACKNOWLEDGMENTS

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# Approaches for Integration of Agile Procedures into Mechatronic Engineering of Manufacturing Systems

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**Abstract**

The mechatronic development of today's products in mechanical and plant construction effects on the close interaction of the three disciplines mechanics, electronics and informatics whereupon a high level of integration prevails. While yesterday's processes were mainly affected by serial engineering, tomorrow's processes have to adapt to the continuously rising software contribution in order to manufacture dependable products and to cope with the various demands of customers and markets. This paper presents an analysis of today's processes and leads to diverse approaches yielding agile practices into the engineering of mechatronic products in mechanical and plant construction.

**Keywords:**

Mechatronic trends; interdisciplinary engineering; incremental development; agile procedures

## 1 INTRODUCTION

Mechatronics is described as the co-engineering of the disciplines mechanics, electronics and informatics [1], [2]. Today's development of mechatronic products effects of the close interaction of these three disciplines whereupon a high level of integration prevails [3]. In consequence, the rising demand of highly individual products has an impact on the corresponding engineering processes that have to deal with complexity increasingly [4]. Though, the involvement of the disciplines has changed during the last decades (see Figure 1).

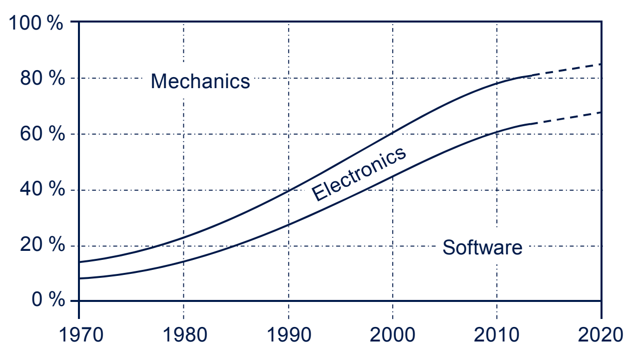


Figure 1: Involvement of disciplines in mechatronic engineering [5].

As illustrated in Figure 1, informatics has risen very much in the last years. Still, informatics will gain a lot more importance in future according to industry's and research's estimations [6]. Whereas the interaction between mechanics and electronics, including software, was called mechatronics in past, today's view looks quite different (see Figure 2). Nowadays, mechatronics is regarded as almost equal and synergetic intersection of the disciplines mechanics, electronics and informatics. According to the current trends, mechatronics will be understood as the embedding of the inseparable fusion of all disciplines in future, in which informatics respectively computer science has captured the major role.

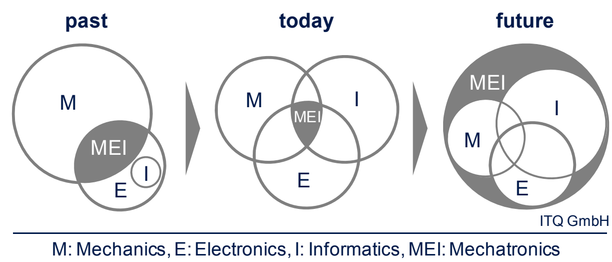


Figure 2: Synergy of disciplines in mechatronics [8].

However, today's most processes are still determined by mechanic procedures [7], neglecting especially software requirements [3]. To come up with all disciplines likewise, a change in product structure is required due to the interdisciplinary interaction [9]. While yesterday's processes were mainly affected by serial engineering, tomorrow's processes have to adapt to the continuously rising software contribution, in order to manufacture dependable mechatronic products and cope with the various customer's demands [10]. In the last years, especially so-called agile models, e.g. scrum, are on the rise in computer science, being highly adopted in numerous development practices, promising diverse advantages concerning current challenges. As the involvement of computer science has become progressively significant in mechatronic engineering, interdisciplinary processes should be adapted to consider this contemplated trend. However, it is quite obvious that an established process or model cannot by substituted just by an agile model overnight [11]. Having the approved capabilities of agile models in mind, approaches to yield agile practices into mechatronic processes should be tasked instead.

## 2 ANALYSIS OF INTERDISCIPLINARY MECHATRONIC ENGINEERING

### 2.1 Procedures

In product development, several procedural models have been established up to now, providing instructions for manufacturing. Mostly, their roots can still be tracked to mechanical and serial procedures, for which reason they are synonymously called

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*conventional* respectively *traditional* models [12]. Aside common software models like the Waterfall-model, agility models came up in computer science especially in the last years. They are known as flexible and fast engineering procedures, being especially defined by the incremental development of functional product artefacts e.g. sub-products [10]. In electronics, only single models exist. Depending on the view, this is due the participation of analogue hardware in mechanics and software applications in informatics even more. Electronics and informatics are often also considered as unity [13], for which reason electronics shall not be discussed in detail in this paper.

*Conventional Engineering*

Conventional procedures are often affiliated with multi-gate processes that are established especially in the mechanical engineering [12]. The main goal of these procedures is to detect faults in time, reduce their impact and prevent subsequent aftermaths. To do so, *gates* are placed between the single phases of the serial process (see Figure 3).

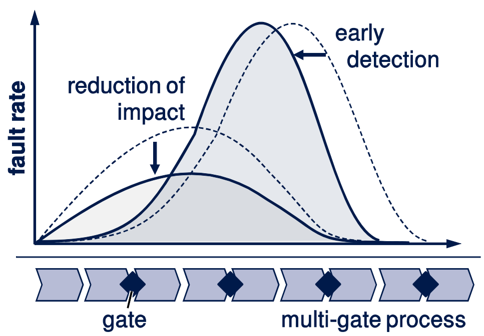


Figure 3: Approaching faults in a quality gate process [12].

Gates are defined as process-immanent, result-oriented points of decision and are to be differentiated between milestones that simply connect the product progress with the estimated production schedule [14]. Furthermore, gates act as a filter for timed objectives and product properties that do not match with the requirements. At once, gates provide operation guidelines to ensure the customer's demand of quality being defined at the beginning of a project precisely. Gates can vary in mode and principle, being placed standardized or variable in a specific quantity according to the project and product complexity [12]. In the case of deviations of the quality properties, change processes take place [10]. Multi-gate processes are often a fundamental object of conventional engineering procedures such as Waterfall-, V- and Quality Gate Model [12] that are especially used for projects of wide scope.

However, some side effects come along with multi-gate processes that influence the results of a project. In many cases, these effects are not in the focus of industry and furthermore not subject of pre-assigned analysis. If several projects are to be handled at one gate, latency may occur blocking other activities. This arises from the fact, that gate scheduling is not affected by just one discipline or task, but is time-boxed because parallelism is basically not supported sufficiently. All in all, multi-gate processes are usually regulated in detail and documented explicitly, affecting non-intended disadvantages in some scenarios.

*Agile Engineering*

In this context, agility is defined as the ability to develop functional product artefacts incrementally, while adapting to the environment flexibly and repeatedly, considering factors of context [3], [15]. Whereas computer science has been determined by the Waterfall-Model for decades, agile procedures are on the rise since a couple of years. Their origin can be lead back to lean principles and the agile manifesto of software-engineering in the year 2011 [16]. According to up-to-date surveys, agile models are already used in a lot of notable companies [11]. In regard to essential modifications that come up with change management, agile models intent to establish a more flexible and lean process of development, efficiently realizing delivery times in a high level. In contrast to conventional engineering, agile approaches focus on the task of functional and psychological aspects as well. Users are assured, that agile practices are very important concerning the acceleration of time-to-market, increased productivity and quality, motivation and transparency for instance [11]. This is realized especially by the frequent delivery of executable, stand-alone sub-products, being verified with the customer's requirements periodically. By limiting the work in progress and parallel development, flexibility is strengthened. Changes that might occur by the customer, the supplier, the market or due to failure situations may be considered step by step. Furthermore, changes are regarded as necessary and are to be integrated in the process contemporarily [10]. Agile models support the self-organisation of teams and intend a close interaction with the customer. According to surveys, agile engineering has promising capabilities that will also influence disciplines beyond computer science [11]. The most significant agile models are Scrum, eXtreme Programming and Kanban that are applied in projects and teams of minor size and are addressed in relevant literature. Especially Scrum, being the most important agile model, is considered as a management-framework that can be combined with other agile and conventional models [16].

## 2.2 Communication and Divisional Work

*Systems Engineering*

A framework of models and principles are summarized being defined in the course of Systems Engineering [10]. Significantly, they all use principles of project management, being adapted by the customer. These models are provided for application- and situation-oriented design of technical systems with high complexity. Systems Engineering follows up an interaction of thinking in systems and process-orientation keeping to general rules. This includes thinking in alternatives by organizing the process with regard to time providing procedures of problem solving. According to Figure 4, the importance of Systems Engineering has become quite meaningful for mechatronic engineering in the past. However, these approaches are too generic and not sufficiently enough, to cope with the specific situations of multi-discipline engineering that have been mentioned above.

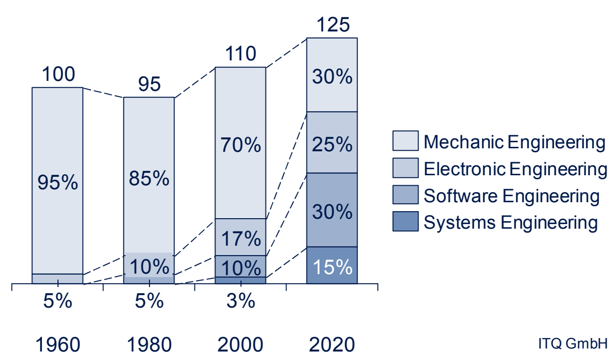


Figure 4: Systems Engineering in the context of mechatronic development.

*Simultaneous Engineering*

In general, Simultaneous Engineering describes the parallelization of activities through the formation of interdisciplinary teams in order to shorten time-to-market and to increase quality properties [6], [17], [18]. The principle of Simultaneous Engineering is described as "designing the product and the process to manufacture at the same time" [3], [15]. This includes all business sectors as production, sales and distribution, thus the whole product life cycle [6], [19]. Although Simultaneous Engineering is applied in mechatronic engineering, a lack of interdisciplinary communication as well as a lack of holistic comprehension of structures are still prevailing the interdisciplinary work [6]. On account of the specific procedures, activities in the diverse disciplines are often parallel. However, they are very often not dependent and do not support the integrative engineering of mechatronic products in an appropriate way.

### 2.3 Tool Maturity

Tool maturity related approaches focus on the technical development of tools for supporting the mechatronic process. Although the single disciplines are established since a long time, the existing tools still offer potential for improvement [6]. While a wide range of such modelling methods and tools exists, they are often limited in their range of use and might not be suitable for the solution of holistic tasks in any case. According to industry's approaches, holistic tools supporting integrated engineering are on the rise (see Figure 5).

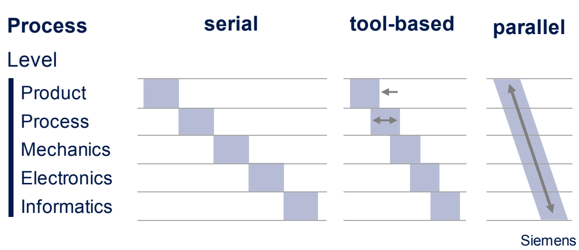


Figure 5: Integrated tool-supported engineering.

Keeping the agile approaches in mind, Figure 5 leads to the fact, that users rather apply common tools for their project management instead of specific agile or holistic tools. This implies questions concerning approaches and tools that support agile and conventional co-engineering.

### 2.4 Conclusion of Analysis

As mentioned above, different procedures are used in mechanics and informatics that are mostly specific on the one side. On the other side, users don't know exactly which model to apply best [6]. In spite of the approaches of Systems and Simultaneous Engineering, the isolated applications and partial systems do not support parallel mechatronic engineering in a high level yet [2]. This arises from the fact, that a bulk of procedures exists, but no suitably holistic model is truly supporting the engineering process. Because of the strictly division of functional fields, communication and work flow are handicapped [20]. Affiliated with the divisional work, lack of communication appears that particularly has an impact on expensive iterations and changes in the late process [6], [21]. Beyond that, insufficient interdisciplinary communication comes with a limited comprehension of structures and dependencies within the disciplines [6]. Due to specific definitions, mindsets and procedures, interdisciplinary co-operation in mechatronic engineering is difficult [6]. This is intensified by a flood of tools that do not support this issue up to now. From this fact, the problem of risen complexity is increased even more [6], [22]. Additionally, multiple-discipline engineering cannot be determined by the application of either a conventional or an agile model. Hence, the new approaches being presented here affiliate both procedures according to the development terms and conditions by assignment of criteria.

## 3 GOAL

In order to cope with the analyzed challenges in the area of mechatronic development, approaches will be introduced that combine the advantages of both conventional and agile models. As an enabler, a reference model will be used to distinguish the integrated engineering process for an arbitrary business' project in mechanical and plant construction. The single steps, being relevant in a specific case, can be identified by factors of context. By comparing the ideal process to the existing one, an agile model can be selected that fits best for software engineering. This paper focuses on the adaption of the chosen agile model to an existing process. Furthermore, concepts will be presented to integrate agile procedures in multiple-discipline engineering according to the business' context of mechanical and plant construction.

## 4 INTEGRATION OF AGILE PROCEDURES INTO MECHATRONIC ENGINEERING

### 4.1 General Approach

Although agile models come with a lot of advantages in the field of challenges, we have to understand why conventional models are still used and why agile approaches were not considered frequently beyond software engineering up to now.

On the one side, multi-gate principles being used particularly in conventional models have been established for a long time. Due to the domination of mechanics, that often prevails within mechatronic development, engineers keep to these well-known procedures as they have used them for years. Besides, conventional models are known to be well comprehensive even for non-technical staff. Furthermore, they just need a low degree of organizational maturity to be established. On the other hand, agile procedures are not initiated because users worry about struggling with the chaotic aftermath of wrongly applied agility [23]. This often implies the disappearance of familiar mechanisms of planning and control as well as the apparently non-systematic form of documentation. However, an established mechatronic process cannot be adapted to agile procedures overnight [11], [16]. Instead, present conventional models should be supported by agile procedures in an appropriate way.

To combine the advantages of both conventional and agile models, a systematic and scalable agility should be pursued that estimates agile potential best. This is summarized in Figure 6, being subject to the subsequent approaches.

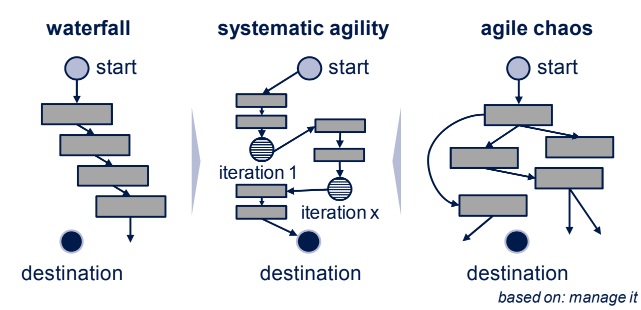


Figure 6: Systematic agility.

*Criteria and Scalability*

Industries often use either a conventional or an agile model, neglecting the advantages of a mixture of both. Whether a conventional or an agile model should be the basis for a combination is depending on the context of the enterprise and the field of application in most cases. The agglomeration of criteria determining the framework of potentials for agile procedures shall be defined as *agile scalability*. Thereby, conventional processes can benefit of agile approaches as well as the other way round. The first criterion to be mentioned is the industrial sector as illustrated in table 1.

| Industry | Product Cycle Time | Process Cycle Time | Procedure |
|---|---|---|---|
| Personal Computer | < 6 Months | 2-4 Years | agile |
| Automotives | 4-6 Years | 2-4 Years | ⇕ |
| Machine Tools | 6-10 Years | 3-10 Years | |
| Aeronautics | 10-20 Years | 20-30 Years | conventional |

Table 1: Cycle times in specific industries [12].

Whereas cycle times of products, organizations and processes are very frequently in the IT sector and benefit from the flexibility of agile procedures greatly, sectors as aeronautic engineering affect in long cycle times and require the high quality and standardization of conventional procedures. Products in mechanical and plant construction are allocated in between and could benefit from both procedures

Also the size, iteration and degree of innovation of a project and amount of engineers working in a team are a matter of decision. Normally five to nine persons work in a common agile team, attending either recurring or pilot projects. Agile models are not appropriate for huge projects of long periods but rather for sub-projects [16].

Additional, a functional agility can be mentioned. Most products, especially in plant construction are of functional structure, existing of basic and optional parts. While the major functions are belonging to the framework, sub-functions often represent customer's specific requirements. Agile approaches are especially relevant for realising these sub-functions, having the involvement of the customer and fast time-to-market in mind.

Last but not least, the scalability is a question of agile maturity as mentioned before. Agile features should be manifested in the organization by senior experts or trained persons that know how to stick to the agile rules. The agile maturity can be regarded as a conclusion, whether the scalability and application of agile procedures is potentially and generally applicable in the context of a specific development. Including team qualification, flexibility of the organisation, stability of the environment, safety and customer's involvement, all criteria can be classified by requirement management, communication management, team leadership and project scheduling so far [10].

The agglomeration of all criteria in the context of engineering needs to be distinguished between a product development, being determined by a conventional or an agile procedure majorly. In most cases, however, a mixture of models should be used, adapted and tailored to the context of development.

*Mixture of Agile and Conventional Procedures*

According to up-to-date surveys, not just a universal conventional or an agile model is used. In almost two-thirds users apply a mixture of both. Thereby a combination can be used that unifies agile and conventional elements in a new, hybrid model, stringing both agile and conventional models together according to sub-projects. This mixture can be regarded as output of the scalability, evaluating how to use agile procedures best in the context of development [11].

Two specific approaches to profit by agile procedures for software development in mechatronic engineering shall be presented consecutively.

### 4.2 Horizontal Agility Approach

A hybrid of a conventional and an agile model can be regarded as horizontal approach, serially stringing both procedures together. Both an agile process with a conventional quality assurance in the test phase can be considered for instance as well as a conventional process that involves agile aspects for realizing the customer's requirements in production.

Having a close look at the iteration cycles of a typical quality gate process as illustrated in Figure 7, waterfall characteristics can be extinguished.

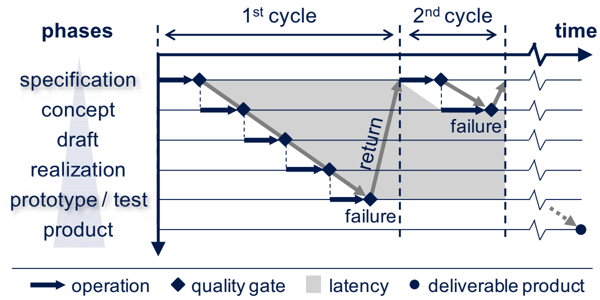


Figure 7: Iterative cycles of a quality gate process [2], [24].

Having the phases on the vertical axis, the horizontal axis represents the total time and progress of development. At the very end of multiple iteration cycles, the delivery of the whole product will take place. In case of failures being detected at the quality gates in between, returns take place revising the preliminary product. Having no parallelism in this advance, latency occurs in the single phases. Additionally, planning and consistency are hindered due to the varying length of iterations.

In contrast, an agile process aims to an incremental chain of periodic activities as shown in Figure 8.

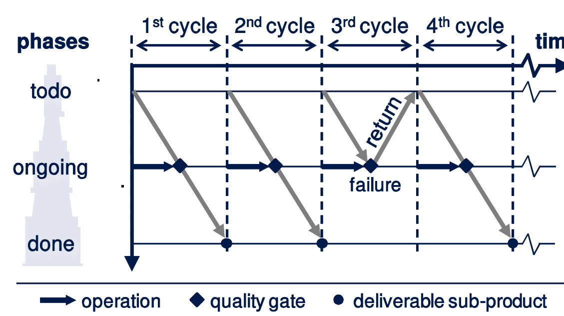


Figure 8: Incremental cycles of an agile process [2], [24].

As the common phases are not congruent to an agile process, because the tasks are executed parallel by the team of development, the vertical axis includes the general phases *todo*, *ongoing* and *done*. Presenting the total time of development on the horizontal axis, the periodic cycles of defined and same length can be recognized. This is due to the incremental development during one cycle. At the end of every cycle, an executable, stand-alone product artefact of small size can delivered to the customer. Due to the specific length of the cycle, all failure situations can be handled in between avoiding returns. At once, multiple artefacts are developed so that waiting times are reduced.

Combining agile and conventional procedures in a hybrid chain model in the context of multi-discipline mechatronic engineering requires a connection of tasks in regard of cycle times. With the use of the criteria presented before, conclusions can be made defining the length of cycles. At the same moment, idle times can be reduced to a minimum having a constant sequence of cycles. In turn, the collaboration of disciplines is improved and new ideas can be implemented very fast. This implies the evaluation, whether product artefacts can be developed parallel at the same time. This is also a question of information that is transferred between the disciplines, being addressed in the vertical agility approach.

### 4.3 Vertical Agility Approach

As mentioned before, the vertical agility approach focuses on the combination of conventional and agile procedures in the intercommunication of disciplines.

Products are usually divided into a hierarchic structure defining the devices and principal elements [6], [25]. Generally, the combination of physical and functional structures and its interconnections are described to the product's structure synonymously [2], [26]. However, they are still prevailed by the mechanic orientation, obstructing interdisciplinary comprehension [6]. Against this background, the questions is how the mechanics, sticking to quality-gate principles, can interact best with computer science using agile models as shown in Figure 9.

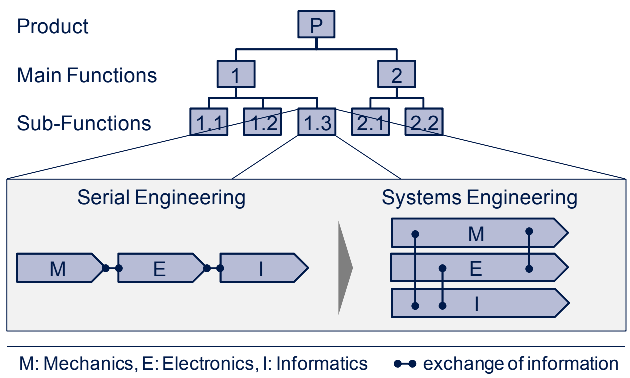


Figure 9: Functional division and realization of mechatronic products.

In this context, the vertical approach addresses isolated applications, partial systems and division of functional fields. This approach aims at the avoidance of the problem that the disciplinary outcomes of development are often not linked together in time or in accurate maturity. Therefore, interdisciplinary communication and comprehension of structures and dependencies have to be improved to ensure parallelism. [6], [27], [28]

However, information is a question of view (see figure 10).

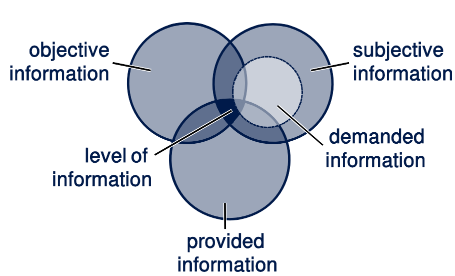


Figure 10: Information needs [2], [24].

Available information is a result of the intersection of objective, subjective and available information [2], [29]. Objective information is derived from the function or task being provided to the user in point of fact. Subjective information includes all elements that are known to the user. If information is requested, the demand of information includes all elements that seem to be relevant from the user's point of view. Additionally, these types of information have only a small intersection with the information being offered in general [2].

In the development of complex technical systems only approximately 50-60 % of activities add value. The remaining part, especially in mechatronic engineering, falls upon latency and synchronization [2]. To improve the lack of communication and the limited comprehension of structures, needed information for interdisciplinary engineering has to be adapted to the available information. This implies to provide the relevant information at the right place and in time by data networking and common nomenclature [2], [14]. Furthermore, it is necessary to adjust the different process cycles times of mechanics and informatics. As the agile models imply short cycles in comparison to the multi-gate processes of mechanics, information that is relevant for informatics should be provided at the beginning of the processes as shown in Figure 11.

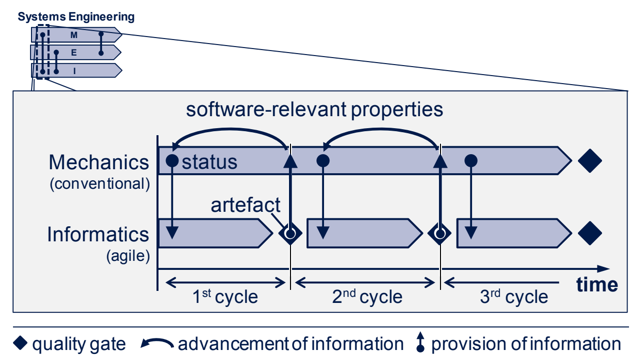


Figure 11: Information depending on intercommunication.

This information should contain virtual models like CAD-models, digital mock-ups and so on. Besides, software artefacts should be also delivered to mechanics having an interdisciplinary quality assurance. Information being exchanged between the disciplines should be discussed in an interdisciplinary team repeatedly. The frequency of exchange, relevant information and organizational aspects are subject of the criteria mentioned before and have to be detailed in future being highly determined by the context of development.

### 4.4 The Route to an Agile Organisation

As mentioned before, agile procedures require a certain organisational maturity. Therefore a selective choice of agile models and integration into proven frameworks of existing processes is more successful than a complete revolution by changing to an agile development model completely [10]. Hence, the very first step is to review one's own organization and to define its maturity in order to use agile approaches as presented [23]. Practiced staff or skilled coaches should support this analysis using checklists, containing the criteria such as listed above. Furthermore, experience of the team of development is essential as to use agile models and to assure the confidence of the advantages. This can be learned by realizing pilot projects initially, in order to satisfy the expectations being connected with agility. Last but not least, requirements for tools have to be derived supporting agile procedures in project management.

## 5 SUMMARY AND OUTLOOK

In order to cope with the high level of integration and complexity, approaches should be tasked that adapt to the continuously rising software contribution in mechanical and plant construction. In regard of these challenges, existing approaches such as Systems and Simultaneous Engineering do not support the development sufficiently. Besides, the wide range of models and tools are still limited in their range of use and are not suitable for the solution of holistic tasks. Hence, approaches are introduced that combine the advantages of both conventional models used in mechanics and agile models used in computer science according to the business' context using various criteria. These approaches focus on the combination of both procedures on the one hand and the interaction between the disciplines on the other hand.

These approaches have to be qualified by a reference model that identifies the single steps of development for arbitrary business' projects. By comparing the ideal with the existing process, agile models can be identified that fit best. According to the estimation of the authors, the presented concepts are important enablers for coping with today's challenges in multiple-discipline mechatronic engineering that should be focused in future intensively.

## 6 ACKNOWLEDGMENTS

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# Control of Reconfigurable Manufacturing Systems Using Object-Oriented Programming

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**Abstract**

Agent Based Control (ABC) has been used widely in research into Reconfigurable Manufacturing Systems (RMSs), but industry is hesitant to adopt ABC. Therefore object-oriented programming (OOP) is considered here as an alternative, since it is more widely used and has many capabilities that are valuable when implementing an RMS. Using the key characteristics for RMSs and the critical factors for holonic system architectures, agents are compared to OOP, evaluating the functionality that OOP can provide for reconfigurable manufacturing systems. The paper shows that OOP offers significant advantages for the control of less complex systems and where timing is more critical.

**Keywords:**

Control; reconfigurable manufacturing systems; object-oriented programming

## 1 INTRODUCTION

Reconfigurable manufacturing systems (RMSs) are aimed at dynamic situations, such as variations in products, production volume requirements and available resources [1]. RMSs in research environments in most cases used Agent Based Control (ABC) [2][3][4], but the main automation vendors in the industry do not support ABC. This inhibits the acceptance of RMSs by the industry. The focus of this paper is to investigate when Object-Oriented Programming (OOP) would be suited for implementing RMSs, since OOP is used more widely and therefore is likely to be more acceptable to industry than ABC.

Holonic control architectures [5] are generally used in RMSs and therefore, in the present research, the use of a holarchy is assumed. A holarchy is a community of autonomous holons structured in a dynamically changing hierarchy/heterarchy. Holons have the ability to autonomously make decisions, e.g. solve a local optimization problem in order to reach a global goal.

Two common holonic architectures are PROSA [5] and ADACOR [6]. The former has three primary holon types, i.e. product, order and resource holons. These basic holons can be further subdivided into different kinds of holons, e.g. a customer order can consist of batch orders which in turn can consist of work orders. The ADACOR holon types are sufficiently similar in function to the PROSA holon types so that in this paper, only PROSA holon types are considered.

The research reported here is related to a project for CBI Electric: Low Voltage. This South African company produces a large variety of circuit breakers (a few hundred variants) in batch sizes varying from 20 to 60000. These circuit breakers are currently manually assembled, but the company is considering automating some of the assembly and quality assurance processes to improve consistency.

To be cost effective in the CBI context, automated systems will have to be suitable for the wide range of product variants and batch sizes. The RMS approach provides a potential solution in this context since RMSs are designed to quickly adapt to a new product being introduced without the need for long reconfiguration times.

CBI further requires that manual control options be provided to handle ad hoc requirements. The automated system must therefore be designed with dynamic scenarios in mind and must have human-machine-interfaces (HMIs) to allow humans to take over control of subsystems.

## 2 OBJECTIVE

The objective of this paper is to investigate the circumstances under which an OOP-based approach will be effective for developing the control software of an RMS. Since ABC is the de facto standard approach, OOP is compared to ABC. The paper particularly considers a holonic, reconfigurable manufacturing system for CBI's needs and other similar cases in industry. In other words, this paper considers the functionalities of agents that are essential or highly desirable when implementing a control system for an RMS aimed at use by CBI. The paper also considers how an OOP-based approach can provide those or additional functionalities in a way that is more acceptable to industry.

Other researchers (such as [7]) have compared agents and OOP, but in the context of software development and not specifically manufacturing control systems. Their conclusions are therefore not necessarily applicable to the cases considered here.

It should be noted that, since the software for agent platforms are developed in object orientated languages (e.g. JADE in Java), an OOP-based controller can be developed eventually to the point where it is an agent based controller. The purpose of this paper is, however, to avoid the need for doing that, but rather to evaluate which functions of ABC are important to replicate in OOP.

## 3 RMS DESIGN REQUIREMENTS

To determine the required features for OOP-based RMS control, the alternatives are evaluated in terms of the six core characteristics of RMSs [1]: customization (flexibility limited to a part family), convertibility (design for functionality changes), scalability (design for capacity changes), modularity (system components are modular), integrability (interfaces between system components promote rapid integration) and diagnosability (design for easy diagnostics which allows for quick ramp-up after reconfiguration). The first three are characteristics of the whole RMS and are critical for a system to be considered to be reconfigurable. The last three characteristics, on the other hand, allow reconfiguration to be done efficiently. Therefore OOP-based control must support modularity, integrability and diagnosability to be a suitable alternative to ABC.

RMSs are here considered to be holonic systems and Christensen [8] reports that the HMS Consortium identified the following as critical factors for systems:

M.F. Zaeh (ed.), *5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013), Munich, Germany 2013*,

DOI: 10.1007/978-3-319-02054-9_39, 

- Disturbance handling: Provide better and faster recognition of and response to machine malfunctions, rush orders, unpredictable process yields, human errors, etc.
- Human integration: Support better and more extensive use of human intelligence.
- Availability: Provide higher reliability and maintainability despite system size and complexity.
- Flexibility: Support continuously changing product designs, product mixes, and small lot sizes.
- Robustness: Maintain system operability in the face of large and small malfunctions.

Except for the human integration factor, the other factors are closely related to RMSs' properties.

When considering IEC 61499 function blocks as a means to control holonic systems, Christensen [8] identified capabilities required to provide autonomy. These capabilities should also be considered for OOP approaches:

- encapsulated local data bases;
- local process/machine control;
- local optimization;
- local product tracking;
- self-scheduling;
- self-diagnosis;
- self-repair;
- self-configuration.

Further, for distributed and cooperative holonic architectures, OOP should provide communication and negotiation capabilities, as required by Christensen [8] of function blocks.

One of the particular capabilities of RMSs is the ability to be dynamically reconfigured. Christensen [8], when considering the use of IEC 61499 function blocks for RMSs, implied that dynamic reconfiguration is when humans, other holons, or the holonic application itself can:

- dynamically create, modify, destroy and relocate both instances and type definitions of functional units (e.g. function blocks or agents);
- dynamically create and destroy connections among functional units;
- dynamically activate and de-activate functional units;
- perform version management of functional units and applications.

The above is closely related to a system's flexibility and disturbance handling capabilities, i.e. its ability to manage change dynamically. The lack of support in IEC 61131-3 for these capabilities [9] limits their use in the control of RMSs.

In the CBI application mentioned in Section 1, the situation is dynamic (including requiring occasional reconfigurations), but the company does not require the RMS to be able to autonomously reconfigure. On the contrary, it is the impression of the authors that the company would be uncomfortable with such a level of automation. Autonomous reconfiguration is therefore in this paper not seen as a requirement, but manual reconfiguration is, as are flexibility and disturbance handling capabilities. The CBI application therefore demonstrates that the relative importance of the requirements given in this section depends on the case being considered. One cannot assume that all practical systems must fully support all of the above requirements.

The formulation of a strategy to find and/or rank the requirements for a specific application, is not the focus of this paper, but is considered by Hoffman and Basson [10]. However, in this paper we assume the following, taken from the CBI application:

- The system is customizable to the extent that it is able to handle changes within a predetermined part family without being shut down.
- The system is convertible and scalable, but the associated system changes may be implemented during a shut-down period.
- The control system is modular, holonic and distributed, in particular that the resource holon associated with each hardware resource runs on its own software platform, and that product information is retained in product holons (and not in the resource holons) that reside on a cell controller platform or another controller higher in the holarchy.
- The system can handle disturbances when, for example, a subsystem fails and parts have to be rerouted. The system must also provide HMIs at various points and allow manual override capabilities.
- The system is diagnosable to the extent that each holon can at least assess and report on its own health to a cell controller.

## 4 OBJECTS VS AGENTS

### 4.1 Key Properties of ABC

ABC has been applied in a large proportion of RMS research since it suits the requirements of RMSs so well. Not all aspects can be considered here, but some key capabilities are pointed out:

According to Bellifemine et al [11], an agent is essentially a special software component with an interoperable interface to an arbitrary system, and is characterized, among other things, by:

- Autonomy: It can independently carry out complex and often long-term tasks, i.e. it operates without the direct intervention of humans or others and has control over its actions and internal state.
- Pro-activity: An agent can take initiative to perform a given task even without an explicit stimulus from a user.
- Ability to communicate: Agents can interact with other entities to assist with achieving their own and other's goals.

Furthermore [11], an agent is social, because it cooperates with humans or other agents in order to achieve its tasks. An agent is reactive, because it perceives its environment and responds in a timely fashion to changes that occur in the environment. If necessary, it can be mobile, with the ability to travel between different nodes in a computer network, and it can learn, adapting itself to its environment and to the desires of its users.

The abovementioned characteristics make agents a very attractive option for implementing an RMS's control system:

Agents are easy to integrate with one another because they make use of the same communication protocol (e.g. FIPA ACL [11]) and adhere to the same rules. A newly created agent will be registered at the agent management system (described below) and when it wishes to publicize its services, it will announce them at the directory facilitator (described below) so that other agents can request to make use of its services. In this way agents can always be aware of one another's presence and the system is self-structured.

Agents are also modular and integrable because they have an interoperable interface to an arbitrary system, and they keep their internal working to themselves, always showing the same interfaces to the outside world. This means that nothing needs to be changed in the rest of the system when a change is made to an individual agent, e.g. one can let an agent run on a new platform or make it control a different physical resource and as long as the interfaces behave the same, the rest of the system will not be affected. Therefore humans can seamlessly be integrated into an automated manufacturing system by implementing an HMI on the inside of an agent which will then appear like a regular agent as long as it provides a standard interface to the rest of the system.

Since agents have control over their internal state, they can easily report on their health status while they are still responsive, and since agents are proactive, they are capable of detecting when other agents stopped responding and can try to resolve the problem. This makes them suitable for diagnosability and self-repair.

According to Van Brussel, et al. [5], disturbances and changes to the system can easily be handled when using the Contract Net Protocol as a negotiation mechanism between agents. Because each agent is autonomous, it will try to find the optimal solution to its local problem, and because it is also proactive, it will, after disturbances occurred, re-evaluate its solution to the current problem. When using the Contract Net Protocol, the system is self-scheduling: idling agents or agents whose current job is nearing completion, will bid more to get a new offer than agents who have already been assigned more than one task. This ensures that when tasks can be performed in parallel, the work load will be distributed amongst agents rather than piling up at an individual agent, and will reduce agent idling time.

In ABC, dynamic reconfiguration is made possible by the following two components of an agent platform: the agent management system and the directory facilitator. Their main roles are as follows [11]:

The agent management system is responsible for managing the operation of an agent platform, including the creation and deletion of agents, the migration of agents to and from the agent platform, and maintaining a directory of identifiers of all agents present within the agent platform and their current state (e.g. active, suspended or waiting).

The directory facilitator (DF) provides "yellow pages" services to other agents and maintains a list of services that agents can offer. Every agent that wishes to publicize its services to other agents would request the registration of its agent description in a DF. At any time an agent may request the DF to modify its agent description. The registration with a DF does not imply a future commitment or obligation on the part of the registering agent and an agent can subsequently request deregistration of its description at any time.

The agent management system and DF allow agents to be developed off-line, and then be dynamically added to the rest of the system without bringing the system to a halt. They also allow dynamically creating, modifying and destroying instances of and connections among functional units, as well as the dynamic activation and de-activation thereof.

### 4.2 Key Properties of OOP

The four key concepts of OOP are abstraction, encapsulation, inheritance and polymorphism [12]. There are some important synergies between these OOP concepts and the modularity, integrability and diagnosability characteristics of RMSs:

Modularity and encapsulation are closely related, in that a software object can be instantiated as many times as required, because each instance's data is independent of other instances, unless explicitly specified differently. RMS modules are often considered to be holons [5] and a set of OOP objects is well suited to form the software part of a holon. New instances of holons without hardware (e.g. the order holon in PROSA) can easily be created in an OOP implementation by instantiating another object. Similarly, when the order holon's tasks have been completed, its object-instance can simply be deleted. Inheritance in OOP provides another dimension of modularity for which there is no parallel in agents. When creating a new holon during reconfiguration, an appropriately designed OOP implementation will allow the object representing the new holon to inherit "modules" of functionality from previously defined super-classes. This allows for code re-use, thus reducing controller reconfiguration times and risks.

Integrability can be promoted through objects' properties of inheritance, polymorphism and abstraction: A key part of abstraction is that an object hides the complexity of its internal working and presents a simple interface to the outside world. Further, inheritance (e.g. of an abstract class) and polymorphism can be used to define a generic interface for all holons that provides, for example generic diagnostic and communication aspects. Therefore, abstraction, inheritance and polymorphism can be used in an OOP implementation of a holon's information processing part to create generic interfaces, which enhances an object's integrability. However, OOP implementations will still require the development of, for example, communication interfaces using general approaches (e.g. XML strings exchanged over TCP/IP links), while agent platforms have much of that functionality built in.

Mature OOP software development platforms are available, thus providing excellent software tools to diagnose control software problems. Further, the multi-threading abilities of OOP languages allow diagnostic processes to run concurrently with normal operations, thereby enabling near-real time monitoring of the state of the RMS and providing good diagnosability.

### 4.3 Objects and Agents Compared

A number of researchers have compared objects and agents. A brief summary of the comparisons is first given here, followed in the next section by an assessment with the CBI application in mind.

Odell [7], adapting the work of Parunak [13], placed OOP and agent programming in a broader perspective (Figure 1) and pointed out that a fundamental difference between object-oriented and agent-oriented programming is that agents can invoke their own units, whereas objects do not.

Two key areas that can differentiate the agent-based approach from the traditional OOP approach are autonomy and interaction [7]. Proactive agents poll the environment for events and other messages to determine what action they should take, while objects are conventionally passive.

For Booch [14, cited by 7], employing agents with object systems is useful, because the agent-based approach:

- provides a way to reason about the flow of control in a highly distributed system;
- offers a mechanism that yields emergent behaviour across an otherwise static behaviour; and
- codifies the best practices in how to organize concurrent collaborating objects.

| | Monolithic Programming | Modular Programming | Object-Oriented Programming | Agent Programming |
|---|---|---|---|---|
| Unit Behavior | Nonmodular | Modular | Modular | Modular |
| Unit State | External | External | Internal | Internal |
| Unit Invocation | External | External (CALLed) | External (message) | Internal (rules, goals) |

Figure 1: Evolution of Programming approaches [7].

Although there are certain similarities between object- and agent-oriented approaches (e.g. both adhere to the principle of information hiding and recognize the importance of interactions), there are also several important differences [15]:

- Objects are generally passive in nature: they need to be sent a message before they become active.
- Although objects encapsulate state and behaviour realization, they do not, in principle, encapsulate behaviour activation. Thus, any object can invoke any publicly accessible method on any other object.
- Object orientation fails to provide an adequate set of concepts and mechanisms for modelling complex systems.
- Object-oriented approaches provide only minimal support for specifying and managing organizational relationships (basically, relationships are defined by static inheritance hierarchies).

In OOP, there is no "built-in" provision in current languages for an object to “advertise” its interfaces. The result is that the programmer needs to have some idea what interface to ask for [7]. In contrast, an agent can employ mechanisms such as the directory facilitator, mentioned above, or specialized broker agents to which other agents can make themselves known for various purposes, but are otherwise unlisted to the rest of the agent population.

## 5 EVALUATION

The preceding comparisons between agents and objects are not specific to manufacturing, nor to control. One should therefore question to what extent the above conclusions are applicable, particularly when considering a relatively simple application such as the control of a manufacturing cell or a subsystem contained by it, as in the intended application of RMS for CBI. This section therefore reconsiders the comparisons and also a number of other issues, with the specific application in mind. Figure 2 summarises the key differences.

### 5.1 Encapsulation of Behavior

Consider the external vs internal "unit invocation" difference shown in Figure 1 and the related issue of encapsulation of behaviour, in the context of a holonic control architecture: for a holon there is little difference in the logic, and its implementation in coding, between an agent-based and an OOP approach. An object can just as easily be programmed to initiate its own methods as an agent can initiate its own behaviours. Also, the programmer can decide which of an object's methods are publically accessible and can therefore expose no more than a communication interface, thereby mimicking this property of an agent. In agent platforms such as JADE, the ideal is that each agent runs in its own thread, which can be limiting for manufacturing control scenarios. However, objects running different methods in different threads (e.g. to handle communication or diagnostics in parallel with other activities) is commonplace.

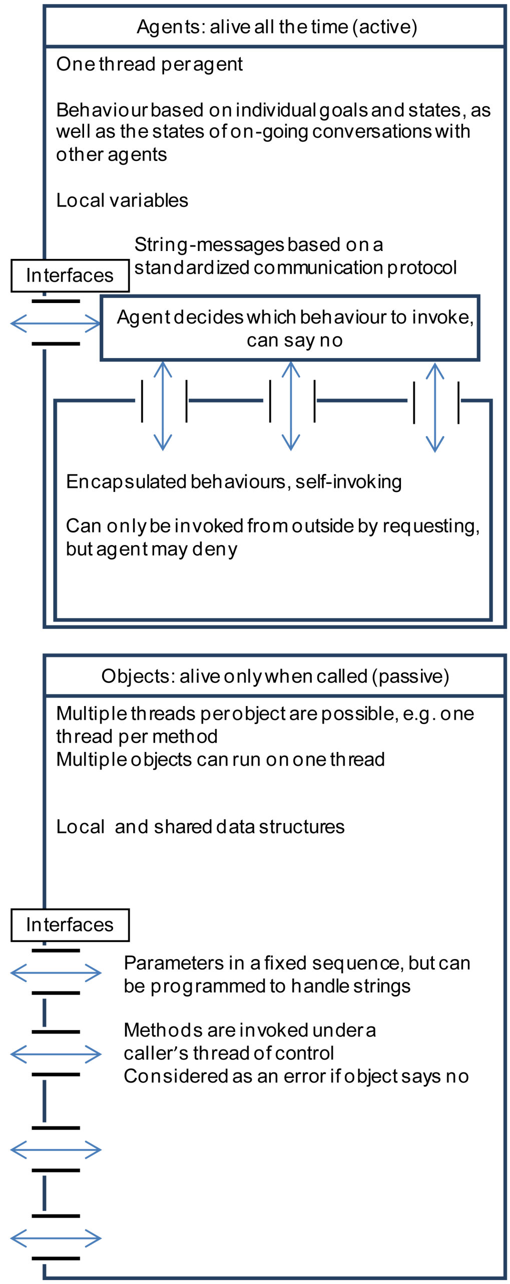


Figure 2: Key properties of Agents and OOP.

Regarding the, in theory, different active vs reactive natures of agents and objects, again in a holonic control architecture for a manufacturing cell, there is little difference between the logic and programming that will be required for agents and objects. This is even more so since some OOP implementations now have event-listener frameworks giving objects some of the dynamic capabilities of agents.

### 5.2 Dynamics, Complexity, Autonomy and Hierarchy

As mentioned in the Introduction, RMSs are aimed at dynamic situations. As can be seen from Section 4, agents are well suited to adapt themselves to dynamic situations. Objects do not have all those capabilities built into them. For an OOP based system to be as autonomously reconfigurable as agents, designers would need to implement many of the standard ABC features in OOP, and then agents might just as well be used in the first place.

The advantages that agents offer in terms of emergent behaviour and reasoning are significant for complex systems and highly dynamic situations. Unstable and unpredictable environments benefit from decentralization and self-organization [7]. In manufacturing systems, complexity arises from the large number of interacting subsystems, for instance the transportation system responsible for the material flow in a factory containing many cells. Optimizing such a system would be challenging and time consuming, but systems consisting of autonomous, proactive agents have emergent behaviours which allow for optimization to be done automatically if the correct rules are set for the agents.

On the other hand, for scenarios where the systems are relatively simple and/or reconfigurations are infrequent, the autonomous reconfiguration capabilities are of less value, and it might be more cost effective for humans to provide inputs [10]. The systems that are being considered for CBI are cells containing subsystems such as 6DOF-robots and automated riveters, for which material flow and resource management is much simpler than for an entire factory. The control system of a manufacturing cell with limited (if any) redundancy, is a relatively simple system. Handling of, for example, disturbances (such as subsystem break-downs or unanticipated changes to production schedules) and throughput optimization are therefore simple enough to be handled effectively by a hierarchical control approach.

The Contract Net Protocol is well suited for a holonic system, but is not needed for a hierarchical system, since decision-making is done on a higher level, and decisions are enforced on the holons situated on a lower level in the hierarchy. The directory facilitator of agent platforms is very valuable when handling autonomous reconfiguration of systems. However, there is little need for such autonomous reconfiguration in many industry applications. Particularly if reconfigurations occur relatively infrequently or have a fairly predictable nature, it is feasible to provide HMIs that can be used to provide not only the functions that a directory facilitator would, but also diagnostic and manual override capabilities.

### 5.3 Modularity and Integrability

In terms of modularity and integrability, which are key aspects of RMSs as described in Section 3, agents offer little advantages over objects. Both agents and objects that represent holons will have to provide a communication interface to other holons. An agent platform will provide some infrastructure to handle these messages, while an OOP-based approach will have to build it up from a lower level. In the case of agents, at least an application specific ontology, and possibly also an inter-agent communication language, must be designed. The equivalent effort will be required for objects that are running in different platforms, for example using TCP/IP sockets and XML encoding. Further, for objects in the same executable code, a library of object types based on one or more abstract classes, as used in e.g. C++ and C#, can provide a means of specifying a standardized interface, thereby simplifying integration and customization.

Another practical consideration is that many popular agent platforms are programmed in Java, which is much more cumbersome to interface with hardware than, for example, common OOP platforms like C#. In the CBI application, which involves the control of the subsystems of reconfigurable manufacturing cells, there are a large number of interfaces between controllers and hardware. Using Java-based tools in such a context is therefore less integrable than C#.

### 5.4 Hard and Soft Real Time Requirements

One of the significant limitations of agents, in a machine control situation, can be their autonomy: each agent has autonomous control over its own behaviour. In many machine control situations, specific sequencing or timing of actions is required for safe and efficient operations. Close timing or rapid sequencing that are guaranteed and safe, is therefore difficult to achieve when multiple agents are involved. Such timing is easier to achieve with objects running in the same thread, but unless a real time operating system is used, there is still a measure of uncertainty in the timing. One can therefore conclude that agents are not suited to any form of real time control, while objects are suited to so-called "soft real time", where latencies of approximately 50 ms or more are acceptable.

Another limitation of the agent platforms considered by the authors is that no provision is made for allocating agents different levels of priority in their allocation of CPU time, while it is easier to allocate priorities to threads using standard OOP implementations. An manufacturing scheduling optimization algorithm can be therefore run in one thread at a lower priority on the same CPU as another thread running timing-sensitive machine control routines. This approach may not fully obviate the need to separate the “intelligent” part of the system from the real-time part of the system [9] and to use a layered architecture consisting of low level controllers (LLCs) and high level controllers (HLCs). Traditionally LLCs would be written in software which allows for exactly predictable timing, whereas HLCs would be written in software more suited to implementing complex algorithms and that are more amenable to reconfiguration. LLCs are usually more difficult to reconfigure, particularly when more complex algorithms have been implemented. Therefore using OOP instead of ABC for the HLC will allow more functionality to be moved from the LLC to the HLC, thereby enhancing reconfigurability.

## 6 CONCLUSION

The Agent Based Control (ABC) approach is the de facto standard for controllers for Reconfigurable Manufacturing Systems. However, due to industry's reluctance to adopt ABC, an object-oriented programming (OOP) approach is considered in this paper as an alternative. OOP is more widely used and has many capabilities that are valuable when implementing an RMS.

The paper has shown that ABC's advantages can be decisive in complex, highly dynamic systems requiring autonomous reconfiguration. However, in simpler systems and systems where timing and sequencing are important, OOP will have significant advantages. For CBI, the industry partner of this research, the advantages of OOP exceed that of ABC, primarily since autonomous reconfiguration and emergent behaviour are not high priorities in their situation, while OOP provides better integrability with hardware.

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# Towards Alternatives for Agent Based Control in Reconfigurable Manufacturing Systems

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**Abstract**
Most researchers in reconfigurable manufacturing systems (RMSs) have used the agent based control (ABC) approach, because the capabilities of agent based software and their development platforms make it easier and quicker to test their research. Due to the reluctance of industries to adopt ABC, this paper considers the factors that would affect the choice of alternatives for ABC, with an emphasis on cell-level control rather than on factory-level control or production planning related aspects. The paper shows that design considerations include reconfiguration level, self-reconfiguration intelligence and controller platform splitting. Some design choices will lead to ABC having significant advantages, while others will allow the use of software approaches more often used in industry.

**Keywords:**
Reconfigurable; agent-based; control

## 1 INTRODUCTION

The South African industry has an increasing need for automated manufacturing. However, the conventional form of automation is not cost effective for the low volumes and high variance of products that are found there. The reconfigurable manufacturing system concept potentially provides a solution for this dilemma.

Most researchers in reconfigurable manufacturing systems (RMSs) have used the agent based control (ABC) approach and some researchers even state that ABC is the only way of implementing RMSs [1]. RMS researchers use agents because the capabilities of agent based software and their development platforms make it easier and quicker to test their research [2].

However, ABC has not found general acceptance in manufacturing industries [1]. Although agent software has features that benefit RMSs, they also have features that are unnecessary or unattractive in the industrial environment [1, 3]. Since industry is reluctant to adopt ABC, alternative ways for controlling RMSs, that would be more acceptable to industry, should be sought. However, little has been published on the alternatives that should be considered and what factors should be considered when selecting an alternative.

The focus of this paper is therefore to review the considerations that would influence the choice of alternatives to ABC, within the context of the control of holonic and reconfigurable manufacturing systems. The emphasis here is on cell-level control rather than on factory-level control or production planning related aspects. The notions developed in the paper are applied in two case studies.

## 2 SYSTEM DESIGN REQUIREMENTS

The controller's design requirements, and therefore the requirements for alternatives to ABC, should be related to the requirements for the system that is being controlled. System requirements are therefore a good place to start.

Ideally, an RMS should exhibit the six core characteristics given by Koren, et al. [4], i.e.:

- Customization: flexibility limited to a part family.
- Convertibility: designed for future functionality changes.
- Scalability: designed for future capacity changes.
- Modularity: the system comprises distinct modules.
- Integrability: modules have interfaces suited for rapid integration.
- Diagnosability: designed for easy diagnostics.

Christensen [5] derived the following key architectural requirements for holonic system architectures:

- Disturbance handling, availability, robustness
  - Provide intelligent system elements for self- and cooperative planning, scheduling, fault recognition, diagnosis, and repair.
- Human integration
  - Provide more intuitive, flexible, responsive, user-customizable human interfaces.
  - Provide “intelligent assistants” to augment human intelligence and prevent human error.
- Flexibility
  - Provide greater human control over system configuration and functionality.
  - Provide self-reconfiguration (“metamorphic”) capabilities.
  - Support continuous/incremental changes in roles and relationships of system elements (“fluidity”).

In addition to the above-mentioned requirements, some industries, e.g. the industry partner in the case study discussed below, are so concerned about the reliability of complex high level controllers that they may require that the subsystems in the RMS must be able to be operated without the central controller, i.e. the option must be available to revert back to a form of manual control when a part of the HMS fails. Manual control options can also be used to do trial runs of new products or small, ad hoc batches.

## 3 RECONFIGURATION LEVELS

When considering alternatives to ABC for RMSs, the authors found that the type of reconfiguration, envisaged at system design time, will have a significant influence on the functionality that is required

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from the control system. The type of reconfiguration, the frequency of occurrence of the reconfiguration and the acceptable down time should be taken into account in determining the properties required.

For the purposes of control design, it is useful to distinguish between the following levels of reconfiguration:

Low-level reconfiguration, which usually relates to customization, is typically a change within a product family that can be accommodated without significant physical changes in the RMS and only operator-level human input (no particular technical skills). An example is a change in the sequence of operations or an exchange of similar parts.

Low level reconfigurations can usually be accommodated in IEC 61131-type PLC programs, either through an HMI (human-machine-interface) or in response to commands from a higher level controller.

Medium-level reconfiguration, which relates to some applications of convertibility, is for example a change in the target product family that was or was not anticipated when the system was designed, but still requires changes and/or setting parameters that can be done by the operators, e.g. changing fixtures or grippers. An operator would provide reconfiguration information to the control system about the new product family and the physical changes. This level requires specific training, but also rudimentary technical skills.

Medium-level reconfigurations often can be accommodated in IEC 61131-type PLC programs, but more advanced software functionality (such as IEC 61499 and object orientated programming) could in some cases be beneficial.

High level reconfiguration, which can be encountered when applying some cases of convertibility and scalability, entails the introduction of a new subsystem into the RMS, the removal of a subsystem or a combination of the two. A reconfiguration of this nature could require engineering level supervision. These changes can include wiring changes and control software changes. The engineer would also have to supervise the ramp-up phase when the system is tested after reconfiguration.

When considering the impact of the level of reconfiguration on the choice of control software, it is clear that ABC (with functionality such as the directory facilitator and a contract net protocol) can have significant advantages for high level reconfiguration, but even then the cost of the initial development should be balanced by reconfiguration cost over the system's lifetime (this balance is addressed in the next section). If high level reconfiguration is unlikely, then control approaches that do not require the high level of training that ABC does, become much more attractive, both from development cost and reconfiguration cost perspectives.

## 4 SELF-RECONFIGURATION INTELLIGENCE LEVEL

This section considers the question: Given the number of reconfigurations expected by the client, to what extent should the control system be able to reconfigure autonomously. This question is relevant when looking for alternatives to ABC since ABC is well suited to highly autonomous reconfigurations, but there will be situations where the development cost required to provide the autonomy is not warranted.

To help answer this question, Le Roux [6] developed a model that employs the concept of "self-reconfiguration intelligence" ($I_{SR}$) to guide the controller design process. $I_{SR}$ is an index (between 0 and 1), representing the ability of the controller to autonomously reconfigure, where 0 is for completely manual reconfiguration and 1 is for completely autonomous reconfiguration. Le Roux's model trades off $I_{SR}$ with the human effort required for controller reconfiguration, i.e. when $I_{SR}$ is high, then required human effort is low, and *vice versa*.

The model assumes that when $I_{SR}$ is small, then small (low cost) additions of computer intelligence can dramatically reduce the human effort (and associated cost). This effect can be seen from the impact of many low intelligence computer programs (e.g. word processors) that are widely used in offices. Conversely, the development cost of a system with a high $I_{SR}$ will be substantial, but can be reduced significantly by a small addition of human effort. For example, consider a control system that is able to fully reconfigure itself (after a human arranged and connected all the hardware) by executing randomized actuations with its actuators, measuring hardware activity with sensors and discover its own configuration [7]. Such a system must make use of state of the art machine learning technology to slowly discover things, while a human operator can easily discover the same information about the system at low cost.

In addition to $I_{SR}$, the number of times a system will be reconfigured, $R_N$, should be taken into account. If $R_N$ is large, the higher design cost investment associated with a high $I_{SR}$ may be warranted. Le Roux [6] suggested the following relationship for the combined cost of controller design and controller reconfiguration, $C_{dr}$:

$$C_{dr} = a\,I_{SR}{}^2 + b\,I_{SR} + R_N\left[C_{asr} I_{SR} + C_{msr}\left(\frac{C_{hyp}}{I_{SR}+s} - s\right)\right] \quad (1)$$

The first two terms represent the controller design cost in addition to what would be incurred for a system relying on fully manual reconfiguration. If $I_{SR}$ is small, then one would expect its effect on $C_{dr}$ to be small too, while its effect will increase rapidly as the value increases. The simplest approach would be to assume that

$$b = \left.\frac{\partial C_{dr}}{\partial I_{SR}}\right|_{R_N=0;\,I_{SR}=0} \approx 0 \quad (2)$$

The coefficient $a$ then can be obtained for a particular case by estimating the additional controller design cost to reach a typical level of $I_{SR}$, e.g. $C_{dr} = 10^6$ when $I_{SR} = 0.2$, giving $a = 25\ 10^6$. Clearly, if cost estimates for two values of $I_{SR}$ are available, it will allow the calculation of estimates of both $a$ and $b$.

The term in square brackets in Equation 1 represents the cost of one reconfiguration, with $C_{asr}$ and $C_{msr}$ respectively the cost of one fully autonomous ($I_{SR} = 1$) and one fully manual ($I_{SR} = 0$) controller reconfiguration. The coefficients $C_{hyp}$ and $s$ determine the shape of the hyperbolic relationship between $I_{SR}$ and human effort, with $s$ given by the following equation (please refer to [6] for details):

$$s = 0.5\sqrt{1-4C_{hyp}} - 1 \quad (3)$$

Using typical values for the inputs required in the preceding equations, Figure 1 shows the shape of the cost surface (normalized by the manual reconfiguration cost, $C_{msr}$) and the optimum $I_{SR}$ as the expected number of reconfigurations change.

The method presented in this section will be useful when considering a scenario with high level reconfiguration (where increasing self-reconfiguration intelligence can have advantages), but not for low level reconfigurations.

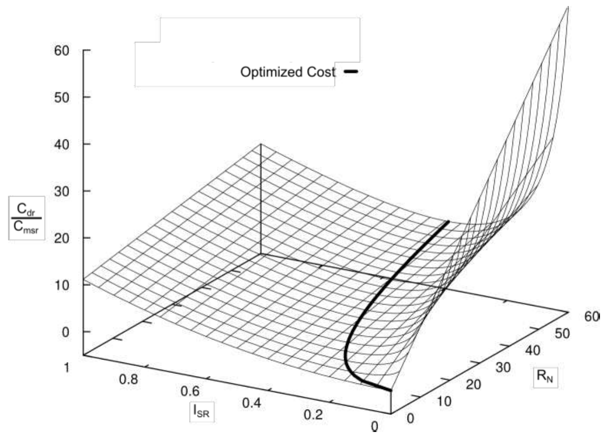


Figure 1: Controller design and reconfiguration cost vs self-reconfiguration intelligence level ($I_{SR}$) and number of reconfigurations ($R_N$) [6].

## 5 RESOURCE CONTROLLER SPLITTING

Another factor to consider, when evaluating alternatives to ABC, is how the control functions are split up, particularly when considering resource holons, RHs (in terms of PROSA [8], or operational holons in terms of ADACOR [5]). Other holon types, e.g. product holons (PHs) or order holons (OHs), are normally not split up.

A commonly used division in a resource holon is into a high level controller (HLC), a low level controller (LLC) and a hardware component (HW). In such functional splitting, the HLC is normally responsible for communication with other holons as well as managing the resource/hardware. This includes resource-level planning, scheduling and diagnostics (system level planning and scheduling are handled by other holons). The LLC normally handles real time control aspects and manages the detailed operation of the hardware it controls. It is also responsible for the safety and diagnostics of the hardware.

Control functions other than those mentioned in the previous paragraph can be assigned to either the LLC or the HLC, depending on various factors. This separation of responsibilities can be useful to address the need for both real-time control and higher levels of controller intelligence. Some of researchers [9, 10, 11, 12, 13] use IEC 61499 as the control software for the LLC, while using agents for the HLC.

In a manufacturing system, a resource holon's software part can reside on more than one platform (e.g. some parts on the same computer as the central controller and others on a PLC or industrial PC at the hardware). Therefore, in addition to considering functional splitting between a HLC and a LLC, the physical control hardware where each of the control functions is located (platform splitting), must also be considered. Platform splitting decisions affect a system's design cost, procurement cost and reconfigurability.

The level at which platform splitting is done depends on the physical layout of the system, the purpose of the resource, as well as the hardware used in the resource holon. Three levels of splitting can be considered (Figure 2).

In considering splitting, it should be kept in mind that in many practical holonic systems, the holons are structured into a hierarchy of holons, i.e. a holarchy. In such a system, a holon at one level will in itself consist of a set of lower level holons. For example, a resource holon's control can internally be structured into lower level product, order and resource holons. The most appropriate level for functional and platform splitting may be different for different levels of the holarchy.

HW-level platform splitting:

This is the one extreme splitting option where the product holon, the order holon and the software for the resource holons (assuming PROSA is used) are located on one platform, i.e. the HLCs and LLCs of one or more resources are located on a main controller, and the LLCs interact with the resources' hardware through distributed IO if the controller is remote from the hardware or regular IO if the controller is close to the hardware.

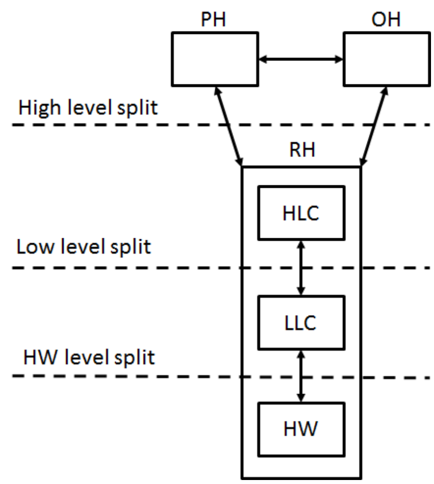


Figure 2: Levels of platform splitting for a resource holon.

Even though a holonic approach is used for the control development, externally the control system appears to have a centralized controller architecture. Adding/removing a resource to/from such a system will require modifications to the main controller, which can disrupt other holons. Such modifications will also require that the person doing the modifications has knowledge about the main controller.

The integrability of the system will be reduced by this approach if the controller and the hardware are seen as separable modules in the system, since the IO connections are often complex and hardware specific.

Introducing manual control options in this approach can become complex if numerous resources are handled by the same main controller. The HMIs all have to be provided by the main controller since without the main controller, the system hardware will be completely unusable.

One can therefore conclude that this approach would be more appropriate for simple systems, e.g. in lower levels of a holarchy where holons are responsible for relatively simple resources, or for situations where only low level and/or very infrequent reconfigurations are anticipated. In such situations, the complexity of the additional interfaces created by splitting the control is not warranted by the advantages of the finer level of modularity.

High level platform splitting:

The other extreme splitting option is where the resource holon's software is located on a different platform from the other holons. Typically the resource holon's controller will be close to its hardware.

An advantage of this approach is that the resource can be modified without affecting the main controller, as long as inter-holon communication is unaffected by the changes. Adding or removing a resource holon will require changes in the main controller and the associated human effort will be determined by the $I_{SR}$, as described in the previous section. However, since a whole resource is moved, it would typically require much simpler changes to the main controller than when HW-level platform splitting is used.

Because the HLC and LLC are located on a platform specifically allocated to the resource, manual control or human integration will have a small effect on the main controller. Manual override can take place at the HLC or the LLC. Manual override at the HLC will allow a human to replace the order and product holon interface to the resource holon. The HLC will also still be able to provide advanced diagnostics and control during a manual override. Introducing manual override at the LLC will allow more direct control over the hardware, thus allowing tasks to be performed that HLC does not provide for, but will require more human effort to perform tasks already provided for in the HLC.

From the above, it is clear that high level platform splitting will have substantial advantages for complex resources, e.g. a transport system that involves a conveyor with multiple movement paths. The internal details of such a complex system (and any reconfigurations thereof) are hidden from the main controller. Also, if manual control is required for a resource, then high level platform splitting is likely to be advantageous.

<u>Low level platform splitting:</u>

In this arrangement, the HLC is located on the same platform as the product and order holons in a main controller, while the LLC is located on another platform, typically near the hardware. A custom communication protocol will be required between the HLC and the LLC, such as using XML-formatted messages exchanged using TCP/IP sockets.

This arrangement would suit a situation where different software and hardware is required for the LLC and HLC, e.g. respectively IEC 61131 on a PLC and ABC on a PC. Such an arrangement allows the use of software better suited to implementing complex intelligence in the HLC and software capable of hard real-time for the LLC.

Manual control over the LLC will be relatively simple to introduce with low level splitting, since the HMI can communicate with the LLC using the same protocol as the HLC.

## 6 CASE STUDIES

### 6.1 Background

The most suitable level of reconfiguration, self-reconfiguration intelligence and level of platform splitting will be influenced by the particular application and the envisaged frequency of reconfigurations. This section therefore demonstrates the use of the notions presented above, in two subsystems of a laboratory-scale RMS.

CBI Electric: Low Voltage, the South African industry partner supporting this research, assembles circuit breakers in a factory in Lesotho. Most of the assembly operations are done manually due to the large product variety compared to modest (by international standards) production volumes. However, CBI is considering automating some of its assembly and testing operations with the objective of improving consistency of quality. CBI requires the ability to turn off the advanced automated control and to be able control the subsystems using HMIs. This is necessary because they occasionally have to do small ad hoc batches of specialist products. Another factor is that the assembly plant is in a rural area, more than 300km away from the technical support and, in the event of a fault occurring in the system, they want to be able to continue production.

Due to the high product variety and batch mode of CBI's production, conventional automated systems would be too expensive. As a first step towards determining whether an RMS will provide a feasible (technically and financially) solution for CBI's needs, Stellenbosch University has been developing a laboratory-scale reconfigurable assembly system. This system comprises a pallet magazine, a feeder subsystem, a mock spot-welding robot, a testing/inspection station, a transport subsystem that moves pallets (which house fixtures) between the other subsystems and a cell controller. A holarchy based on PROSA is used, with the system-level product and order holons located on the cell controller and each physical subsystem allocated to its own resource holon. Some of the resource holons are internally also structured as a set of holons. The system was designed so that product-specific information is retained only by the cell controller (in the product holon).

In this paper the transport subsystem and the welding robot are considered. The former is a relatively complex subsystem, while the latter is much simpler, but still comprises separable modules.

### 6.2 Transport Subsystem

The transport subsystem is a Bosch Rexroth TS2 Plus conveyor (Figure 3) that transports pallets between the various stations of the cell. The conveyor includes a central circuit, transverse conveyor sections, a parallel section, a feed-in/feed-out section leading to the pallet magazine and positioning units at each station. The main conveyor sections run continuously and pallets move with the conveyor unless they are stopped by stop gates (at e.g. intersections with transverse conveyors or at position units). The pallets each carry a product-specific fixture and in this case study provision was made for 3 different products. The pallet magazine houses the different types of pallets and moves the pallets onto/off the conveyor as required by the production schedule.

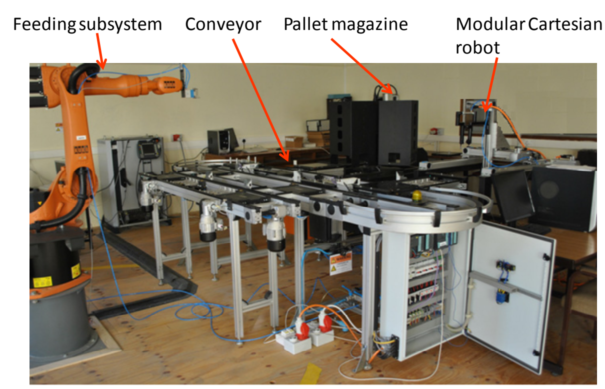


Figure 3: Assembly cell used for case study.

Since the conveyor has a substantial number of actuators and sensors, and requires safety-critical sequencing for normal operation, a PLC using IEC 61131-3 software was chosen as LLC. However, the PLC does not provide the necessary programming capabilities to employ more advanced approaches, such as IEC 61499 function blocks or ABC. Therefore the HLC is located on a PC. The HLC provides a resource holon interface to the cell controller, but is structured into internal product, order and an resource holons. The internal holons are at a lower level in the holarchy than the cell controller's resource holon.

The communication between the HLC and the cell controller are operational (e.g. move a pallet from one station to another) or diagnostic (e.g. report status). The HLC launches an internal order holon for each operational command received. All the routes that the pallets could take are contained in an internal product holon. The order holons therefore obtain the required route for a specific pallet from the product holon and then passes commands through the internal resource holon to the LLC. In this way, the HLC keeps track of all the pallets on the conveyor.

The HLC and LLC communicate through a data table. The LLC was programmed to receive instructions in the form of transitions, which entails moving a pallet from one position to the next position on the conveyor. The program of the LLC contains all the possible transitions and these transitions are activated by the HLC using the data table mentioned above. The route that the product holon gives to the order holons is therefore in the form of a sequence of transitions.

In this case study, a low level reconfiguration would typically be a change in the order of operations for a part. Since this change will be implemented by the cell controller, it requires no reconfiguration on the transport subsystem. A medium level reconfiguration would typically be replacing the fixtures on some of the pallets. For the transport system, this would not require any reconfiguration since the pallet magazine and cell controller would have the responsibility of ensuring that the correct type of pallet is used.

A high level reconfiguration for the transport subsystem would entail changing the physical layout of the conveyor system (e.g. adding/removing transverse conveyors, position units, etc). Controller reconfiguration would then require, in addition to the physical connections with the LLC, to set all the available transitions in the data table and to inform the product holon of all possible routes. To provide for a range of options in terms of the design cost vs $I_{SR}$, it was decided to also store the route information in a data table, which can be read by the product holon. When a new/changed path is defined, a new sequence is created in the data table and the HLC can then use the new sequence to command the LLC. If physical reconfigurations are expected to occur rarely, then the routing data table and the transitions data tables can be edited manually by a suitably trained technician. However, if reconfigurations are expected to occur more regularly, then the $I_{SR}$ can be increased by providing additional software tools (e.g. a "wizard") to simplify the updating of the data tables.

The use of the data tables for route definition and for communication between the HLC and LLC provides a convenient means for manual override. If the operator assumes the role of the HLC, he will have to also assume the duty of tracking the pallets and issuing the correct sequence of transitions, but if he assumes the role of the cell controller, then he needs only to issue commands like "take the pallet currently at station x to station y".

Low level platform splitting was considered inappropriate for the conveyor system, since it would burden the cell controller with complex IO, as well as complicating physical and software aspects of reconfigurations. On a cell level, high level platform splitting was employed for the transportation system, but internally there was also a low level split. Whether this approach is optimal, is not clear. One could consider including the HLC on the same platform as the cell controller (i.e. low level splitting on a cell level), which would reduce the number of platforms and interfaces, but would require the central controller to provide manual override capabilities (interjecting commands between the cell controller and the transportation resource holon). Manual control entering between the HLC and LLC can still be handled at the resource.

In the case study, ABC and IEC 61499 function blocks were evaluated, as alternatives, for the HLC. ABC was capable of performing the necessary operations, but much of ABC's features were not utilized. IEC 61499 function blocks were, on the other hand, found to be too restricted for the HLC [6] and had to be augmented with C++ for some parts of the HLC. A route that is subject to further investigation, is to implement the whole HLC in C++. Using C++ for the HLC would, however, make a low-level platform split less attractive, unless the cell controller is also developed in C++.

The above case study illustrates how the architectural design choices have an impact on the choice of a potential alternative for ABC, but also that ABC may be an "overkill" in many practical situations.

### 6.3 Modular Cartesian Robot

The second case study is a modular Cartesian robot that, in the RMS described above, positions a mock spot-welding head to simulate the fixing operations. A real spot welding head was not used for cost reasons. The robot has 3 Festo linear drives, mounted mutually perpendicular to create the X-, Y- and Z-axes. Each axis has a servomotor and its own motor driver, and the three drives are interfaced through CANOpen, with a Beckhoff IO card in a PC controller. The robot controller acts as a weld robot resource holon for the cell controller.

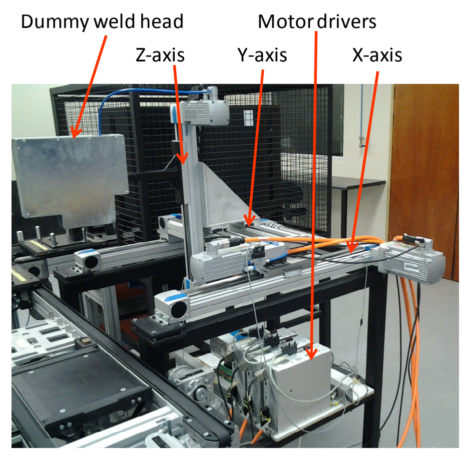


Figure 4: Cartesian robot.

The motor drivers each fulfill the role as an LLC, one for each axis. The robot controller contains a HLC, which coordinates the sequence of movements of the axes. Linear interpolation (simultaneous, coordinated movement of two or more axes) was not required in the case study and neither was a fourth (rotation) axis. For the sake of modularity in the controller, three identical intermediate level controllers (ILCs) were used too. Each ILC provided an interface between a motor driver (over CANOpen) and the HLC.

A typical sequence of events is as follows: The HLC receives the weld coordinates of the product that has to be welded from the product holon in the cell controller. If the positions are not stored in the motor drivers, the HLC first stores the new stop positions via the ILCs over the CANOpen bus. Assuming that the weld head is at a safe height, it moves the weld head to the correct X-Y-position and then moves the Z-axis downwards to the target position. It would then trigger the weld head and wait for the weld to be completed. After completing the weld, it moves the weld head upwards to a safe height.

As with the transportation system case study, a low level reconfiguration would typically be a change in the details of the operations for a part, e.g. changes to weld positions, or weld-head parameters (e.g. weld time and clamp time). These changes will be implemented by the cell controller and communicated to the weld controller. It therefore requires no reconfiguration on the welding subsystem. As before, a medium level reconfiguration could entail replacing the fixtures on some of the pallets, which will not require reconfiguration of the weld controller, as long as only 3-axis movement is still sufficient. A medium level reconfiguration could also include changing the weld electrodes, which may require some setting some parameters in the weld controller for the electrode positions relative to the robot axes.

A high level reconfiguration could be the replacement of one of the axes with one of a different length or the addition of a fourth axis. Replacing one of the axes with another Festo linear drive, would require technical knowledge to set the CANOpen interface and/or the motor driver, but would not require significant changes to the controller otherwise. Adding a fourth axis would, however, require significant changes since it was not provided for at design time. Automating some controller reconfigurations (such as replacing one Festo drive with another) by adding sufficient intelligence, is therefore possible, but other possible reconfigurations are too open ended to be cost effectively provided for at design time.

As with the transport system, a high level platform splitting arrangement was chosen, with the same pro's and cons applying. A hardware level platform split would not be feasible, due to the use of the proprietary motor drives. A low level platform split could entail either placing only the HLC on the same platform as the cell controller, or placing both the HLC and the ILC on that platform. Again similar pro's and cons apply, as for the transportation system. Modularity, integrability and manual control considerations make high-level platform splitting the most appropriate choice in this case too.

## 7 CONCLUSION

As stated in the introduction, this paper is aimed at helping to identify alternatives for ABC, due to the low level of acceptance of ABC in industry. Industry's view of ABC is in stark contrast to researchers in RMSs, who have extensively used ABC. It is the impression of the authors that these differences in acceptance of ABC are related to the differences in the selected levels of reconfiguration and self-reconfiguration intelligence. Researchers typically aim at the highest levels of reconfigurations and self-reconfiguration intelligence, while industry places greater emphasis on reducing controller design cost and provision for more moderate levels of reconfiguration. In the scenarios considered by researchers, the intelligence and "hot updating" capabilities of ABS hold significant advantages, but the same cannot be said of the more moderate scenarios anticipated by industry. Avoiding the need for an ABC's more advanced intelligence by providing a moderate amount of human input, can significantly reduce the design cost and also make it possible to use controllers more widely accepted by industry.

The considerations of platform splitting also affect the cost-benefit considerations of ABC. If hardware or, to a lesser extent, low level platform splitting is used, the complexity of the central controller's software will be such that ABC's modularity holds significant advantages. Whether these advantages, compared to other approaches such as object orientated programming, are sufficient to warrant the additional cost of using a programming approach that very few people in industry are comfortable with, is not clear. However, if a more distributed approach is taken, i.e. high-level platform splitting, then the benefits of using ABC is substantially reduced and therefore ABC will probably not be the best approach.

In summary: when considering alternatives for agent based control (ABC) for reconfigurable manufacturing systems (RMSs), this paper has shown that design choices made for reconfiguration level, self-reconfiguration intelligence and controller platform splitting should be considered. Some design choices will lead to ABC having significant advantages, while others will allow the use of software approaches more widely used in industry.

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# Performance Assessment of Heterogeneous Engineering Tools along the Development Process of Mechatronic Manufacturing Systems

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**Abstract**

Information technology tool chains are an integral component within development processes. When aligned optimally and adapted to the particular company's needs, they ensure process efficiency and product quality while transforming an initial idea into a mature solution. The increasing amount of discipline specific software tools in combination with the heterogeneous mixture of these tools from different software suppliers outline today's challenge in finding the optimal tailored IT tool chain. This paper describes a methodology that assesses the holistic performance of digital engineering tool chains and establishes a performance index for comparing various chains with each other by a hierarchy-oriented weighted scoring method.

**Keywords:**

Engineering Software Tools; Tool Chains; Mechatronic; Systems Engineering

## 1 INTRODUCTION

Engineering processes in production technology are influenced by continuous impact factors such as product individualization and functional integration [1-3]. Meeting these challenges, manufacturing companies need novel approaches to improve engineering processes. One example can be seen in the design and verification of mechatronic units. By enabling the reuse of components and the standardization of workflows, mechatronic units reduce the complexity of manufacturing systems. On the downside, the appearance of heterogeneous software systems within the engineering process can hardly be prevented [4].

The positive effects of information technology on engineering processes are undisputed, especially underlined by the reduction of development time and increase in process/ product quality [5]. The integration of mechanical, electrical and control engineering architectures, in terms of digital development tools, provides a constant challenge for users and system suppliers [4, 6, 7]. Thus, various constraints and limitations in the discipline-specific engineering systems arise [8, 9]. Engineering tools concentrate on suiting discipline specific requirements and omit current challenges, especially in the interdisciplinary transitions of development artifacts between heterogeneous software systems. Despite of standard data formats, description languages like AutomationML or product data management tools (for example Siemens PLM and PTC), interoperability of heterogeneous software systems has been of limited success [10]. The lack of contemplation of other disciplines leads to misunderstanding, quality and time losses in the engineering process [11].

The engineering processes in the past, present and future (Figure 1) amplify the verge of a paradigm change currently happening in the production industry [12-14]. The modular product character, supported by functional and system engineering approaches [10], enable production companies to gradually transform into a modular and fractal organizational structure [15]. Thus, the former hierarchical and process-oriented engineering cooperation transits to multidisciplinary organizations. Subsequently, a company-tailored and discipline-spanning solution must be developed. One approach can be seen in company-tailored software tool chains. The paper outlines a new evaluation methodology for the systematic selection to the optimal software tool chain.

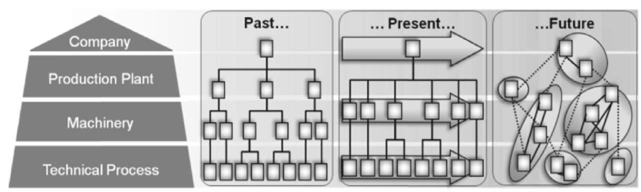


Figure 1: Evolution of Mechatronic Engineering according to [12-14].

## 2 PREREQUISITS

Today's production systems contain an increasing part of mechatronic components. They are characterized by a mechanical principle, driven by electrical devices and synchronized by complex software systems. This leads to a steady rise of functional integration and an increasing complexity of the technical systems [16]. In order to meet these challenges, interdisciplinary process models, like Systems Engineering [17], were introduced, which integrate all the disciplines in early phases of development process. To support these new approaches, several engineering tools are used that contain individual software modules with a particular functionality. In order to find the appropriate key to the lock, meaning, matching the appropriate engineering tool mix with the engineering process, both need to be assessed, current approaches merged and mutually aligned with each other.

## 3 STATE OF THE ART

In order to combine engineering processes and heterogeneous software engineering systems, the state of the art in the field of maturity measurements of engineering process, current strategies to modularize manufacturing systems as well as software evaluation and selection methods are presented in the following literature review.

### 3.1 Mechatronic Engineering Maturity

The maturity of engineering processes can be assessed by various types of methods. One example can be seen in the software industry. Due to high development failures and delayed projects in

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the 1980ies, the *Software Engineering Institute (SEI)* was founded aiming to reverse a decline of the US software industry. Thereby, various process assessment methods were developed leading to the most recent version of the *Capability Maturity Model Integrated (CMMI)* in 2006 [18]. The CMMI differentiates between two points of view: The assessment and improvement. Furthermore, companies are separated in the categories by its maturity level [19]. In accordance to the CMMI for the software development process, similar assessments have been developed for the mechatronic engineering process. One example can be seen in the maturity model described by Rauchenberger [20] and Spiegelberger [21]. They developed a mechatronic maturity model, having four maturity levels and six process areas in order to evaluate companies: project planning, project traceability, requirements, quality and configuration as well as supplier management. Other approaches add further categories such as organization, technology and human factors [22, 23] to the pool of criteria.

The maturity models are instruments to evaluate process quality, identify potentials and help to measure process improvements. Nevertheless, the above mentioned models often neglect the impact of the heterogeneity and interoperability between the various development software tools along the engineering process.

### 3.2 Mechatronic Modularization

Modular system kits, mutually exclusive and collectively exhaustive, support flexibility and customization in order to fit costumer needs [24]. The growing complexity in the engineering of machines and plants can be curbed by flexible and interconnected standard modules [25] that are assembled according to customer needs [26]. The modular notion does not only exist in the product and production environment, but is also common in engineering software solutions [27]. Due to the different understanding, a gap emerges between the system-oriented, mechatronic user perspective (production industry) and the information-oriented view of the IT solution suppliers of digital engineering tools.

The modular design of logical units is an established standard in the software industry and is also commonly used in the development of engineering tool chains by IT system suppliers [28-30]. For example generic programming, feature or aspect-oriented modularity and related derivatives as well as combinations are applied in order to increase reuse and dissolve the integrative context of software modules [31, 32].

### 3.3 Software Evaluation Methods

The quality of software products is often analyzed by qualitative assessments of functionality, usability, reliability, performance and support, so called FURPS [33]. The Carnegie Mellon University in Pittsburgh developed a fundamental methodology for analyzing software solutions. Based on the scenario technique and the integration of different stakeholders, the *Software Architecture Analysis Method (SAAM)* [34] has been developed and forms a basis for various derivatives of other performance evaluation methods for software systems [35] such as the *Cost Benefit Analysis Method (CABAM)* that introduces economic aspects in addition to software quality requirements [36].

However, the current approaches focus on individual software products and neglect the requirements of heterogeneous software tool chains [10, 37].

### 3.4 Software Selection Methods

Software quality assessments are important throughout the software life cycle in different industries. Thus, various evaluation attributes and selection methods exist for choosing between different software packages. With regards to various multi-criteria decision problem sets, an overview of frequently used approaches is outlined in the following paragraphs [38].

The Analytical Hierachy Processing, often referred to AHP, was introduced by Thomas Saaty in late 1970s and has been applied in wide variety of applications in various fields. The method considers objective and subjective factors in selecting the best alternative [38]. Thereby, it evaluates a complex system by multiple criteria [39]. The AHP ranks according to the overall objectives, calculates an eigenvector in order to obtain the priority weights and uses weighted sum of all decision alternatives to obtain the final weight of the overall objective [40] . AHP are well structured, flexible and well suited for multiple criteria problems. Nevertheless, the method is time consuming and sensitive to parameter changes.

The fuzzy multiple criteria decision making (FMCDM), as applied by Cochan for the evaluation of simulation software, uses the fuzzy set theory and algebraic operations of fuzzy numbers to characterize simulation software [41]. Thereby, it enables to deal with imprecise data and criteria that are vagueness inherent in its information [42]. Disadvantage of the method is the time consuming and complex calculation of fuzzy indices.

In comparison to the AHP and the FMCDM, the Weighted Scoring Method (WSM) enables to decide between various alternatives with deterministic criteria. Each alternative is rated with regards to each evaluation criterion [38]. Thereby, a decision matrix is calculated that includes the impact of each alternative on a set of criteria in the matrix. The weights represent the relative importance of each criterion. Contemplating m alternatives ($A_1$, $A_2$, .., $A_m$) and n criteria ($C_1$, $C_2$, …, $C_n$), $w_j$ represents the weight of importance of the criteria $C_j$ and $a_{ij}$ is the impact of the alternative $A_j$ when assessed considering $C_j$. The score of each alternative can be calculated by following formula.

$$S(A_i) = \sum_{j}^{n} w_j a_{ij} \;\; for\; i = 1, 2, 3, .., m.$$

Finally, a ranking of all alternatives can be generated. WSM is simple to apply, but the weighting is highly influenced by subjective criteria. Furthermore, numerical criteria are necessary in order to apply the method.

In summary, various evaluation and selection methods exist in order to choose between single software solutions. Current methodologies lack approaches for a decision making framework comprising evaluation criteria, selection method and techniques for evaluation [38, 43]. Furthermore current approaches rather concentrate on technology-driven factors and omit the engineering process, system oriented tasks and the specifics of interoperability and heterogeneity of software tool chains.

## 4 EXISTING CHALLENGES AND AIM OF THE PAPER

This paper describes a novel selection methodology for engineering software tool chains. Due to the previously outlined obstacles of current approaches, the methodology needs to

- be a holistic approach along the entire mechatronic engineering process of manufacturing companies,
- structure the evaluation based on the widely used principle of mechatronic units,
- account for heterogeneity and interoperability between software systems and
- outline a comparison for alternative software tool chains.

The paper concentrates on the mechatronic software tools that are commonly used along the engineering process in the machine and plant industry. A requirement for the application of the methodology is a mechatronic engineering process, as outlined by the German Engineering Federation [44].

## 5 EVALUATION METHODOLOGY FOR THE SELECTION OF SOFTWARE TOOL CHAINS

### 5.1 Overview

The evaluation methodology for the selection of software tool chains is divided into four main steps.

Firstly, technical and methodical constraints are elaborated and information dependencies are analyzed in state-of-the-art IT infrastructures, for example from the digital factory of the automotive industry. So, starting from the development task and the development process, a functional abstraction and modularization is established. Particular tasks of engineering companies are grouped according to the phase of the development process, mapped into a context framework for digital engineering tool chains and, thereby, represent the input for the performance assessment.

The second step uses a holistic assessment method. Beginning at the individual software modules up to an entire heterogeneous software tool chain, hierarchy specific performance indices are generated. The methodology comprises two evaluation categories: The evaluation of the single IT chain element, meaning the specific standalone software assessment, and the IT chain connection, meaning the degree of holistic integration with other software tools. Considering a single IT chain element, such as a specific software solution, the assessment rates the fulfillment of a specific task by the software tool. The IT chain connection is evaluated by criteria such as interdependencies between software tools, data integration and contingency of data models within IT infrastructures. Merging these criteria, a universal performance index assesses the performance of an entire IT tool chain.

The third step capitalizes the maturity of the engineering process and amends the technology-driven evaluation of tool chains. Thereby, a key-lock-principle is introduced helping to explain the interdependency between mechatronic process and its support by mechatronic tool chains.

Finally, the engineering tool chains with the according performance evaluation are related to each other and visualized in a decision cockpit. The cockpit displays a traffic light pattern to ensure a user-friendly interface and a possibility of engineering tool chains *quick-checks* for the management of engineering companies.

As a result, the methodology enables the comparison of different tool chains, increases transparency and helps to find an optimal company specific IT tool infrastructure. All steps are detailed and described in the upcoming paragraphs.

### 5.2 Modularization of Software Tool Chains

The development task and the associated development tools can be systematized according to the process hierarchy (Figure 2). At the highest level, digital tool chains focus the entire development task. These are mostly heterogeneous software products that can be further dissembled into individual software modules. Each software module provides a functionality of the engineering task and process. The complex process of assigning engineering functions to software modules is supported by a set of rules. For example, necessary functions are linked with software modules. A more detailed modularization might be necessary until proper rule fulfillment.

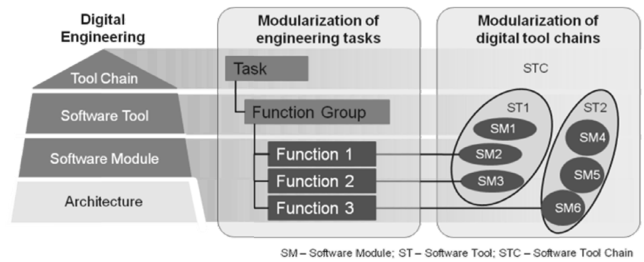


Figure 2: Classification of Engineering Tool Chains.

The linkage of the functional and the software tool perspective uses the principle of a domain mapping matrix (Figure 3) [45]. Starting with the main task of the production plant (e.g. *packaging processes)* functional groups can be formed. Each group incorporates various functions until a specific software module can be assigned to the function. A 1:1 relationship between function and software module is established. One example can be seen in the function *planning the engine wiring* which is assigned to a module of the software tool (e.g. EPLAN Engineering Center). The direct assignment of functions to the engineering tools enables the grouping of software modules and the generation of alternative engineering tool chains. The binary domain mapping matrices enable the linkage of dependencies within heterogeneous software systems. Thus, the approach provides the basis for the development of a holistic performance index as part of the evaluation framework.

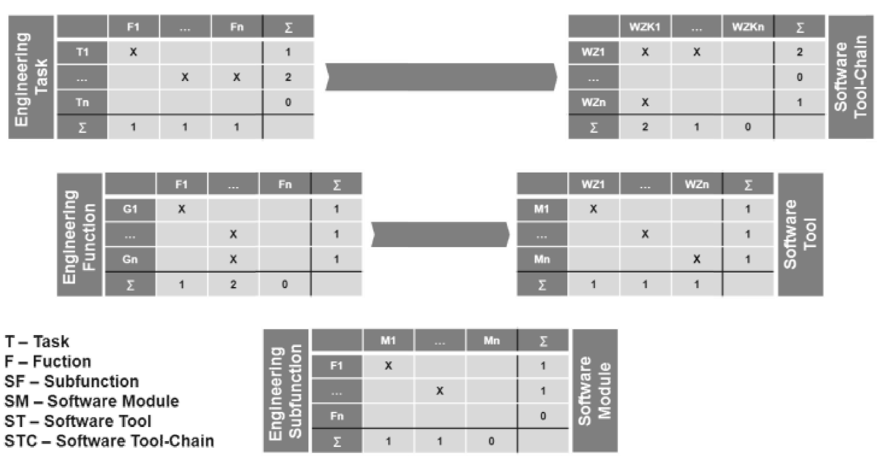


Figure 3: Function orientated decomposition of engineering tasks and composition of software tool chains.

The domain mapping matrices provide the link between specific engineering functions or sub-function and the selected tool chain. Thereby, a 1:1 relation is the required and optimal solution. For very complex engineering tasks with a variety of subfunctions, the proof of the capability can be a time consuming process. In this context the mapping matrices are used for an additional consistency check. For this purpose, the values of the rows and columns of single mapping matrices are summed, thus, the type of mapping can be derived. If the check sum is zero, the mapping has not been successful and the linkage between the needed function and the software module could not be established. In case of an over-determined relation (check sum lager than 1) the maturity of the modularization is not yet sufficient or the needed function is represented in several software systems. For example, a simulation system, such as a CAD system, provides the ability to create simple geometries. As a result of the consistency check technical performance indices, as shown in the next chapter, are scaled accordingly to the coverage ratio between engineering task and engineering software system.

### 5.3 Evaluation Framework

The evaluation framework focuses on the assessment of software modules and components of various software solutions. The performance indices are established by the means of various, mostly quantitative, key indicators. Thereby, discipline-specific as well as holistic aspects are considered, grouped and assigned to five main categories: tool chains, development tools, software modules as well as internal and external module interfaces (Figure 4).

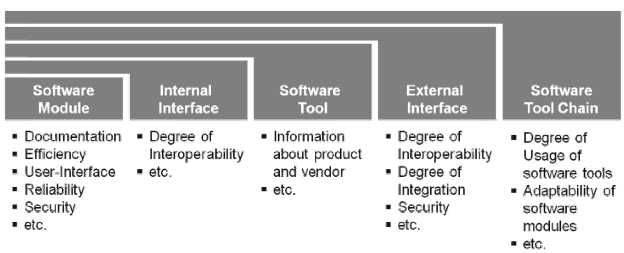


Figure 4: Scope of Evaluation.

The evaluation methodology of an entire tool chain is based on the mechatronic dissection of the IT landscape. Initially at a high level of detail, a technical performance index is calculated. Depending on the focus of analysis, various categories of criteria further scrutinize the approach (Figure 4). One example can be seen in the evaluation of software modules: The key indicator *efficiency* is assessed by the number of clicks and the elapsed time span, among other things, that is needed to perform the specific function.

The number of clicks helps to assess the complexity to perform a certain task by a user group with a software module. In combination with the elapsed time, you can calculate *efficiency* as one indicator that is included in the overall calculation of the performance index. Similar to the technology readiness level [17], the indicator *efficiency* is one example for assessing the readiness of an engineering tool chain for its application in industry practice. Further measurements have been established for the other indicators to ensure a quantitative assessment.

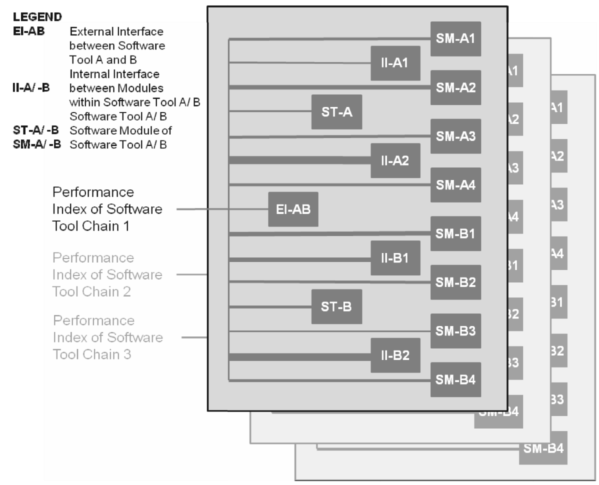


Figure 5: Performance Index calculated based on a hierarchy-oriented Weighted Scoring Method.

Based on WSM, a hierarchy-oriented calculation approach has been developed, that spans over the previously mentioned five main categories. Gradually performance indices are calculated and combined to an overall performance index for the software tool chain. Depending on the scope of evaluation, different evaluation criteria are formed and weighted according to the company-specific importance (weights are represented by the line width in Figure 5). As Figure 5 outlines, alternative software tool chains are evaluated. The layers of perspective orchestra the alternative software tool chains and render different keys which matching potential with a company-specific process profile can be further assessed by the key-lock-principle in the upcoming chapter.

### 5.4 Key-Lock-Principle

The key-lock-principle combines the mechatronic process maturity, elaborated by Rauchenberger and Spiegelberger [20, 21], and the mechatronic software tool chain.

The mechatronic process forms maturity levels along the engineering process (example in Figure 6, top). Herby, the paper fosters four mechatronic maturity levels: *classic (level 1), partially managed (level 2), managed (level 3)* and *advanced (level 4).* Imaging the engineering process as a company specific lock, that can only be opened by the appropriate key. The right key, represented by a combination of software tools, correspond to the maturity of the engineering process (lock). A high maturity level could eventually mean a high possibility of digitalization by software tools due to stability of process and the probably already high degree of information technology within the company. The bottom of figure 6 shows such an example, in which, with regards to the process phases requirements engineering and realization, the process maturity is high. Subsequently, the software tool chains within these phases should be of equal quality and reach at least a corresponding evaluation performance index. An analog software tool chain must be found when the companies profile shows a rather lower mechatronic process maturity level. In order to prohibit tension and initiate realistic targets for change within a mechatronic engineering company, the software tool chain should show a rather attainable level of specific performance indices.

The key-lock-principle is crucial to incorporate company-specific criteria into the selection of heterogeneous software tool chains.

Amending the context specific model as described by Drescher [46], it supports the increase of efficiency in the engineering process of machine and plant industry.

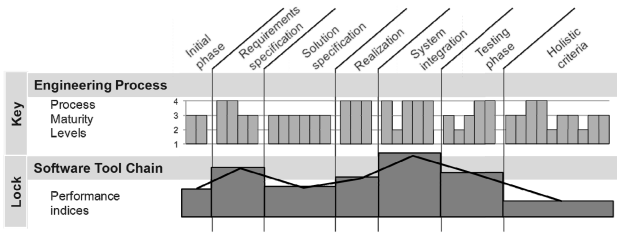


Figure 6: Example of the Key-Lock-Principle.

### 5.5 Selection Cockpit

Based on the established *performance indices*, a ranking is established that takes the function, technical interdependencies between various software tools and modules into account. Supporting the engineering process from the initial idea phase to the final product, each development software tool as well as the entire tool chain is evaluated on basis of a performance index with its key indicators. Figure 7 shows an example of a comparison between various engineering tool chains. Three different digital tool chains are compared and classified by a traffic lights pattern.

The performance indices range from zero to five and correspond to a specific traffic light: Green means a high, yellow a mediocre performance index and red corresponds to a high level of improvement potentials. The traffic lights are generated on each evaluation scope (as described in figure 5). Since the evaluation method bases on a hierarchy oriented approach, the weighted sums of key indicators (corresponding to the scope) lead to the performance index of the overall software tool chain and its corresponding traffic light.

Furthermore, Figure 7 outlines the importance of the company specific engineering process. It does not only build the basis for the evaluation in form of the engineering lock, but also outlines the importance to find the appropriate and corresponding software tool chain.

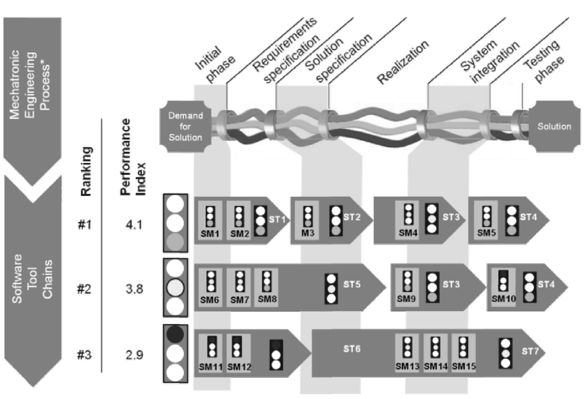


Figure 7: Evaluation Cockpit of Software Tool Chains.

## 6 SUMMARY AND OUTLOOK

The methodology outlines an evaluation and selection framework for software tool chains in the manufacturing industry. Thereby, it follows a four step approach: The modularization of the engineering software tool chains according to the tasks/ steps within the engineering process, an evaluation framework based the calculation of a performance index, a key-lock-principle between engineering process and IT system as well as a decision cockpit in order to find the best fit to company requirements.

The methodology fulfills current gaps in literature as well as industry. The modularization of software tool chains according to the engineering process is a novel approach to establish standardized tool kits in the future. The evaluation method contemplates heterogeneous software chains, which according to the state of the art, has not been considered so far. Besides the introduction of the key-lock-principle, the decision cockpit allows a comparison between different alternative software tool chains.

The methodology will be applied, further detailed and validated within a consortium of engineering companies in the automotive, packaging and medical area. Furthermore, current maturity models will be amended by the methodology to improve assessments with regards to heterogeneity and interoperability between software tool chains.

## 7 ACKNOWLEDGMENTS

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# A New Approach to Interpolation of Tool Path Trajectories with Piecewise Defined Clothoids

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**Abstract**

The tool path trajectory generation for CNC machining has been a main topic in the improvement of the manufacturing process for many years. Different approaches tried to merge efficiency and minimal tool wear with reasonable computing times. A smooth curvature progression of the tool path is a main requirement to limit jerks in all axes and thus ensure minimal tool wear. Currently this requirement is met by constructing tool paths with polynomials or smoothing simpler linear and circular curves. This paper presents an alternative interpolation method based on curvature-smooth clothoids.

**Keywords:**

G1-Interpolation; Clothoid; Cornu spline

## 1 INTRODUCTION

In the area of machine tools the machining results are heavily influenced by the tool path that is generated by a CNC. Well known generating methods are the rather simple linear and circular interpolation as well as advanced interpolation strategies with polynomial splines. Another approach is the here presented cornu spline interpolation method, that is derived from route planning.

### 1.1 Requirements for Interpolation in Tool Paths

In order to refrain from stimulating vibrations in the machine and to prevent the drives from damage, acceleration steps in the tool path trajectory have to be avoided to limit the jerk in all axes. This calls for a smooth-curvature tool path. A smooth-curvature tool path offers continuity in the first and second derivative [1]. Whereas various polynomial spline interpolation strategies already meet the required constant-curvature transitions, the linear and circular interpolation methods show neither tangentially constant nor curvature-constant transitions. Nevertheless, these interpolation methods are heavily used. When generating tool path trajectories through the CAD/CAM chain, for example, the primarily used interpolation methods are said linear and circular interpolation.

### 1.2 Existing Optimization Strategies

To optimize these tool path trajectories multiple strategies have been presented. CNC systems try to compensate the shortcomings of these interpolation methods with feed and curve optimization techniques at connecting path segments. Acceleration profiles like the smooth sinus-quadratic acceleration, for example, minimize the jerk that highly affects the machine wear [2]. This avoids stress on the spindle and machine that would be caused by unsteady acceleration. For small block lengths, however, this strategy keeps the machine from reaching maximal feed rates and thus lengthens machining times [3]. Hence, further strategies such as Look-Ahead or Smoothing of the generated tool path were developed to provide higher feed rates.

The Look-Ahead optimization plans the axis acceleration with perspective over numerous following blocks to lessen unnecessary breaking or stopping [4]. Smoothing on the other hand concentrates on the given tool path trajectory and evens out the transitions between two interpolation segments. The resulting path is quasi-curvature smooth and thus limits the jerk resulting from the followed curve. Even though the Look-Ahead is often successful in reducing machining times when a relatively smooth tool path is given [4], it often cannot prevent deceleration or stops if the progression of the curves does not allow fast transitions. The downside of smoothing is a lessened precision due to deviation from the original curve [1].

### 1.3 Strategy Used in Route Planning

In route planning for streets and railways, a different approach is taken to guarantee constant curvature transitions [5]. Safety and comfort issues due to the transition from straight tracks to curved tracks motivated the search for a connecting segment with a linear change in curvature. The mathematical element known as the clothoid or cornu spiral is used. They are defined by the demanded constant, linear change in curvature and were since used in route planning to connect any two different curvatures. Previous to the use of computerised calculations, value tables and stencils were used to design the connecting clothoids. Nowadays the calculation of the cornu spiral, which is based on Fresnel integrals, has been simplified by existing series calculations. The calculation costs of these numerical calculations are currently comparable to those of trigonometric calculations. The cornu spiral therefore has become an interesting option to be used in the area of CNC systems with its requirements for jerk limited tool path trajectories on the one hand and its real-time constraints on the other hand.

This paper presents an interpolation strategy based on cornu spirals. A given approach to the boundary value problem builds a foundation toward the development of a spline made of cornu spiral segments. The first part of the paper presents a closer look into the characteristics of said boundary value problem and the development of an interpolation method called cornu splines. In the second part, computation strategies for the cornu spline are presented and the applicability of such interpolation methods in the field of CNC machining is examined. Finally further perspectives are given on how an extension to an interpolation with constant curvature change, based only on clothoids, circular and linear elements, could bring up an interpolation method equal if not superior to currently used polynomial splines.

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## 2 FITTING A CORNU SPIRAL INTERPOLATION – A SOLUTION TO THE BOUNDARY VALUE PROBLEM BY WALTON AND MEEK [6]

In order to establish an interpolation that extends the currently used linear and circular interpolation, we take a closer look at the clothoid and its characteristics. The following section addresses the approaches by Walton and Meek [6] to interpolation with cornu spiral segments. A simplified representation and the calculation of needed variables are presented. The extension toward a multipoint interpolation offers the possibility to check basic characteristics of the created cornu spline. In the following discourse, cornu spiral and clothoid are used as equivalent terms when referring to the curvature constant spiral.

### 2.1 The Clothoid

The main element of the interpolation method is the cornu spiral, also known as Euler spiral or clothoid. In what follows, the tangent angle is denoted by $\theta$ , the arc length as $s$ and the imaginary number as $i$ . The distinctive feature of the cornu spiral is its gradual change in curvature $\kappa$ which is given by

$$\kappa(s) = \frac{d\theta}{ds} = \pi s \tag{1}$$

Integrating equation (1) yields the tangent angle as a function of the arc length and therefore defines the vector of the tangent in complex coordinates: $\xi' = \exp(i\theta)$. A second integration results in a complex representation of the clothoid in terms of Fresnel integrals.

$$\begin{aligned}\xi(\theta) &= \int_0^{s(\theta)} \exp\left(i\tfrac{1}{2}\pi s^2\right) ds \\ &= \int_0^{\theta} \frac{\exp(iu)}{\sqrt{2\pi u}} du\end{aligned} \tag{2}$$

The wound spiral shape of any clothoid is, except for scale, identical to that given in Figure 1. In order to satisfy certain boundary conditions, the unit clothoid given in equation (2) is scaled and transformed into arbitrary coordinate systems by

$$P(\theta) = P_0 + \rho\xi(\theta). \tag{3}$$

The parameter $P_0$ represents the origin of the clothoid. The parameter $\rho$ defines a scaling and rotation into the clothoid coordinate system. Both are complex numbers. With the general scaling parameter $a$ it holds

$$\rho = a\exp(i\varphi). \tag{4}$$

Another useful feature is the easy calculation of the arc length of any segment on the general clothoid (3). The arc length from the origin to a point $\theta \to P(\theta) \in \boldsymbol{C}$ on the cornu spiral is given by

$$l(\theta) = \int_0^{\theta} \sqrt{\overline{\left(\frac{dP}{d\theta}\right)} \frac{dP}{d\theta}} du = \int_0^{\theta} \sqrt{\overline{P'}P'} du = a\sqrt{\frac{2\theta}{\pi}} . \tag{5}$$

Thereby $P'$ denotes the derivative in respect to $\theta$ and $\overline{P'}$ its conjugated complex value. Consequently, the general case of a point to point arc length is given by

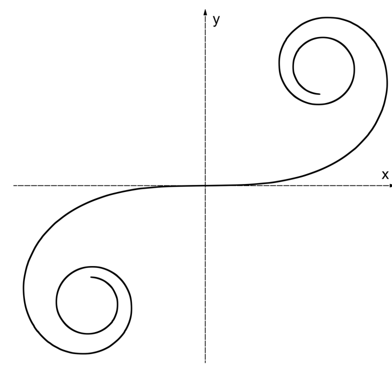


Figure 1: Shape of a clothoid.

$$\begin{aligned}l(\theta_0, \theta_1) &= l(\theta_1) - l(\theta_0) \\ &= a(\sqrt{2\theta_1\pi^{-1}} - \sqrt{2\theta_0\pi^{-1}})\end{aligned} . \tag{6}$$

This enables us to calculate the length of any segment on the spiral, provided that the curvatures $\kappa$ or main deviation angle $\theta$ of the start and end points are known. Figure 2 shows the composition of this calculation. As the calculation of the arc length, curvature at any given point of the cornu spiral can be easily computed due to the linear development of the curvature over its arc length.

### 2.2 Approach Presented by Walton and Meek

Walton and Meek's improved method of interpolation between two given points with defined tangent vectors with cornu spiral segments distinguishes between three different cases of interpolation cornu spiral segments:

- C-Shape with tangent vectors in start and end point pointing to opposite sides of the line connecting start and end point,
- S-Shape with tangent vectors in start and end point pointing to opposite sides of the line connecting start and end point,
- S-Shape with tangent vectors in start and end point pointing to the similar side of the line connecting start and end point.

They further provide a case-sensitive formula that allows finding a cornu spiral segment, and then fit it through scale, translation and rotation into the two given points to match the tangent vectors. The used variables and their relevance are collected in Table 1.

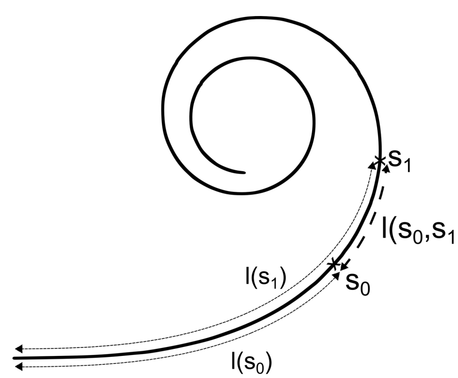


Figure 2: Segment length of the cornu spiral.

| Variable | Relevance |
|---|---|
| $P_1, P_2$ | Given points |
| $T_1, T_2$ | Given tangent vectors in P1, P2 |
| $D$ | Line segment connecting P1, P2 |
| $\phi_1$ | Angle from tangent T1 to the connecting line D<br>Referred to as tangent angle |
| $\phi_2$ | Angle from connecting line D to tangent T2<br>Referred to as tangent angle |
| $\theta_1, \theta_2$ | Angle between main tangent T0 of the cornu spiral and tangent T1 in point P1 / tangent T2 in point P2<br>Referred to as the main deviation angle |
| $a$ | Scaling parameter of the cornu spiral<br>Referred to as scaling factor |
| $P_0$ | Origin of the cornu spiral |
| $T_0$ | Main tangent of the cornu spiral |
| $N_0$ | Main normal of the cornu spiral |

Table 1: Variables and their relevance.

### 2.3 Complex Representation of the Walton-Meek-Approach

Motivation for a complex representation of the interpolation problem, as depicted in Figure 3, is an easier handling of the planar curve. The vector notation can be omitted, the rotation and scalar factor can be combined in a single term and the later developed function $f(\theta)$ offers a simple derivative that helps when solving for zero.

In complex coordinates the clothoid is defined as in (2). Using this representation any point $P_k$ on the interpolating segment is defined by its deviation angle $\theta_k$ as

$$P_k = P_0 + \rho\xi(\theta_k) \tag{7}$$

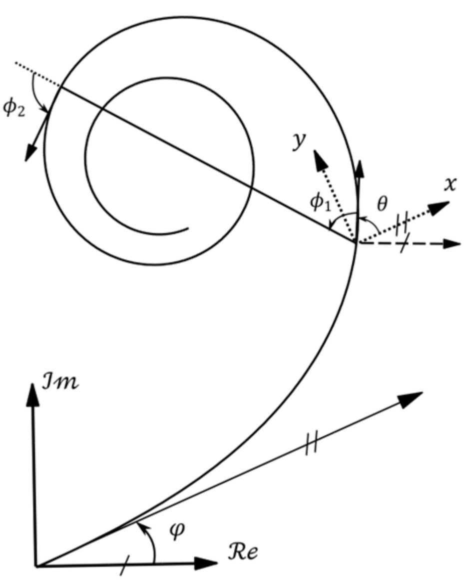


Figure 3: Complex representation of the cornu spiral.

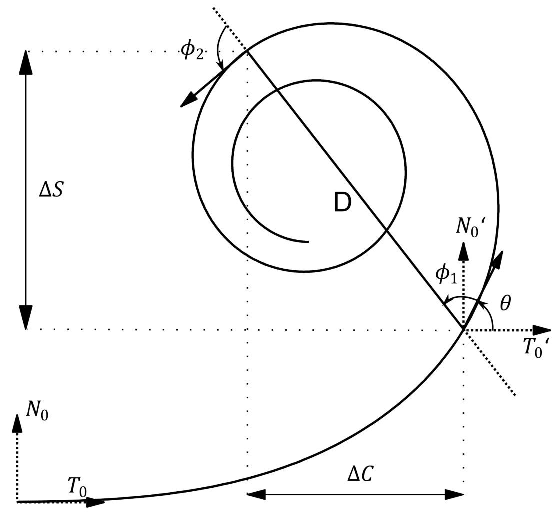


Figure 4: C-Shaped cornu spiral with measurements.

Define the following distance vectors on the unit clothoid (2):

$\delta_{C-Shape}(\theta) := \xi(\theta_2) - \xi(\theta_1)$ , and

$\delta_{S-Shape}(\theta) := \xi(\theta_2) + \xi(\theta_1)$ ;

or combined

$$\delta^{\mp}(\theta) := \xi(\theta_2) \mp \xi(\theta_1) . \tag{8}$$

See Figure 4 and Figure 5 for reference. In cases of C-Shapes the parameter $\rho$ is determined by the equation

$$P_2 - P_1 = \rho(\xi(\theta_2) - \xi(\theta_1)) = \rho\,\delta^{-}(\theta) , \tag{9}$$

where

$$\theta_2 = \theta_1 + \phi_1 + \phi_2 \tag{10}$$

defines the end point P2 of the cornu spiral.

The rotation into the coordinate system of the clothoid yields

$$\widetilde{P}_2 - \widetilde{P}_1 = |D|\exp(i(\theta_1 + \phi_1)) = a\,\delta^{-}(\theta_1) \tag{11}$$

A simple calculation leads to

$$\delta^{-}(\theta_1)\exp(-i(\theta_1 + \phi_1)) - \frac{|D|}{a} = 0 . \tag{12}$$

Since the imaginary part of this function does not depend on the real scaling factor $a$, it defines a condition for the angle $\theta_1$ to be fulfilled. The resulting equation has to be solved numerically.

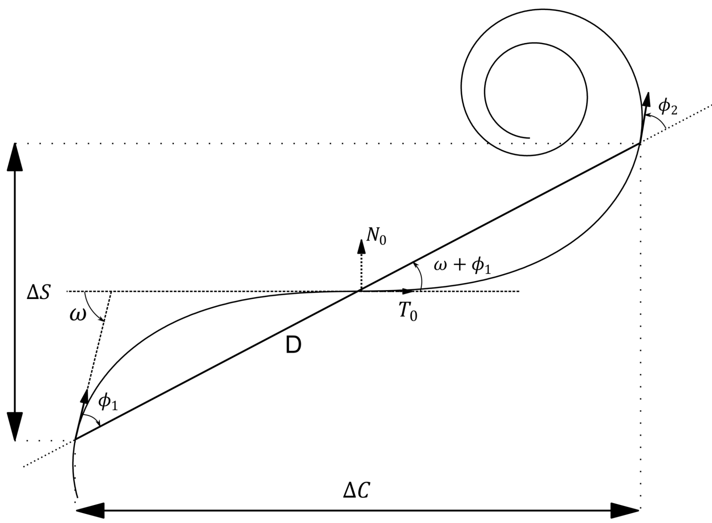


Figure 5: S-Shaped cornu spiral with measurements.

Once the initial angle $\theta_1$ is calculated, it defines the remaining parameters with

$$\rho = (P_2 - P_1)\delta^{-}(\theta_1)^{-1}, \quad (13)$$

and finally

$$P_0 = P_1 - \rho\xi(\theta_1). \quad (14)$$

The first formula to be evaluated is given by the imaginary part of formula (12)

$$f(\theta)_{C-Shape\,/\,S-Shape} = \delta^{\mp}(\theta)\exp(-i(\theta + \phi_1)). \quad (15)$$

It is to be solved for zero in order to obtain the main deviation angle $\theta_1$ for the starting point $P_1$ of the connecting spiral. The approach by [6] offers a similar formula. Their formula uses the possibility to describe a given point on the spiral either with trigonometric functions and the extent of the spiral or with the spiral parameterization itself. Therefore, if a solution to $\theta = 0$ is found, there exists a spiral segment that can be used as an interpolation element. The main deviation angle $\theta_2$ is not relevant for the evaluation of the segment's position, since it follows directly from the main deviation angle $\theta_1$. All following mentions of $\theta$ thus refer to main deviation angle $\theta_1$. The found main deviation angles $\theta_1$ and $\theta_2$ define the range of the unit spiral segment. In a second step, the scaling factor $a$ is found by evaluating

$$P_{0_{C-Shape/S-Shape}} = P_1 \mp \rho\xi(\theta_1). \quad (16)$$

The origin $P_0$ of the cornu spiral segment and the main tangent vector $T_0$ can be reconstructed with the found deviation angle $\theta_1$.

The so calculated cornu spiral segment is the interpolation element that fits between any two given points and matches their tangent vectors. The following shows the foundation for the previous formulae both for the S-shaped and the C-shaped occurrence.

### 2.4 Extension to a Multipoint Interpolation

The above mentioned approach only considers interpolation between two given points. The extension toward an interpolation between $n$ points can be broken down to $n-1$ interpolations based on the Walton-Meek approach. In foresight of the needed optimization of the spline, characteristics of each interpolation segment, such as arc length or curvature range are to be tracked. The resulting interpolation method, further referred to as "cornu spline" provides a locally curvature constant tool path trajectory made of connected cornu spiral segments. In the transition points, however, only tangentially constancy can be secured, as a step in curvature may occur. This characteristic is known as a $G^1$ interpolation: geometrically constant up to the first differentiation.

The constructed interpolation method is helpful for determining the characteristics of cornu splines and is a first step toward developing an overall curvature constant interpolation method consisting of cornu spline segments.

## 3 CORNU SPLINES AND THEIR APPLICABILITY IN CNC MACHINING

The presented concept of a cornu spline can be broken down into multiple steps that are necessary for the interpolation with a clothoid segment. Essential is also the computation of the Fresnel integrals as the foundation for the cornu spiral. A conclusion to the applicability of cornu splines in CNC machining is given.

### 3.1 Calculation of a Cornu Spline

The fitting process of a clothoid passes through 5 main steps. Figure 6 present an overview of the calculation process. In case of offline computation it is sufficient to document the respective defining parameters of the cornu spiral. With these parameters the cornu spline can be precisely reproduced.

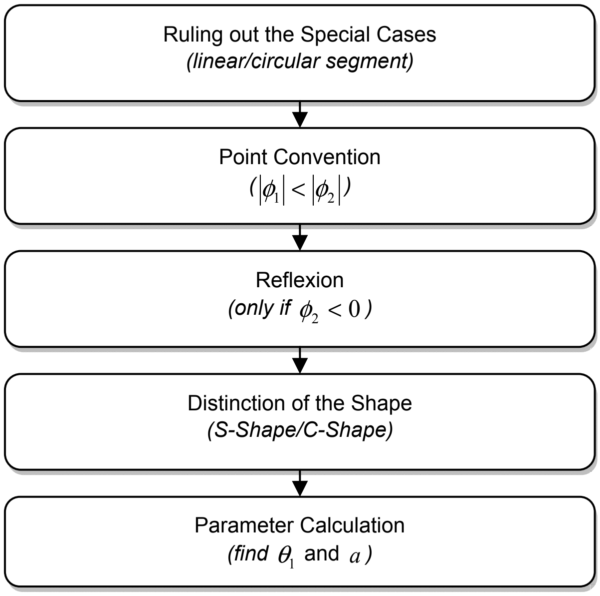


Figure 6: Steps of the calculation for an interpolating clothoid segment.

1. Special Cases:

   Two special cases are excluded, that are identified by $\phi_1 = \phi_2$. If the given angles yield $\phi_1 = \phi_2 = 0$, the joining segment can be simplified by a straight line segment. In the other case of $\phi_1 = \phi_2 \neq 0$, a circular arc can be found to join the given points. For all other cases, a connecting cornu spiral segment can be found.
2. Point Convention:

   The two points are named $P_1$ and $P_2$ such that $|\phi_1| < |\phi_2|$
3. Reflexion:

   If $\phi_2 < 0$, a clothoid for $\tilde{\phi}_2 = -\phi_2$ has to be calculated and then reflected over $D$ to generate the interpolating clothoid segment.
4. Shape Distinction:

   The discriminant $h(\phi_1, \phi_2)$ and the angles $\phi_1, \phi_2$ determine the shape of the clothoid segment used for interpolation. See [6] for details.
5. Parameter Calculation:

   The parameters $\theta_1$ and $a$ define the used clothoid segment. See 0 for details.

   When looking for the main deviation angle, finding the smallest root possible is critical to a reasonable interpolating clothoid. Due to the spiral pattern, multiple solutions are possible. If a different root is chosen, the interpolating clothoid segment will show unnecessary coils. The new representation of the function $f(\theta)$ offers a simple derivative, so that Newton's method can be used when solving for zero.

The parameters enable us to find the origin of the clothoid. The second deviation angle follows as mentioned in 0. When interpolating multiple intervals, those parameters have to be saved to reconstruct the cornu spline later.

### 3.2 Numerical Computation of Fresnel Integrals

In order to compute the Fresnel integrals used to define the cornu spiral, we use a MATLAB implementation of the series calculation presented by Mielenz [7], which provides the value of Fresnel integrals with an error of less than $1 \cdot 10^{-9}$ [8]. Due to the calculation via series, the computation costs of Fresnel integrals are comparable to those of trigonometric functions.

### 3.3 Applicability in CNC Machining

The presented cornu spline can be easily computed by repeating the above mentioned steps for each interpolation interval. Each connecting clothoid segment is fully defined by its origin ($P_0$, $T_0$), its scale ($a$) and the starting and end point, represented by their deviation angles ($\theta_1$, $\theta_2$). Therefore, each interpolation only requires the deposit of two vectors and three scalars.

The computation of the resulting tool path rests upon the given parameters and their Fresnel integral computation to calculate a planar curve connecting the two interpolation points. The sequence of those curves gives the overall tool path. The special cases, that offer no connecting clothoid segment, can be covered by linear and circular interpolation. This aspect shows the close relation of the clothoid as a smooth curvature element to the constant curvature elements known as the line and the circle. A combination of a linear, circular and clothoid interpolation therefore covers all possible cases.

The applicability of the cornu spline in CNC machining is given. The required data is - with five needed parameters per interpolation - in an acceptable range, the computation of a tool path is possible very quickly and joined with the linear and circular interpolation, all possible combinations of points and tangent vectors can be interpolated.

## 4 CONCEPT OF A SMOOTH-CURVATURE CORNU SPLINE

The examined cornu spline does not meet all the needed requirements for tool path trajectories in CNC machining. They need to exhibit not only tangentially smoothness but also a smooth curvature progression. As the currently constructed cornu spline still exhibits curvature steps in the transition points between two interpolation elements, the tool path trajectory is not globally curvature-constant. The regular approach taken in route planning to connect two different curvatures at fixed points is a combination of two or more clothoid segments. This builds a $G^2$ interpolation, where the resulting curve is geometrically constant up to its second differentiation in respect to its arc length.

Since the curvature of a single cornu spiral segment depends linearly on its arc length, a required curvature range and a required covered distance cannot be met at the same time. A pair of clothoids creates an additional degree of freedom to meet both requirements at the same time. This interpolation problem could probably be solved by splitting it into three underlying problems: One initial value problem for each cornu spiral segment and one connecting boundary value problem that solves the connecting point of the two spirals.

A solution to the problem of fitting a $G^2$ hermite curve between two given points with given tangents and curvatures has been presented in [10]. They offer connecting curves consisting of a single clothoid segment combined with circular arcs or straight lines to span over the desired distance while simultaneously meeting the condition or a continuous curvature change. Their approach splits the problem into various different types with corresponding solving techniques.

## 5 CONCLUSION

In this paper a new approach has been presented for using clothoids for CNC tool path interpolation. The paper demonstrated that clothoids are suited to be used for interpolation due to their advantageous characteristics, namely the possibility to define them easily in length and curvature, scaling and orientation. The idea of this paper is based on the approach of Walton & Meek [6] and simplifies, as a contribution to the interpolation with clothoids, the way of calculating these by using a complex representation.

In the context of this work a $G^1$ cornu spline was developed that enables to interpolate arbitrary sets of points. The missing smoothness in curvature at transition points and a missing criteria to define the geometrical ideal path segment between two points currently proves to be disadvantageous. However, an interpolation method based on clothoids seems to be promising as in comparison with polynomial spline interpolation the resulting path shows a better behavior regarding oscillation, the computational effort is acceptable and first experiments with a subsequent optimization routine to find the geometrical ideal connecting path segment for two given points have been successful, though still time-consuming.

Further steps in the context of this work will be the development of the $G^2$ cornu spline as described in chapter 4. This method would cover global curvature smoothness and could either represent the missing link in the mainly used linear and circular interpolation method to connect segments with different curvature or being an independently used interpolation method.

Table 2 summarizes the characteristics of the proposed $G^1$ and $G^2$ cornu spline interpolation method and compares them with other common interpolation methods.

| | Linear/circular interpolation | Polynomial spline | Single clothoid | Cornu spline $G^1$ | Cornu spline $G^2$ - Outlook |
|---|---|---|---|---|---|
| Smooth tangent | -- | + | + | + | + |
| Smooth curvature | -- | + | + | -- | + |
| Calculation cost | + | + | o | o | o |
| Oscillation | + | -- | + | + | + |
| Scalable/transformable | + | -- | + | + | + |
| Control over curvature | n.a. | -- | + | + | + |

Table 2: Compared characteristics of different interpolation methods.

(+ = good, o = acceptable, -- = insufficient/is not offered, n.a. = not available)

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# Systematic Procedure for Handling Complexity in the Automotive Production

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**Abstract**

Volatile influences from global markets force manufacturing companies to be more flexible, innovative and efficient. Implementing these attributes in products, processes and production resources, requires a high rate of change in development periods of decreasing lengths. The increasing level of perceived complexity is a critical result of these changes. Manifold approaches were developed and studies were conducted to derive measures for complex issues. But in the industrial field, the usability of such measures poses a major challenge. In this paper, we bridge the gap between the scientific and the practical perspective on complexity and extract three basic complexity cases. On this basis, our procedure supports the systematic analysis, classification and quantification of complex issues in automotive production. The approach has been successfully applied in an industrial use case of an automotive assembly line.

**Keywords:**

Complexity; Quantification; Automotive Production

## 1 INTRODUCTION

Over the last decades, the manufacturing industry has been facing an increasing number of global changes and fluctuating markets. The most important challenges are variable sales, short development cycles and the necessity to offer individualised and ecological products. In order to ensure economic success in the future, every business unit has to meet these new requirements. The production and it's periphery tend to show the most problems with meeting those requirements as they are dependent on the results of the technical development, planning and operation with all of its possible faults. Hence, effects on the production should be focused on when making strategic decisions about enlarging the product portfolio, using innovative production technologies, constructing new parts or building new plants.

In the automotive industry, the understanding of current changes in the company's environment and the knowledge about their internal impact play a key role for strategic decisions. These external changes build a dynamic net of requirements, boundary conditions and target values with an increasing level of complexity that is reflected in production sites. This trend was already postulated by Asbhy's law of requisite variety in the middle of the 20th century, based on considerations of system theory [1]. Therefore, volatile external factors cause a need for changeable processes and flexible production resources – an agile production system. There is a strong interaction between the complexity of a production system and its agility, so that more changeability of resources means increasing complexity because of more degrees of freedom and possible dynamics.

In the industrial field, there is still a lack of awareness for the multiple impact of complexity in the production, because no established description models or methods for a systematic handling are available. Therefore, measures are taken, that usually solve the occurring problems for a short period of time. Our goal is to increase transparency in dealing with complexity and to support the analysis, assessment and finally the selection of appropriate measures by a procedure model. Our contribution introduces the definition of three prevalent complexity cases and a quantification model for complexity, which is embedded in a procedure model.

In section 2, we briefly discuss the current research regarding the nature of complexity, characterise the perception of complexity in the industrial field and give an overview of present strategies. In section 3 we define three cases to classify practical complexity problems. Section 4 describes the six single steps of our approach in detail. A case study of an automotive assembly line shows the practical application of our method in section 5.

## 2 THE NATURE OF COMPLEXITY

The difficulty of making complexity describable and assessable is the motivation for our approach, as shown in Figure 1. This problem originates from the nature of complexity and becomes apparent while looking at the main issues from the scientific and the practical point of view. Hence, we discuss complexity from both points of view, work out the current challenges in handling complexity and point out our contribution in the following subsections.

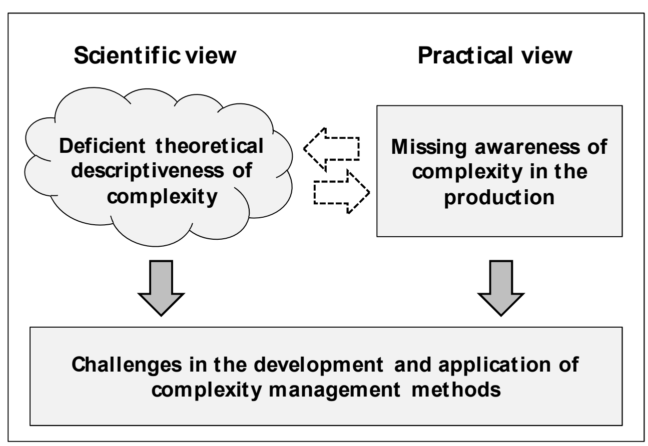


Figure 1: Motivation for a systematic procedure for handling complexity.


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### 2.1 Complexity as System State

Today, the term “complex” is used more and more inflationary. The discussion about complexity increases in the same way as society, economy and environmental phenomenon changes or rather the awareness of their dependencies raises. But there is no clear definition of what exactly is meant by calling something complex. Nicolis and Prigogine characterise complexity as a term whose definition is an essential part of the problem complexity poses [2]. In literature, many different sciences are concerned with the explanation of complexity and consequently, a lot of descriptions and definitions can be found [3]. The fact all considerations have in common is paraphrased by Flood: “In general, we associate complexity with anything we find difficult to understand” [4]. This statement contains two important aspects, which help to understand complexity. There is always a person “we”, who appreciates the difficulty and an object “anything” that has specific properties. Hence, complexity occurs only during the interaction of a subject (person) with an object, but not as property or state of an item or circumstance. For example, running a machine or planning the layout of a shop floor may be complex tasks, but neither the machine nor the layout plan are complex objects.

The description of complexity can be enlarged by a system theory perspective, if the person interacting with the object and the object itself are understood as a system. According to Cotsaftis, simple, complicated and complex are states a system can be characterise with [5]. Maurer combines these system states with structural system attributes (the number of dependencies, the number of system elements and the existence of dynamic), which allows a clear differentiation and subsequently precise classification of systems. In addition, Maurer takes the user into account and describes the interaction with the system [6]. Schuh et al. transfer the mentioned system states explicitly on production systems and distinguish four occurring types of systems: simple, complicated, complex, complicated and complex. Hence, they divide up production systems into a complicated and complex part [7]. Coming from the same three states, this comparison clearly shows that complexity is related significantly different to the system. It becomes obvious that different conclusions are drawn and that there is no common classification of complexity even from an abstract point of view.

### 2.2 Complexity in the Industrial Field

Modern production systems consist of a high number of strongly connected elements with internal and external dynamics. Different production strategies, products, processes, machines and boundary conditions build a broad area of possible complexity cases. Because of the system size, which grows with each change, it becomes more and more difficult to keep track of all causal connections. In the past, a planner could describe the activities of a work station, for example the mounting of a car’s frontend, only by the knowledge of the input and output. Nowadays, it is necessary to take also not directly previous assembly activities into account, like the installation of a radar sensor which has to fit with the frontend. The current trend poses increasing challenges in planning and operating production systems, but is complexity the right explanation of this phenomenon or even the reason?

Even though there are a concrete field of observation and describable problems, no resilient definition of complexity can be given from the industrial point of view. So, it’s not surprising that everybody quotes to have a complex job or has to cope with complex problems. The people working in the automotive industry, we have interviewed in our case study confirmed that impression. There are some feasible reasons for it. First, having a complex job can be interpreted as “distinction” and emphasises the importance of someone. This has its seeds in missing objective agreements concerning complexity, because no obligatory assessment and quantification methods are established. A handicap for introducing such methods is the demand for making complexity measurable, exclusively by costs. Based on scale effects, some approaches were developed in terms of complexity costs induced by variety (cp. [8], [9]). But reliable approaches, which consider all relevant influences, are not known. Another aspect is the often missing institutionalisation of complexity management in producing industry or even the missing person in each project team which is responsible for the consideration of complex issues. The insufficient implementation in the organisation seems to be similar to former changes in terms of quality management.

### 2.3 Challenges in Handling Complexity

As shown in the previous explanation of the theoretical and the practical view on complexity, a consistent and universally applicable form of description is missing. So, it is obvious that the handling of complexity results in a similar range of scientific approaches and practical case studies. In both fields, one can find the keywords avoid, reduce and control. Lindemann et al. quote the three measures in terms of Structural Complexity Management based on the objects market, product, process and organisational complexity [10]. But selecting the best fitting measure depends on the necessity of the occurring complexity. This demands a previous assessment.

From a system theory perspective, complexity can be defined by characteristics of basic system attributes (cp. [6]). In literature, there are only a few approaches that are generally applicable to assess and measure the system complexity using these attributes. Most of them focus either on products or on manufacturing systems [11]. But based on these three facts, a useful and purposeful assessment is not possible, because the impact of complexity in a technical system depends on the interaction with the system user, e.g. a production planner or machine operator. Heylighen sees the key problem in the decomposability of a complex system, because it handicaps the modelling, the usage of models, the interpretation of results and finally the development of a simple assessment method [12]. The approach of Feliz-Teixeira and Carvalho Brito also depicts the difficulty arising from a universal assessment without a concrete reference object [13]. Their proposed model focuses the holistic interpretation of system behaviour by the use of system simulation combined with Fourier-analysis and quantum mechanics. This discrete approach needs to be evaluated in a real use case.

Marti’s Complexity Management Model is a more realistic approach for the assessment of product complexity [14]. He differentiates between internal and external complexity, whose balance poses the objective of this method. Internal complexity results from the multitude and variety of elements (components) and correlations to products, similar to the previously mentioned system attributes. Coming from a complexity induced change of the product architecture, he derives recommended activities in a three step procedure. Practical approaches aim almost exclusively at the early avoidance or the belated reduction of product variety. This kind of complexity management is synonymous to the well-known variant management, because only negative and direct influences of variety are observed. In the case of influenced assembly processes, Samy and ElMaraghy present a detailed approach based on dependency matrices [15]. Regarding current trends in automotive industry, the increasing number of variants is not per se bad, but rather essential to be able to offer a growing and attractive product portfolio.

Consequently, it becomes clear that in practical action there is hardly any causal context between the occurring problem, the presence of complexity and appropriate measures. Numerous examples from companies, where product variants were removed from the portfolio due to a supposed reduction of costs and complexity serve as proof. The frequent use of additional resources in terms of employees and an increasing invest for solving problems, demonstrates the necessity for a strategic handling of complexity by a systematic approach. The literature review about analysis and assessment methods indicates that no approach exists, which copes with the disclosed problem.

## 3 AUTOMOTIVE PRODUCTION – A COMPLEX SYSTEM FROM THE USER'S PERSPECTIVE

Starting from the problems on the scientific and the practical side identified in the previous section, we have developed a basic understanding of complexity, which is shown in three specific complexity cases. Based on these definitions, the question is whether a system designed, engineered and built by humans can ever be called a complex product. We argue that complexity is a subjective perception of the person who interacts with a complex system. In relation to the issues that arise in production systems, this view is consistent with the approaches of Landry et al. and Fox, that problems cannot be understood as objective realities that exist independently of the subjects [16], [17]. Even if the problem objectively exists, a subjective view of the parties is always reflected in the problem solving process. This subjectivity depends on factors like the background knowledge of the person.

The transfer of this definition into existing processes in productive systems brings up three major cases in which those attributes can be true, visualised in figure 2.

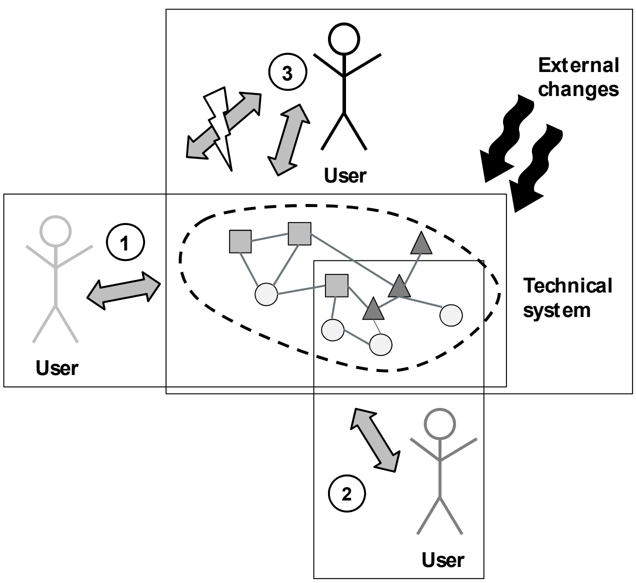


Figure 2: Complexity cases.

### 3.1 Lack of Information under Dynamic Influence (1)

It is conceivable that the working environment of a single person or a group changes relatively to the current known state. The perceived dynamic arises from temporary effects in the system environment, which influence the environment. The user does not know about the source of this dynamic influence and its impact. Despite of this lack of information, the system is describable at a particular time, so that all system elements are known and dependencies become clear. After a finite length of time, there is no longer a lack of information and the system is perceived as complicated instead of complex.

The mentioned scenario can be found in the planning of production systems. During the planning activities, dynamic effects which cause complexity cannot be considered, because they are not known. Otherwise they would be compensated. Consequently, there is a static system design in the end of the planning process which behaves static and robust in the real implementation. But it is immediately evident that such an optimal case can only appear under particular circumstances in reality. The climate in a factory work floor can strongly influence the production process, for example the temperature and humidity which can interfere with welding and bonding processes. Based on such incidents, a static system can easily become dynamic if the incident is significant for the system stability. Due to this, the behaviour of our completely described production system is quickly perceived as complex by the user. A certain rest of complexity remains, which is caused by effects outside the user's scope. In this case, elimination measures for dynamic system changes characteristically take effect in the beginning, but not for the next time. Hence, the information about external influences concerning the occurring problem was insufficient.

### 3.2 Lack of Information under Quasi-static Influence (2)

In the previous subsection described systems with dynamic influences can be perceived in a snapshot as static, non-complex systems. Such a system is in a stable state when it has settled and all the dynamic effects were compensated for example by control. Nevertheless, the system can be considered as complex when the cognitive performance of the user is not sufficient for the system size and the density of the inherent relations.

Referring that facts to the working environment of the user, this situation means that he loses track of the system either by a current training process (solvable complexity problem) or by the number of dependencies in the system (not solvable complexity problem) Thus, the system seems to be complex and dynamic although it actually remains in a static state. In addition to the density of relations, the number of tasks can also prevent the user from being aware of all links and taking them into account according to their causality for problem solving. Finally, the user cannot decompose or systemise the problem. This situation especially occurs in change processes in the production. In this paper a system like that is called quasi-static, as it only seems to be non-transparent and consequently complex for the user.

Finally, one could state that any system can be transformed into a quasi-static condition. This requires that the field of observation is chosen large enough and all influencing factors are analysed and described according to their potential impact. But this is unrealistic compared to the expense and the potential speed of analysis and therefore, dynamic systems have a right to exist.

### 3.3 Interrupted Information Flow (3)

In addition to the consequences of the size and the inherent degree of crosslinking of the system and the cognitive abilities of the user, there is another aspect that can lead to a lack of information to the user.

In large systems, information is often shared via a multitude of different points of interaction between the actors in the system. Here the single planner A is not aware that planner B requires information to solve his problem. At the same time, planner B does not know that planner A has the necessary information and thus did not ask him. If the number of interfaces which are needed by the user to interact with the system increases, the probability that he consciously or unconsciously does not have all information also rises. Thus, a non-communicated system change in one area can negatively influence the perceived complexity in a other area, although a comprehensive system overview is provided.

## 4 SYSTEMATIC HANDLING OF COMPLEXITY

Based on the developed definitions of complexity, as a practical interpretation of the theoretical understanding, the same approach leads to an application-oriented model that supports the management of complexity. Our approach of handling complexity includes six standard steps and enables an objective assessment of a subjective perception of the system in a systematic and sustainable way. Starting with the problem description, the single steps are sequentially passed through up to the selection of measures. In certain situations, it is possible to skip a step. The premises for those situations are explained in detail in the following subsections.

Figure 3 visualises the procedure, which begins by analysing the occurring complex issue. Afterwards, the problem is clearly classified and differentiated into complicated issues by using the three different cases of occurring complexity mentioned in section 3. To identify the causal parameters, all sources of the considered problem and the related departments have to be determined. After assessing the complex issue in terms of valuable and valueless complexity, the quantification follows in a separate model, which is based on the identified parameters. In the end, appropriate measures can be selected and used to handle the system complexity. Because of the subjective perception of complexity, as already pointed out in section 3, we advise to execute step 2 and step 5 in a larger group of planners to minimize individual influences.

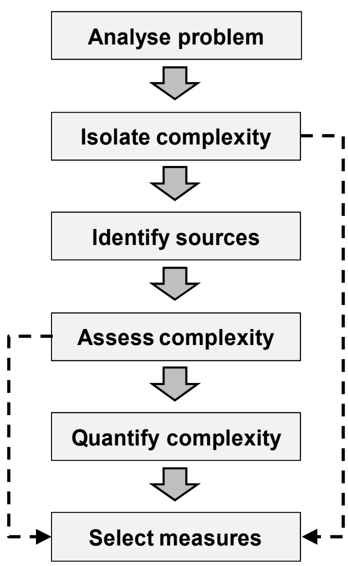


Figure 3: Procedure model for handling complexity.

### 4.1 Analyse Problem

The problem analysis (respectively problem description) is the first step of the procedure and aims at the characterisation of the supposed complex situation in order to subsequently isolate the complexity. For that purpose, we have formulated key questions in order to be able to classify the situation by local, temporal and modal aspects. Since the problem appears with a negative impact, first the negative phenomena which occur in this context are described. Then, the relevant objects (products, processes, resources or a combination of them) which are linked to the problem are identified. Consequently, the temporal aspects are clarified, when and how often the problem occurs, which indicators were considered and how long the problem existed until it was discovered. As a last step, it is important to identify at which position in the process the problem occurred, who has seen it, and in whose area of responsibility it falls, so that the identification of the source is possible.

### 4.2 Isolate Complexity

After the problem is comprehensively described, a characterisation on the basis of these criteria divides it into complex or just complicated situations. It is also decided, if further specification of the problem is needed. This characterisation allows a classification in the complexity cases mentioned in section 3. There is no strict guideline, but the criteria are indications and may be assigned as follows:

- Location of occurrence and responsibility: Dimension of the system boundary and position of the user.
- Temporal aspects: Localisation of the lack of information and existence of external influences.
- Modal aspects: Affected system elements and criticality of the problem.

After this characterisation, if no link is made to a complexity case, it is most likely just a complicated situation. To confirm this hypothesis, some more general questions that are based on the basic properties of complex systems can be answered, e.g.:

- Is the problem reducible or decomposable? Would it be easier to solve the problem with several people?
- Is it a problem whose consequences can be deterministically described and can it consequently be solved by effort?

If these questions can be answered with yes, one can jump to the selection of measures, which are appropriate for complicated problems.

### 4.3 Identify Sources

If the presence of a complex issue was found in the previous step, the sources are identified now. In this context, a source means a parameter which is defined and changed outside the field of observation. The goal is to identify all the relevant complexity drivers for the problem and determine who is originally responsible for them. It is necessary to distinguish whether the responsibility lies with a neighbouring department of planning or operation, which works on the same hierarchy level or with an area outside the production system (e.g. marketing). Moreover, the interaction of sources has to be examined, because this information is essential for the subsequent assessment and quantification.

### 4.4 Assess Complexity

After going through the steps 1 to 3, the problem is described in sufficient detail in order to be able to start the analysis. Basis for the next steps and finally the application of appropriate measures is to assess the occurring complexity in terms of valuable and worthless. The value-adding processes in production are relevant for the assessment. If the complexity is related to non-value-adding processes, such as travel paths of employees, it should be at least reduced or if possible completely avoided. The same applies for supposed value-adding processes, such as producing an additional component version which finally contributes no commercial value because it addresses no additional customers.

If it is complexity, which occurs in the context of value-adding processes and also contributes to the economic success, we talk about valuable complexity. This may be for example an additional engine variant a market niche is occupied by or by which customers will be won from competitors. In this case, the associated complexity must be handled as effectively as possible. Then, we speak about the control of complexity.

### 4.5 Quantify Complexity

If the previous assessment has shown that the examined problem is associated with worthless complexity, one can directly jump to the selection of appropriate measures. Otherwise, the quantification has to follow in order to be able to describe the criticality of the problem by the relative complexity increase or decrease.

As defined earlier, complexity rises in the user's perception within the interaction process with the system. Complexity is no explicit system variable, its quantification depends on the user's background experience and on the patterns he uses to evaluate situations. To quantify the perceived complexity, it is necessary to have a unified language and a consistent structure. Therefore, we have developed a structure for the evaluation process that is, because of its degree of abstraction, transferable between the subsystems of a production system. This makes its results comparable to earlier evaluations. The practical use depends on the quickness of conduction and simplicity of the evaluation process. The process is shortened by knowledge transfers between evaluations in different subsystems and over time between evaluations in the same. Figure 4 visualises the quantification model consisting of seven steps. How to pass through the single steps depends on the particular application.

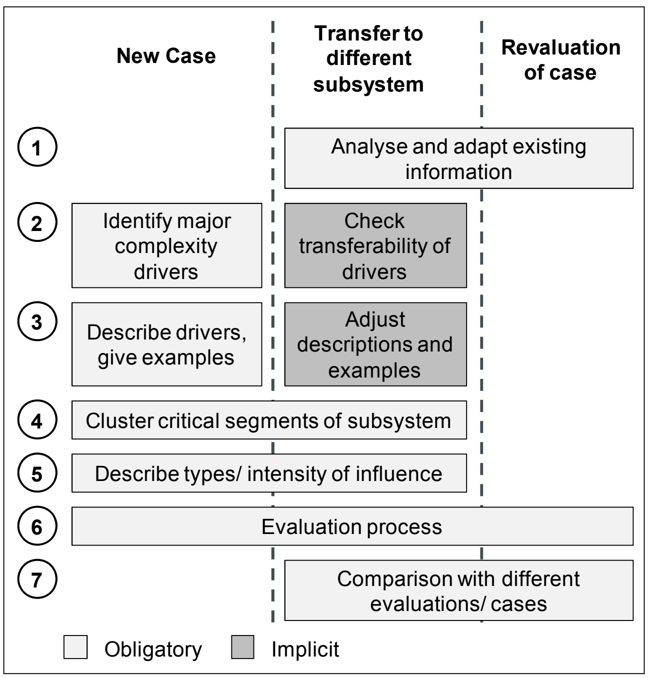


Figure 4: Quantification procedure.

The model differentiates if the user is confronted with a new problem (2 to 6) which has never been evaluated before, if he wants to transfer the evaluation process to a different element of the production system (1 to 7) or if there is already data of an earlier evaluation which shortens the expansion for the evaluation (1, 6, 7). The boxes coloured in dark grey depict implicit steps, which are already included in the first step.

The first step of the procedure is the analysis of existing information if there were earlier evaluations. It has to be checked if the evaluation strategy of an earlier case fits with the current problem. In a second step, the major complexity drivers have to be aggregated to a small, abstract and well-defined collection. The third step is the description about what is behind those abstract drivers concerning the specific subsystem. The fourth step is about the clustering of the subsystem in single parts, which can be evaluated individually. They must be sufficiently separated from each other. In the fifth step, the impact of a complexity driven problem on other system parts has to be described and assigned to the specific criticality classes. Therefore, we differentiate between *significant criticality*, *normal criticality, less criticality,* and *no system influence.* For the evaluation in the sixth step the assessor has to describe under which conditions he would rate a problem accordingly. The sixth step is about the assignment of complexity driven problems to the system influence criticality by reference to the specifications generated in step five. Summing up the specific numeric values assigned to the criticality classes can generate a global value of the system complexity. If there is already a numerical value scale, it has to be adapted to guarantee comparability. If not, we suggest using the 6-3-1-0 emphasis with decreasing criticality, which is also used in our case study. If there was an earlier evaluation, it is possible to compare the results in a seventh step.

### 4.6 Select Measures

In the selection of measures, we have to distinguish between valuable or worthless complexity which arises with the initial problem. In the first case of valuable complexity, one of the most important steps have already been done by the quantification, because this procedure already contributes significantly to increased system transparency. In terms of our three complexity cases, this means reducing the lack of information. In addition, different forms of visualisation can be used to further increase the transparency of the system and control significant complexity drivers by redesigning the product architecture or the transformation of the production architecture (production processes, resources and its dependencies).

In the case of worthless complexity, the causal processes, products or system states that occur should be avoided. This can be done by well-known tools of lean-thinking, e.g. ABC-analysis. If a fully avoidance is not possible, one has to reduce the occurrence of complex situations by defining barriers for certain parameters and eliminate problematic combinations. The operation of a manufacturing system in a better controlled parameter range where negative external influences are reduced to a minimum would be a practical example.

## 5 CASE STUDY: COMPARISON OF TWO AUTOMOTIVE ASSEMBLY PROJECT STATES CONCERNING ITS INHERENT COMPLEXITY

For the validation of the theses referring to complexity and its characteristic definitions in relation to its occurrence in automotive production, the assembly process of a frontend was examined after a model change. It states as example for the analysis of a whole automotive assembly line because the identified assessment aspects are valid in all areas of this system.

When assembling the frontend to the car, problems with the installation of the radar sensor were occasionally detected. This failure was first discovered by putting the car in operation and testing the driving assistance systems. Both the assembling and the testing employee did not know any reasons for the problem. By using the earlier described complexity cases, it was ensured, that the analysed problems arose from complexity case number 2. The installation of the radar sensor serves as a proper example for this case, because its assembly requires special knowledge and experience. Furthermore, it has a lot of dependencies to the surrounding parts, following assembly processes and finally to the operability of the whole car. In the next step, sources and complexity enhancing aspects had to be identified. Therefore, the production planning and the operating divisions were interviewed to allocate the responsible department. It became clear that the planning department did not know about the special difficulties in the assembly process of this sensor and kept the established process without informing the assembly employees about the design change of the sensor. The assessment of the problem revealed that the occurring complexity is caused by a changed sensor fixation due to a newly designed frontend. This increases the attractiveness for customers and is therefore a case of value-adding complexity.

To quantify the relative increase of complexity and the consequent criticality of the problem, the relevant assembly segment was isolated and examined for the effect of complexity causes. After that, the resulting complexity drivers were accumulated in more abstract groups:

1. Special variation of assembly / Variance in the assembly process
2. Workload, time pressure, stress
3. Variance in tasks
4. Personal competence
5. Ergonomic circumstances
6. Quality standard
7. Usage of utilities, supportive systems

These key aspects were rated regarding their impact on the system. The impact was significantly critical because the mistake in the assembly of the radar sensor influences downstream processes and was discovered late in the process during the final function test. In assessing the relative complexity increase, compared to the situation before the model change, it showed that an increase from 17 to 64 was found. The higher numerical value is consistent with the perceived increase of complexity. Since it is a valuable complexity, visualising the link between the new setting of the radar sensor and the modified installation parameters could be a useful measure.

## 6 CONCLUSION AND OUTLOOK

This contribution introduces a method for analysing, assessing and quantifying the system complexity in a six step procedure considering specific requirements of usability and target values of an automotive production system. Based on the defined complexity cases from a practical view, focused on the user, complicated and complex problems can be distinguished and appropriate measures can be selected. Since the problem and its causes are systematically identified, measures can be taken purposefully. Through the evaluation of the critical aspects it is possible to find the most critical areas in the system. The cumulated values make it easy to compare the aspects and to identify where a high priority of measures is. The quantification of the relative increase or decrease of complexity allows the comparison of several system states and provides an objective discussion of complexity impact on the production system. Thus, the early dialogue between departments involved in the production process is supported, which results in lower long-term lack of information and consequently in a better control of the perceived complexity. However, further applications to secure the method and to allow a more accurate interpretation of this complexity value are needed. The goal is to define a critical value and derive the maximum tolerated complexity for the production system. For this purpose, the approach will be expanded by the influence of structural criteria in the future. A link to assessment methods for the adaptability of production systems is also planned.

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# Generating Master Assembly Sequence Using Consensus Trees

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**Abstract**

An assembly process plan for a given product provides the sequence of assembly operations, operation times as well as the required tools and fixtures for each operation. Much research has been done on automating and optimizing assembly sequence generation as being the most important part of an assembly process plan. This paper proposes a novel method for generating the assembly sequence of a given product based on available assembly sequence data of similar products. The proposed method uses a binary tree form to represent the assembly sequences of an existing family of products. A Genetic Algorithm is employed to find the consensus tree that represents the set of all assembly sequence trees with minimum total dissimilarity distance. This is similar to defining Generic Bill-of-Material (GBOM). The generated consensus tree serves as a master assembly sequence for the product family. The assembly sequence for a new variant that falls within, or significantly overlaps with, the scope of the considered family of products can be directly extracted from that master assembly sequence tree. The proposed novel method greatly simplifies and enhances automatic assembly sequence generation. It helps reduce assembly planning cost and improve productivity.

**Keywords:**

Assembly Sequence Generation; Consensus Trees; Genetic Algorithms

## 1 INTRODUCTION

The sequence by which assembly operations are carried out for a given product has a great effect on many aspects of the assembly process such as the cost of assembly per unit, level of assembly difficulty, the needs for fixtures, the likelihood of components damage during assembly, the ability to do in-process testing, and the likelihood of rework [1].

Finding a good assembly sequence is not a simple task as the number of feasible assembly sequences could be very large even for a small number of components. The proliferation of product variety and recursive design changes demands responsive and cost-effective process planning activities. Significant research has been done on the automatic generation of assembly sequences [2-8].

Existing assembly sequence generation algorithms do not make full use of available assembly sequence data. This paper proposes a novel method that addresses the problem from a different non-traditional perspective. The proposed method seeks to determine the master assembly sequence. A master assembly sequence is a generic assembly sequence for a given set of products that share a significant number of component and common structures. Upon constructing the master assembly sequence for a given family of products, any new variant that falls within, or considerably overlaps with, the scope of the considered family of products could be directly extracted. Building a master assembly sequence from individual assembly sequences is similar to building a Generic Bill of Material (GBOM) from a set of individual Bills-of-Material of a given product family to improve supply chain and production management activities [9, 10].

The concept of master assembly sequence has been used before using different names. Martinez et al. [11] generated master assembly sequence, called parent plan, for an imaginary product which includes all components of the given product family (called meta-product). However, Martinez et al. employed a traditional assembly sequence planning algorithm to generate the master assembly sequence for the meta-product.

In this research, a binary tree is used to represent any given assembly sequence as well as the master assembly sequence. The concept by which the master assembly sequence is constructed is inspired by the well-known biology problem of finding the consensus tree for a set of conflicting evolutionary trees [12]. A new consensus method based on Genetic Algorithm is developed to deal with the specific characteristics of assembly sequences. An illustrative example is presented to describe the proposed method, where the master assembly sequence is constructed for a set of five hypothetical products, involving a total of eight different components. It is further used to find the assembly sequence for a new product variant that has a new combination of five components.

## 2 RELATED WORK

Assembly sequencing is a mature research topic [13]. Research on automating or semi-automating assembly sequence generation goes back to eighties and may be before [14]. However, the main principle adopted by most algorithms, with few exceptions (e.g. Reconfigurable Process Planning (RPP) [15]), is more or less the same.

A classical assembly sequence algorithm has two phases. In the first phase the set of all feasible or valid assembly sequences are generated according to pre-defined set of feasibility or validity constraints. Geometrical and precedence feasibility of a given assembly operation is the major feasibility constraint. In the second phase, the set of feasible sequences generated are searched for the best sequence according to specified optimization criteria such as minimum total numbers of part orientation changes and assembly tool changes during assembly [14].

Instead of carrying out the assembly sequence generation in two consecutive phases, the Generative Assembly Process Planner (GAPP) developed by Laperriere and ElMaraghy [5] uses an A* algorithm [16] that applies both feasibility constraints (geometric and accessibility constraints) and optimization criteria (number of parts reorientations, concurrent execution of assembly tasks, grouping of

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similar tasks and assembly stability) simultaneously. It searches for the optimal assembly sequence without exhaustively generating all feasible sequences.

Recent algorithms combine the two phases by employing a fitness function that considers both assembly constraints and optimization criteria through a meta-heuristic optimization algorithm. The assembly sequence generation algorithm by Wang and Liu [8] follows this trend and is used here to explain how these assembly sequence generation algorithms work. Wang and Liu consider a sequence to be linear when all product components are assembled one at a time and subassemblies are never formed (i.e. no parallel assembly operations) [14]. A linear assembly sequences is typically represented by a permutation (sequence) vector the length of which equals to the number of assembly components. As a preparation step, the given product design is analyzed and five component-to-component matrices are built. The first three matrices encode feasibility constraints that should be satisfied in the final sequence. These three constraints are geometrical, local assembly precedence and assembly stability constraints. The remaining two matrices represent two assembly optimization criteria that may favour one sequence over another. These are the number of assembly tool changes and number of assembly connection changes in a given assembly sequence. Number of assembly direction changes is also considered as a third optimization criterion and is applied through the same matrix used to represent the geometrical constraint. A discrete Particle Swarm Optimization (PSO) algorithm is then used to search for the best assembly sequence using a weighted fitness function of the mentioned constraints and optimization criteria. A schematic description for this assembly sequence generation algorithm [8] is shown in Figure 1.

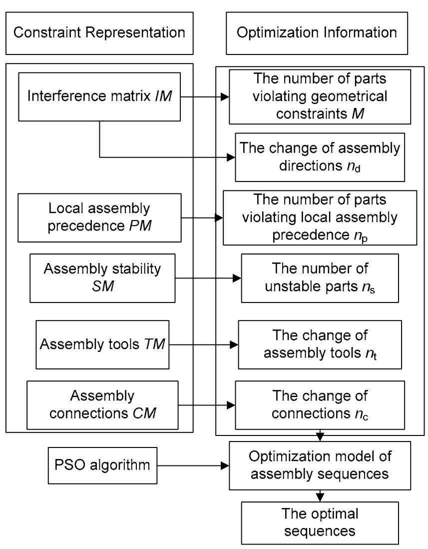


Figure 1: Assembly sequence planning algorithm of [8].

The work of Laperriere and ElMaraghy and Wang and Liu are just few examples of how assembly sequencing has been tackled for decades. Many variants of these algorithms exist in literature. Among the major elements that would distinguish an algorithm is for example the assembly sequences representation. Other common forms of assembly sequence representation include assembly states [5], partial assembly trees [17] and And/Or graphs [18]. As for optimization techniques, many different algorithms have been employed such as Genetic Algorithm (GA) [19], Simulated Annealing (SA) [20], Ant Colony Optimization (ACO) [21], and Artificial Neural Networks (ANN) [7]. Some recent algorithms use CAD models to automatically generate and apply assembly constraints. This approach requires sophisticated geometry handling algorithms [22]. The other way to handle assembly constraints is through user interaction, either by pre-analyzing the product [8] or by using interactive question-and-answer procedures [1]. Interactive methods would be more acceptable with simpler and less complicated products. The type and number of assembly constraints and optimization criteria that an assembly sequencing algorithm considers vary depending on many factors such as product type, assembly facility, assembly volume, and other factors. A comprehensive survey for dealing with the assembly constraints and optimization criteria is found in [23].

## 3 SCOPE

In this paper a non-traditional approach is proposed to address the problem of assembly sequence generation. Existing individual assembly sequences for a given product family or a set of similar product variants that share a significant number of components and common structure are merged together in one generic or master assembly sequence. The master sequence is then used to extract the assembly sequence for new product variant belonging to the same product family.

This research presents a simpler alternative to conventional assembly sequence generation methods by benefiting from the knowledge embedded in available assembly sequences for existing product families. Hence, the problem is to find the consensus (or generic) assembly sequence that best represent the set of available individual sequences even if those sequences have some conflicts among each other (i.e. having different assembly sequence for the same combination of components) .

More specifically, given a set of $N$ assembly sequences, for $N$ products with a total of $n$ different components, it is required to find a single assembly sequence of all the $n$ components that has a minimum conflict with any of the individual sequences. Measuring conflict will be detailed in Section 4.4. The following assumptions are made:

- Parallel assembly operations are allowed (i.e. non-linear assembly).
- During each assembly operation, only one component is added (sequential assembly).
- Assembly sequences for existing product variants are available and it is assumed that those sequences are already optimal or near optimal (i.e. good assembly plans).
- Available assembly sequences are fairly consistent (i.e. generated using the same logic).

If the assembly sequences of available product variants are not optimal sequences as assumed above, the proposed method can still work well; however, the resulting master assembly sequence will be feasible but not necessarily optimal. Non-linear assembly is the general case of linear assembly. Allowing non-linear assembly means that linear assembly is also possible. Assembly sequence for a non-linear assembly problem could be perfectly represented as an un-ordered rooted binary trees or what is known in the assembly planning literature as partial assembly trees [24]. The root of a partial assembly tree represents the final product (complete assembly) and the leaves represent individual components. Every other intermediate node represents the subassembly resulting from adding its two sub-nodes. Figure 2 shows the partial assembly tree representing the assembly sequence for a product of five components. According to this plan, assembling components 1 and

3 may proceed, follow, or done at the same time of the assembly of components 2 and 4. Component 5 is then added to sub-assembly (1, 3, 2, 4) to obtain the final product (1, 3, 2, 4, 5).

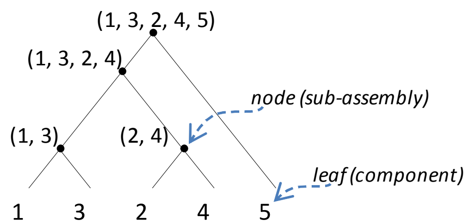


Figure 2: An example for a partial assembly tree.

According to this representation, the problem is then to find the generic or *consensus* tree that best represents a given set of partial assembly trees or *cladograms*. The terms consensus and cladograms are both adopted from the biology and phylogenetics literature where this problem originated. A cladogram is a phylogenetic tree which has the same structure and properties of a partial assembly tree and is used in biological studies to classify species and analyze their evolutionary histories [25]. It is not unusual in biology to have many classifications for the same set of species, thus it is a common problem to seek a consensus tree [12] for these classifications. Existing methods for constructing the consensus tree deal with trees that have the exact same set of leaves, which is not the case here. The next section describes the Genetic Algorithm (GA) method implemented in this research to find the consensus tree for a given set of partial assembly trees (assembly sequence trees or assembly trees for short) that do not necessarily have the same number of components.

## 4 PROPOSED METHOD

This section presents the Genetic Algorithm-based method developed to construct the master assembly sequence tree for a given set of assembly sequence trees in a sequential and non-linear assembly process. For a given set of individual assembly sequence trees, the master assembly sequence tree is equivalent to their consensus tree. Many algorithms and methods have been developed in the biology and phylogenetics literature to construct consensus tree [12]. However, as mentioned before, none of them handle trees with different number of leaves. Thus, a new consensus tree building method is developed to deal with this general case of the problem. MATLAB® programming and numerical computational software was utilized to implement the proposed method. However, the proposed Genetic Algorithm was not implemented through the Global Optimization Toolbox of MATLAB®. It was customized and programmed to fit this application.

### 4.1 Methodology

Any of the available assembly sequence trees is first encoded into $m$ x $m$ square matrix form ($m$ is the number of leaves) that maintains the same information provided by the trees. For any given matrix, the corresponding tree could be easily restored. Consequently, for a given set of $N$ trees and a total of $n$ different components, there is an unknown $n$ x $n$ square matrix that represents the consensus tree of all the available $N$ trees. There are different definitions for the consensus tree that depend on the applied consensus method [26] such as strict consensus and majority rule consensus. Here we define the consensus tree as the tree that has the minimum sum of distances from each of the individual trees. Such a distance is to be measured using the commonly used measure in phylogenetics known as *Robinson-Foulds* distance [27].

Hence, a proposed Genetic Algorithm [28] is applied on a set of initial randomly generated consensus trees (initial population) to search for the optimal consensus matrix that has the minimum sum of Robinson-Foulds distances from each of the individual matrices. Figure 3 shows an IDEF0 model for the proposed method illustrating the main activities as well as inputs, outputs, controls and mechanisms of each activity.

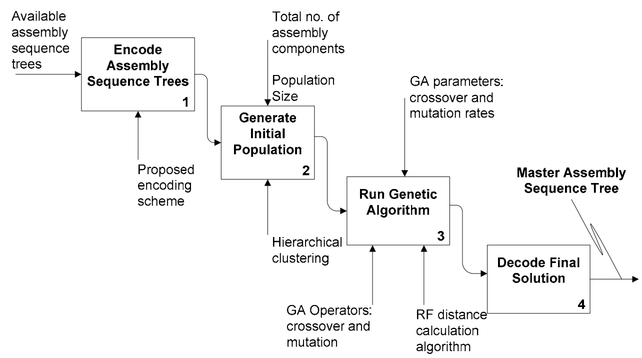


Figure 3: IDEF0 model for proposed method.

### 4.2 Trees Encoding Scheme

A new tree-to-matrix encoding scheme, based on the one introduced by ElMaraghy and AlGeddawy [29], is proposed to calculate the Robinson-Foulds distance between any two trees as well as to support Genetic Algorithm implementation. In encoding a tree of $m$ leaves into a matrix, the information to be represented by the matrix is the hierarchy of those $m$ elements which is equivalent to those elements belonging together to the same node. This is carried out through the proposed scheme shown in Figure 4.

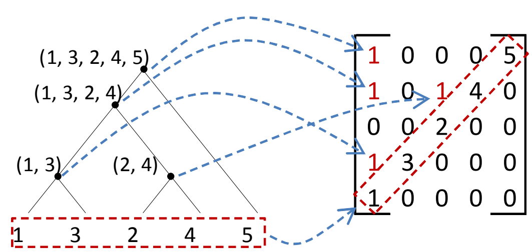


Figure 4: Proposed tree-to-matrix encoding scheme.

Two types of tree information are encoded: *sequence of leaves* and *topology* or structure of the tree. Sequence of the leaves is encoded by the diagonal elements of the encoding matrix, while topology is encoded by the locations of binary (0-1) elements above the diagonal. Elements of value 1 above the diagonal signify the group of leaves belonging together to the same node. For example, the four elements 1, 3, 2 and 4 on the tree shown in Figure 4, belong to the same node. Hence, the cell corresponding to the first column, where leaf 1 (most left leaf of the node) is located in the matrix; and second row, where leaf 4 (most right leaf of the node) is located in the matrix, is filled by 1. In this way, the hierarchy and grouping relationships among elements are maintained in the encoded matrix. In any encoded matrix, the cell (1, 1) will always take the value 1 (this is the root node to which all leaves belong).

### 4.3 Generating Initial Population

A Genetic Algorithm needs an initial set of solutions known as initial population. For this problem, a possible solution should be an assembly sequence tree of *n* leaves or its equivalent matrix, where *n* is the total number of different leaves of all individual trees. Randomly generating an initial feasible population of assembly sequence trees; either in tree or matrix format, is challenging. One way to do it would be to randomly generate a set of *n* x *n* matrices that have random integers (from 1 to *n*) on its diagonal and a number of *n-1* ones (equivalent to number of nodes) on different cells above the diagonal. The main difficulty with this approach is that it will generate matrices that are most probably equivalent to invalid (distorted) assembly sequence trees. Controlling the random generation process so that only valid assembly sequence matrices are generated or even turning invalid matrices into valid ones are both two hard choices that involve a lot of implementation and programming complications.

As a result, the proposed approach is much simpler and easier to implement where valid matrices are to be randomly generated directly. To generate an *n* x *n* matrix, representing a feasible assembly sequence tree of *n* leaves, a set of *n* random coordinates are generated. An agglomerative (bottom up) hierarchical clustering algorithm [30], based on shortest Euclidian distance, is applied to build the corresponding binary hierarchical clustering tree, also known as dendrogram. Dendrogram is an exact equivalent to assembly sequence trees used in this paper. The "Linkage" function of the Statistics toolbox of MATLAB® was used for the hierarchical clustering task. The Linkage function output is converted into the proposed matrix form before proceeding to the Genetic Algorithm iterations. Figure 5 shows the tree obtained by hierarchical clustering if the coordinates (0, 0), (1, 1), (6, 6), (7, 7) and (9, 9) are randomly generated. Equal integer values for x and y coordinates are used here for simplicity, but actually real numbers from 0 to 10 were used. Using integer numbers is not preferred as it might cause tie regarding determining the cluster to which a given leaf should be assigned.

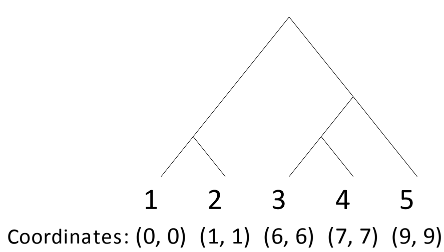


Figure 5: Tree of 5 leaves generated by hierarchical clustering.

### 4.4 Measuring Robinson-Foulds Distance and Fitness

The Robinson-Foulds distance [27], is the most widely used metric for comparing phylogenetic trees [31]. Given two trees *T1* and *T2*, both having *m* number of leaves, *C1* is a set that includes *m-1* subsets. Each subset represents one of the *m-1* nodes of *T1* and the elements inside each subset are the elements belonging to the node representing the subset. Similarly, *C2* contains *m-1* subsets representing the *m-1* nodes of *T2*. Robinson-Foulds distance (*RF*) is then given by Equation 1, where "Δ" refers to symmetric difference (a set theory operation). Equation 1 could be further detailed as in Equation 2, where "\" refers to set difference operation. Hence, *RF* is simply a normalized count of the nodes (i.e. subsets or clusters of elements) that exist in one tree, but not the other.

$$RF\,(T1,\,T2) = \tfrac{1}{2}\,|C1\,\Delta\,C2| \tag{1}$$

$$RF\,(T1,\,T2) = \tfrac{1}{2}\,(|C1 \setminus C2| + |C2 \setminus C1|) \tag{2}$$

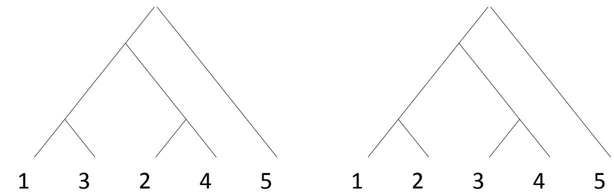


Figure 6: Two Trees *T1* and *T2* with $RF\,(T1,\,T2) = 2$.

For instance, the two trees *T1* and *T2* shown in Figure 6 each has five leaves and four nodes. For *T1*, *C1* = {{1, 3, 2, 4, 5}, {1, 3, 2, 4}, {1, 3}, {2, 4}} and for *T2*, *C2* = {{1, 2, 3, 4, 5}, {1, 2, 3, 4}, {1, 2}, {3, 4}}. The order of sets within *C1* and *C2* or order of elements within any of their subsets has no significance. By substituting in Equation 2, we get *RF (T1, T2)* = ½ (2 + 2) = 2.

Many algorithms have been developed for calculating the Robinson-Foulds distance which mainly differ in computational efficiency (i.e. how to efficiently find and store the *C* sets). Some of these algorithms are exact [32] and others are approximate [31]. However, the most recognized algorithm for calculating the Robinson-Foulds distance is Day's algorithm [33]. In this research, we developed an algorithm based on the proposed matrix representation. As a result of the encoding scheme of this matrix form, obtaining the *C* set for any given tree becomes rather straightforward. With reference to Figure 7, the subset of the *C* set that represents node *D* of the shown tree simply includes the group of consecutive diagonal elements {1, 3, 2, 4}, identified by the position of the cell representing *D* in the corresponding matrix.

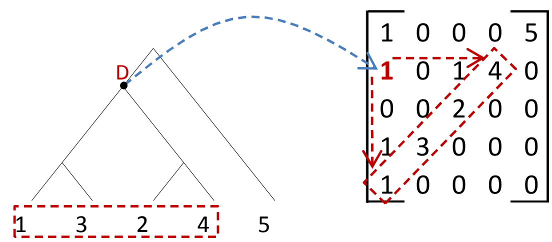


Figure 7: Obtaining the subsets of the C set for a given tree.

Throughout the proposed GA iterations, a fitness function is needed to assess the fitness of any given candidate solution (master assembly sequence tree). For a given set of available assembly sequence trees *N*, having a total of *n* different components, and a candidate master tree *MT*, the fitness function is the average of the Robinson-Foulds distances between the candidate master tree *MT* and every individual tree *T* out of the *N* available trees (Equation 3).

$$Fitness = \frac{\sum_{i=1}^{i=N} RF(MT, T_i)}{N} \tag{3}$$

In most cases, *MT* will have more components than *T*. Thus, during calculating Robinson-Foulds distance between a given master tree *MT* and any individual tree *T*, all elements that exist in *MT* but not *T* are removed from the *C* set of *MT*.

### 4.5 Genetic Algorithm Operators

Genetic Algorithm (GA) is an evolutionary optimization meta-heuristic originally introduced by Holland [28], inspired by the process of natural selection. In a typical Genetic Algorithm, crossover and mutation are the main operators by which a new generation of solutions evolves from current population. An effective GA needs well-designed crossover and mutation operators as well as proper adjustments of their rates.

*Crossover*

Crossover is the main GA operator and it is the mechanism by which a new solution (offspring) is generated from the combination (mating) of two randomly selected solutions (parents). A specially designed cross over operation was developed so as to allow for proper information exchange between any two combined trees that guarantees the feasibility of the new tree. According to the proposed crossover operation, for two given randomly selected matrices, a new matrix is generated by obtaining (inheriting) the topology part of one matrix (elements above the diagonal) and the leaves sequence part of the other matrix (diagonal elements). In this way, there is no chance of generating matrices that are not equivalent to valid assembly sequence trees. Figure 8 (a) and (b) illustrate the proposed crossover operator mechanism in both tree and matrix forms. The tree form is shown for clarification.

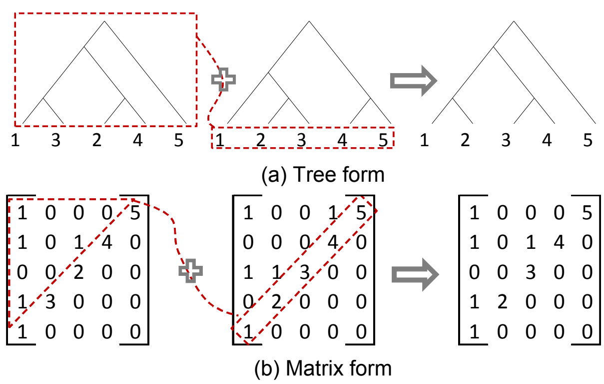


Figure 8: Proposed crossover operator.

*Mutation*

Mutation is an essential GA operator to help evolve new solutions that would not be obtained by crossover alone. Without a proper mutation operator, a premature convergence towards a local optimum solution could easily occur. Three mutation operators where developed; two of them are to mutate sequences of leaves (diagonal elements of the matrix form) and the third is to mutate topologies (elements above the diagonal in the matrix form).

The first mutation operator reverses the sequence of leaves of a randomly selected tree. The second swaps two randomly selected leaves. The third randomly alters the topology of a randomly selected tree. As mentioned in Section 4.3, the initial population is produced by random generation of coordinates that are then clustered into trees through agglomerative hierarchical clustering. Hence, performing the topology mutation task without generating invalid trees could be simply done by assigning a new random coordinate to a randomly selected leaf of a randomly selected tree and then rebuilding the tree again. Figure 9 shows how the tree in Figure 5 would look like if the coordinate of the second leaf from the left (leaf 2) was changed from (1, 1) to (10, 10) without changing the sequence of the leaves. According to that perturbation, the node *D* in the original tree disappeared and new node *K* is formed instead in the mutated tree.

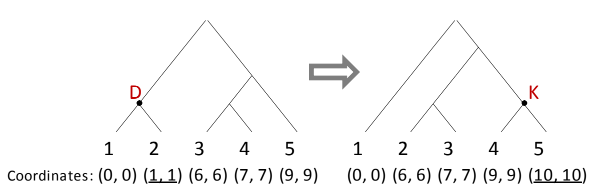


Figure 9: Proposed topology mutation operator.

The mutation operators play an important role in the proposed GA; without these operators no new sequences or topologies would ever be generated other than those generated in the initial population.

## 5 ILLUSTRATIVE EXAMPLE

A simple hypothetical example is presented to illustrate the proposed method. Given five assembly sequences for five variants of a given product family, involving a total of eight different components, it is required to find the master assembly sequence tree of that product family, and then extract the assembly sequence of a new variant that has a new combination of those components. The trees representing the assembly sequences for the given product family are shown in Figure 10. The results of the test runs favored these values for the GA parameters: 0.75 for crossover, 0.15 for each mutation operator and 100 for population size.

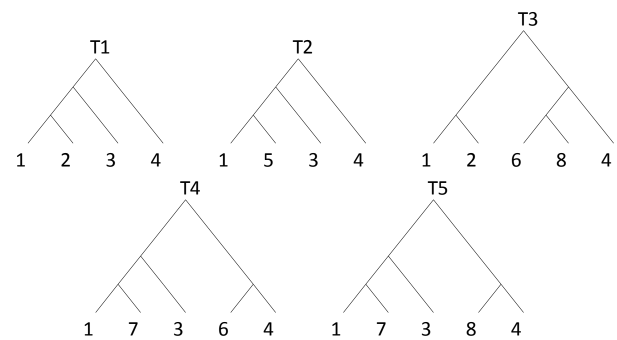


Figure 10: Assembly sequence trees for family of five variants.

Upon running the GA using the mentioned tuned parameters values, the optimal consensus tree (Figure 11 (a)) with zero Robinson-Foulds distance from any of the five trees was obtained in 2 minutes and 43 seconds on a PC of Intel Core i3 2.13 GHZ Intel processor and 4 GB Ram. This consensus tree is the master assembly sequence tree for the given product family.

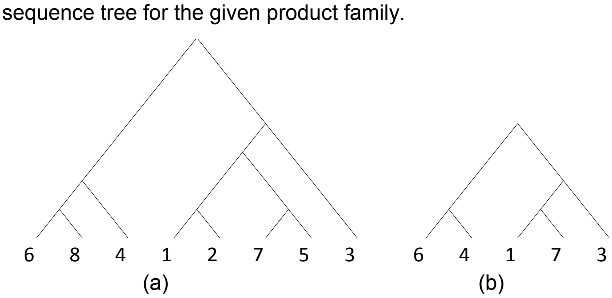


Figure 11: (a) Obtained master tree and (b) Extracted tree.

The assembly sequence tree for a new product variant that has the components 1, 3, 4, 6, and 7 could be extracted from the tree in Figure 11 (a) by removing any component that is not among the new product components. Accordingly, the assembly sequence tree for the new product variant is shown in Figure 11 (b).

## 6 SUMMARY AND CONCLUSIONS

A novel method is developed for generating a master assembly sequence for sequential non-linear product assembly. Given assembly sequences for the set of variants of a certain product family, a master assembly sequence is constructed. Extracting assembly sequence for any new variant that falls within, or significantly overlaps with, the scope of the considered family of products from the developed master assembly sequence was demonstrated. Partial assembly trees, Robinson-Foulds distance, consensus trees, hierarchical clustering and Genetic Algorithms were employed. The new method is a retrieval type assembly sequence generator.

The advantage of proposed method is clear for cases involving conflicting sequences (i.e. having multiple different assembly sequence for the same combination of components). It will generate the master plan with the most probable position for the conflicting components. When extracting the assembly sequence for a new variant, the user should ensure that those conflicting components are in a feasible position.

The proposed method depends on available assembly sequencing data. The quality of the obtained master assembly sequence and the subsequently extracted sequences depend on the quality of the used assembly sequences.

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# Optimal Design Concept of a Reconfigurable Haptic Device

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**Abstract**
Haptic devices are more and more common for human computer interaction or human machine interaction type applications. Using such devices multimodal interaction can be realized, increasing this way immersibility in the virtual reality environment. This paper presents specific considerations regarding the optimal design process of a class of reconfigurable haptic devices. The main focus of the paper is on the presentation of the novel ReHapy concept and on the details regarding the formulation of the cost function on which the optimal design process will be based.

**Keywords:** reconfigurable systems; haptic device; optimization; optimal design

## 1 INTRODUCTION

Virtual Reality (VR) has more and more applications also in production engineering such as computer aided design (CAD), virtual prototyping, virtual commissioning, virtual assembly and much more. Conventionally monitors, keyboard and mouse are used for interaction with the VR, but novel VR methods require novel VR interaction techniques. Haptic interfaces can be defined as dual interfaces (both input and output) that provide force feedback to the movements of the user or vice versa. In other words, defined as an analogy to visual interfaces, vision is to light as haptics is to touch [1]. Using haptic interfaces the user (operator, designer, etc.) can not only see, but can also feel (touch) the VR environment.

In figure 1 different interaction types between humans and objects are presented [10]. The most common interaction is when a direct contact exists between the human and the object (a). Interaction by the means of different tools (b) is also common. In the case of the telemanipulation (c) the mechanical linkages of the tool are replaces by mechatronical systems, dividing the system into two parts, master (the part manipulated by the user) and slave (the part that is actually interacting with the environment). In the last presented case, virtual manipulation (d), the slave part, and its environment is replaced by virtual reality.

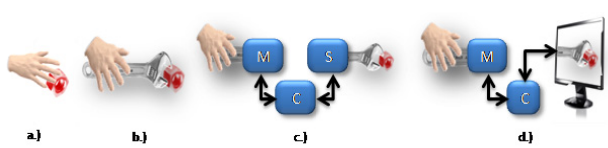


Figure 1: Types of object interaction, a) direct, b) with tool(s) c) telemanipulation, d) virtual telemanipulation. (M is Master Mechanical Structure, C is Control System and S is slave mechanical structure.

The current research project focuses on haptic feedback to the human hands, where the slave system is virtual and it is acting in a virtual environment (Fig. 1d). The research can be later applied also to teleoperation scenarios (Fig. 1c). Force feedback systems where the feedback is targeted at the human hand are also called kinesthetic haptic devices. Throughout this paper these devices are refered to as haptic interfaces or haptic devices.

The goal of this publication is to present a novel reconfigurable family of haptic devices as well as specific design and development aspects of these.

## 2 STATE OF THE ART

Haptic devices are more and more common. Their main goal is to improve immersibility of a virtual reality environment. Immersibility is defined as the quality of a virtual reality environment that it is perceived by the user as real, i.e. the user is immersed in the virtual reality. Common applications of haptic devices are teleoperation [11] (and also telesurgery [12]) and virtual teleoperation [13]. Usually the haptic feedback is applied to the hands and/or fingers, but haptic feedback to the feet is also not uncommon (Advanced Driver Assistance systems, haptic gas pedal [14]).

Many publications underline the benefits of using haptic devices in different production engineering related applications like virtual assembly task [2, 3], virtual manufacturing [4], virtual prototyping [5, 6] and virtual maintenance [7]. These novel interfaces make working with VR more comfortable and convenient [3]. In virtual assembly haptic interfaces are used to better predict manual assembly times [8] and to reduce assembly time by optimizing assembly paths [9]. Rapid virtual prototyping of knob types using haptic feedback is a cost efficient method of human in the loop testing [6]. Haptic devices complete the interaction while using novel VR methods for production engineering with force feedback, this way making the VR tangible, and making the work of the engineer more efficient.

In the scientific literature the benefits of using haptic interfaces in production engineering related application have been presented in different use-cases. In [15] it is stated that usage of haptic devices can assist design for assembly task and can reduce the number of prototypes needed. In [6] a haptic interface is used for rapid prototyping different knob types cost efficiently. In [3] it is stated that haptic interfaces make virtual assembly applications more convenient and comfortable. In [7] haptic interfaces are used to virtually test assembly designs, and the results show that using



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assembly tests with haptic interfaces manual assembly times can be better predicted. In [8] it is demonstrated that assembly time can be improved when using optimized paths from virtual assembly tasks with haptic interfaces. In [6] the benefits of using haptic devices for maintenance planning in the design phase are shown. Other examples of using haptic interfaces in production engineering applications can be found in [16 - 19].

Haptic interfaces can be grouped in two large categories [20]: admittance type and impedance type.

In the case of admittance type devices the user acts with a force (pushes or pulls) on the haptic device and the device responds with a movement. In other words the input to the device, generated by the user is a force, the output, felt by the user is a movement. Admittance control is used for such devices.

In the case of impedance type devices, presented in figure 3, the user moves the haptic device and the haptic device responds with a reaction force. In other words the input to the device, generated by the user, is movement, and the output, felt by the user, is force. Based on this operation principle the mechanical structure and control system of the devices differ.

Impedance type haptic interfaces must have high stiffness, back-drivability, low inertia and low friction [21, 22]. Singularities in the movement of the haptic device are not desired. The degrees of freedom (DOF) of the haptic devices in most cases are either 3 or 6 [23]. This is due to different types of contact modeling. If the contact is modeled as a point then only 3 resulting linear forces can be used for feedback, but no angular forces (torques) can be calculated. When modeling contact between rigid bodies, the 6 DOF structure can also render torques. Bimanual interfaces [24] have usually two independent structures for the two hands and are aimed at independent manipulation with both hands (i.e. telesurgery, when the two hands act independently, and do not grasp the same object). Most of these structures have 6+6 DOF.

Very few reconfigurable structures as haptic interfaces are published. In [25] a reconfigurable haptic interface having 3 to 6 degrees of freedom is presented. It is aimed at one hand manipulation by the means of a stylus.

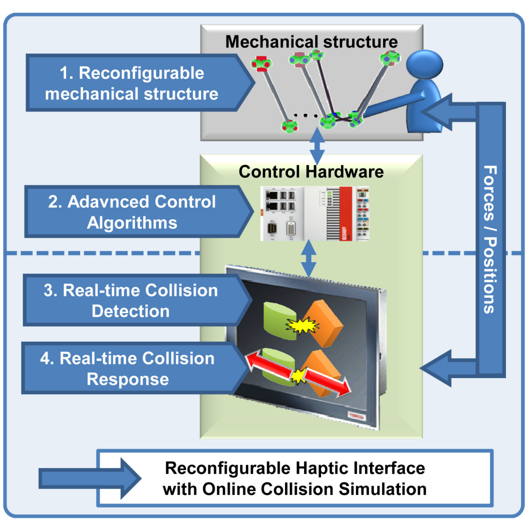


Figure 2: ReHapy concept.

Unconstrained movements of the virtual avatar must provoke unconstrained movements of the haptic device without any display of force (due to friction, inertia, gravitiy etc.). In other words, the overall structure of the haptic interface must be transparent [26]. This transparency cannot be achieved in the mechanical structure alone. An adequate control system has to be implemented in order to compensate the flaws of the mechanical system. Transparent mechanical structures are used both in combination with impedance and admittance type control systems [27], although it is a requirement only for impedance type interfaces. A haptic interface with such a control structure can benefit from the advantages of both types of control algorithms.

Publications in the scientific literature, although present the kinematic structure of haptic devices, usually lack the background information regarding the motivation on chosen design variables. Relying solely on the experience of the mechanical designer is in many cases an acceptable option, but in the case of haptic devices, their complex functionality decreases the intuitiveness of the design process. When considering a reconfigurable haptic device family, build up from common modules the design process becomes unintuitive. Choosing the correct design variable based on an objective decision is considered an open problem in the case of a reconfigurable haptic device family.

## 3 REHAPY CONCEPT

Reconfigurable systems, based on their modularity property, fulfill varying requirements economically. A reconfigurable haptic interface will have the advantage that it can fulfill the varying requirements of different VR interaction scenarios cost-effectively.

Novel real-time simulation methods permit the simulation of collisions with reduced computational power. In order to fully use the potential of haptic interfaces they conventionally need to be connected to VR environments, with high computation power, where the dynamics of the virtual world are simulated in real time. When considering haptics just a part of the calculations of the virtual world are necessary, most importantly collision simulations. Collisions simulated in the control architecture of the haptic interface make possible the exploitation of the full potential of a haptic interface without a need for expensive VR environments with high computational power.

The ReHapy architecture proposes the integration of real-time collision simulation and development of a reconfigurable haptic interface that includes real-time collision simulation in its control system. In figure 1 a graphical summary of the concept is presented.

ReHapY (Reconfigurable Haptic Interfaces) is a concept, which embeds hardware components (mechanical architecture of ReHapY

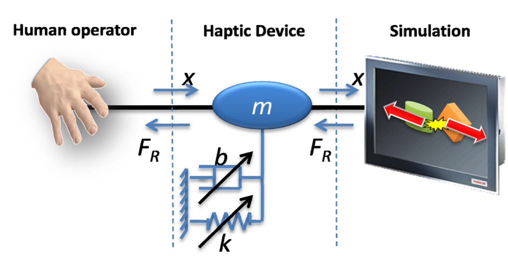


Figure 3: Impedance type haptic device concept [20].

and other Virtual Reality hardware) and software (functionally connecting them) with the goal of reproducing and testing different haptic sensations. Reconfigurable parallel robots are the main hardware component (named ReHapY – PR) of this concept.

Parallel robots are made out of a fixed platform and at least one mobile platform. These platforms are connected by kinematic loops which do not necessarily have similar topology. Because generally the actuators are directly connected to the fixed platform, parallel robots can develop higher accelerations and higher forces/torques and the weight of the parts in motion is lower than in the case of serial robots. This makes them well suited for applications as haptic devices.

The preliminary topological model of the ReHapy haptic device is presented in figure 4.

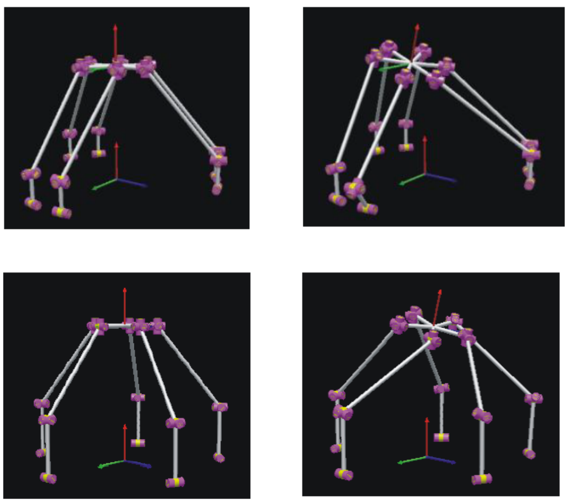

Figure 4: Topology of the ReHapy haptic device, 6 dof configuration (upper) and 5 dof configuration (lower).

## 4 OPTIMAL DESIGN PROCESS

Optimal design, by definition refers to substituting the empirical judgment of an experienced designer with an optimization based approach, when a quantification of the design result is possible. Since empirical judgment is strongly related to experience, the optimal design process reduces the effect of designer experience on the final product. The quantification of the design process results is not always possible. In the case of a robot kinematics, the performance indicators can be used to quantify a design (e.g. dexterity, precision). An optimization procedure is always a minimization (or maximization) of a cost function (also called goal function of fitness function). The optimal design process, if we consider a kinematic performance index as a goal function, can be translated into generating the key geometric features (e.g. length of linkages) of a haptic interface in order to maximize the overall average dexterity of the said structure.

The key to a successful optimization process is the cost function. It has to successfully evaluate the structure, and quantify the results, quantifying this way the quality of the structure. Many factors influence the quality of such a structure, and so many such factors have to be included in the cost function. After a factorial analysis the following factors were considered the most influential on the usability of a haptic device:

### 4.1 Workspace Size and Shape

The size and shape of the workspace of a haptic device should resemble the size and shape of the human arm. The current state of the art describes the kinematics parameters of the human arm, based on which the workspace size and shape [28] can be easily computed [29].

Let $W_{arm}$ denote the sets of points reachable by the human arm. This would correspond to the workspace of the human arm. It can be computed very similarly how the workspace of serial robots ar computed.

Given

$$L = [l_1 \quad l_2 \quad l_3] \tag{1}$$

Where

$l_1$ represents the distance between the shoulder and the elbow

$l_2$ represents the distance between the elbow and the wrist

$l_3$ represents the distance between the hand and the wrist

the motion types of the human arm, namely

- shoulder flexion-extension ($q_1$)
- shoulder adduction-abduction ($q_2$)
- elbow flexion-extension ($q_3$)
- elbow rotation ($q_4$)
- wrist adduction-abduction ($q_5$)
- wrist pronation-supination ($q_6$)
- wrist flexion-extension ($q^7$)

and also the angular limits of these motions

$$Q_{min} = [q_{1_{min}} \quad \cdots \quad q_{7_{min}}] \tag{2}$$

$$Q_{max} = [q_{1_{max}} \quad \cdots \quad q_{7_{max}}] \tag{3}$$

the workspace of the human arm has been obtained.

$$W_{arm} = f(L, Q_{min}, Q_{max}) \tag{4}$$

The values of $L, Q_{min} and\ Q_{max}$ are defined by nature. This workspace is presented in figure 5.

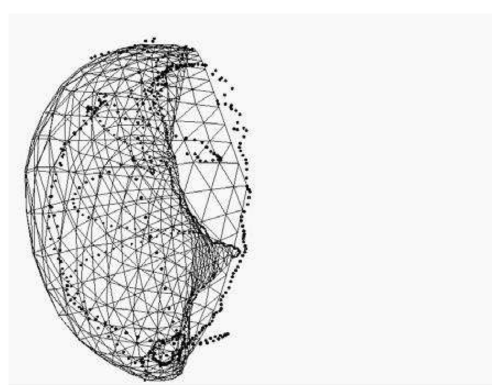

Figure 5: The workspace of the human arm, as presented in [29].

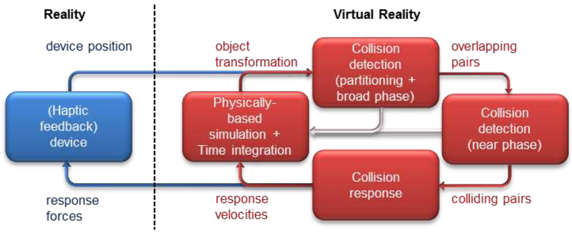


Figure 6: Force control concept.

Based on the set of points $W_{arm}$, a criteria for the optimization process can be formulated. One goal of the optimization is to obtain a workspace that has a similar shape and size of the human arm. Formulated differently, the difference between the shape and size of the workspace has to be minimum. Let $W_{robot}$ denote the sets of point reachable by the haptic device.

In the case of the haptic device, the workspace is dependent of the length of the structural elements and the angular limits of the joints.

Similarly as in the case of the human arm, the workspace of the haptic device can be formulated:

$$W_{robot} = f(L_{robot}, Q_{robo_{min}}, Q_{robot_{max}}) \tag{5}$$

Where

$L_{robot}$ includes all geometrical lengths in the kinematical model of the haptic device

$Q_{robo_{min}}$includes the minimum limits of all joint in the kinematical model of the haptic device

$Q_{robot_{max}}$ includes the maximum limits of all joint in the kinematical model of the haptic device

The cost function can be formulated as the number of points in the intersection between the two sets. Adopting the same resolution fot the two pointclouds, and implementing a tolerance, when decideing if two points are superpositioned or not, the cost function $g_1$ becomes:

$$g_1(L_{robot}, Q_{robo_{min}}, Q_{robot_{max}}) = \langle W_{robot} - W_{arm} \rangle \tag{6}$$

The variables $L_{robot}, Q_{robo_{min}}$ *and* $Q_{robot_{max}}$ will be the subject of the optimization. The brackets ⟨ ⟩ symbolize, that cost function $g_1$is not dependent on the actual difference point cloud, but it is dependent on the number of point that can be found in this difference, thus evaluating both shape and size of the robot workspace, in comparison with the workspace of the human arm. If the two workspaces have exactly the same size and shape

$$W_{robot} = W_{arm} \tag{7}$$

Substituting equation (7) to equation (6) gives

$$g_1(L_{robot}, Q_{robo_{min}}, Q_{robot_{max}}) = 0 \tag{8}$$

This way the best possible solution will be evaluated as the absolute minimum of $g_1$.

### 4.2 Maximum Force

The forces reproduced by the haptic device come from the virtual world. This is presented in figure 6. Forces and reaction in the virtual world can be very high; in some cases (e.g. collision with a stiff wall) can be almost infinite. Obviously this cannot be reproduced on a haptic device.

The force reproduced by the haptic device acts upon the human hand and arm. In the case of an impedance type haptic device the maximum force that has to be reproduced by the haptic device can be identified as a force larger or at least equal to the maximum force that can be developed by the human arm.

$$F_{robot_{max}} \geq F_{arm_{max}} \tag{9}$$

Where the $F_{robot_{max}}$ refers to the maximum force developed by the haptic device and $F_{arm_{max}}$ refers to the maximum force that the human arm can develop. Please note that in both cases the term force refers to the generalized force concept which includes also torques.

The maximum force developed by the human arm can be found in the state of the art. In order to compute the maximum force that the haptic device can develop the dynamic model of the haptic device is required.

A dynamic model has been developed in a strongly parameterized manner, having in mind the multiple configurations of the haptic device. The basis of the analysis is one kinematic chain in the structure of the robot, as presented in figure 7.

The theorem of movement of the mass center point of segment 1 of the kinematic chain i gives:

$$m_1^i \cdot a_{1x}^i = G_{1x}^i + R_{01x}^i + R_{21x}^i \tag{10}$$

$$m_2^i \cdot a_{2y}^i = G_{2y}^i + R_{01y}^i + R_{21y}^i \tag{11}$$

$$0 = R_{01z}^i + R_{21z}^i \tag{12}$$

The theorem of the kinetic moment for segment 1 of the kinematic chain I in realtion to point Bi gives:

$$0 = R_{21z}^i \cdot l_1^i + M_{01x}^i \tag{13}$$

$$0 = M_{21y}^i + M_{01y}^i \tag{14}$$

$$J_{Bi}^i \cdot \ddot{\varphi}_{1z}^i = R_{21x}^i \cdot l_1^i + G_{1y}^i \cdot l_1^i / 2 \tag{15}$$

The theorem of the movement of the center of the mass of segment 2 of the kinematic chain gives

$$m_2^i \cdot a_{2x}^i = G_{2x}^i + R_{72x}^i + R_{12x}^i \tag{16}$$

$$m_2^i \cdot a_{2y}^i = G_{2y}^i + R_{72y}^i + R_{12y}^i \tag{17}$$

$$m_2^i \cdot a_{2z}^i = G_{2z}^i + R_{72z}^i + R_{12z}^i \tag{18}$$

The theorem of the kinetic moment for segment 1 of the kinematic chain in relation to point Ci gives:

$$J_{Ci}^i \cdot \ddot{\varphi}_{2x}^i = R_{72z}^i \cdot l_2^i + G_{2z}^i \cdot l_2^i / 2 \tag{19}$$

$$0 = M_{12y}^i$$

$$J_{Ci}^i \cdot \ddot{\varphi}_3^i = R_{72x}^i \cdot l_2^i + G_{2x}^i \cdot l_2^i / 2$$

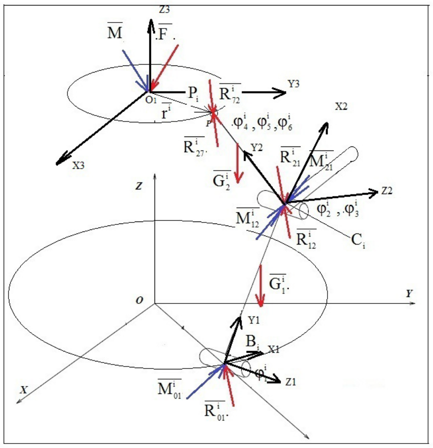

Figure 7: Forces acting on one kinematic chain.

Equations (10)-(21) represent a simplified dynamic model if the haptic device. Based on this model, having as input the maximum force developed by the human arm, as the force on the TCP (tool center point) of the haptic device the motor torques can be calculated.

### 4.3 Force Distribution

The maximum force developed by the haptic device characterizes the device only in one operational state. Given the maximum motor torques, there is only on set of values for the motor joint angles for which the maximum force on the end effector is available.

Since the haptic device is intended to be used not just only in this specific point, the distribution of maximum available force throughout the workspace has to be studied. Unfortunately this is also true for the human hand. The maximum force available at the level of the human hand is dependent on the arm position.

This way a maximum available force in every point Pi of the workspace has to be computed both for the human hand and for the haptic device. The corresponding points must be compared.

Let $\bar{F}_{robot_{P_i}}$ denote the force developed by the haptic device in the point Pi of the workspace, and let $\bar{F}_{arm_{P_i}}$ denote the maximum force developed by the human arm in the same point Pi. The following relation would describe an ideal haptic device:

$$\bar{F}_{robot_{P_i}} \geq \bar{F}_{arm_{P_i}}, \text{ for every } P_i \in W_{arm} \tag{20}$$

In other words, the haptic device, in every operational point can develop a maximum force which is equal or slightly larger than the maximum force that can be developed by the human arm in the same position.

A cost function can be formulated based on the above consideration. The inversion of the inequality can be explained by the tendency to minimize differences and not to maximize similarities.

$$g_2 = \langle \bar{F}_{robot_{P_i}} < \bar{F}_{arm_{P_i}} \rangle_{i=1..n} \tag{21}$$

Where the brackets symbolize the number of points $P_i$ for which $\bar{F}_{robot_{P_i}}$ does not exceed $\bar{F}_{arm_{P_i}}$ for all n points

If in every point of the workspace the haptic device can develop a force larger or at least as large as the human arm in the same point, the value of the cost function will be the absolute minimum, 0.

### 4.4 Pareto Optimum

Optimal design procedure has to be based on both presented cost functions. A pareto type cost function can combine both perspectives of the design procedures. This way the overall cost function can be formulated as

$$g = w_1 g_1 + w_2 g_2 \tag{22}$$

Where $w_1$ and $w_2$ are weighing factors and $w_1 + w_2 = 1$. The two cost functions are in conflict based on their different nature. Cost function g1 defines the workspace size and g2 the maximum force distributions. A very large workspace would lead to an even force distribution, but would cause an over dimensioned robot.

By carefully choosing the weighing factors a pareto optimum solution to the haptic device design can be achieved.

Based on this cost function, the optimal design procedure can be formulated.

## 5 CONCLUSIONS

The presented approach aims to exchange a large part of empirical decisions in the design process with an optimal design approach. The key to such an approach is the cost function, which has been presented in detail. After formulating the cost function, different optimization algorithms (e.g. Genetic Algorithm, A-star algorithm) can be used to carry out the optimization and obtain the desired design parameters, assuring this way an optimal structure of the haptic device.

Novel applications such as industrial robot programming using virtual teaching technique can be researched using the ReHapy interface. Research concerning the training of workers for different manufacturing and/or assembly processes, where human error can lead to major damage, can be carried out partly using VR, reducing costs this way.

## 6 ACKNOWLEDGMENTS

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# Energy Monitoring for Investigating the Sustainability of Extrusion Process

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**Abstract**
It is well known that industrial processes require large consumption of energy and other resources in the realization of products. This exploitation of energy is reflected on the environment, in terms of environmental impact, and on the ecosystem of the entire supply chain, in terms of social and economic impacts, which can be measured through specific tools. The measurement of these environmental, social and economic impacts is an essential step towards both the process monitoring and sustainability energy assessment. Numerous studies have recently been focused on industrial energy use and energy efficiency in various manufacturing sectors.

The aim of this work is to define a new methodology to monitoring the extrusion process and to realize the sustainable manufacturing. This method can be seen as a joint venture between monitoring system and LCA analysis related to the process.

**Keywords:**
Sustainable Manufacturing; Energy efficiency; Process monitoring

## 1 INTRODUCTION

The theme of this paper, “Sustainable Manufacturing,” stems from the growing interest in energy efficiency in industrial processes. In fact, sustainable manufacturing could be considered an effective solution to support the continuous expansion of manufacturing industry, where the environmental, social and economic impacts are the focus in production assessment [1].

The concept of sustainability evolved in the last decade and aims to have a green development that does not compromise the natural resources and the human health for the future generations. The current studies proposed three dimensions to identify the core of sustainable thinking: environment, economy, and social wellbeing [2].

The principles of Sustainable Manufacturing, which are an extension of the principles of sustainable product, include zero waste, low environmental and social impact, fewer raw materials, optimization of product and process parameters, and development of an infrastructure to manage the sustainable manufacturing implementation. The main difference between these two principles, one applied on the product and one on the process, is the introduction of energy as an important asset in the sustainability assessment. The inputs in the environmental and economic assessment of a product are the raw materials, the transports, and the processes involved. If the focus changes from products to processes, the sustainability assessment necessarily involves all production inputs such as raw materials, energy, water, manpower and the other resources that contribute to the final product manufacture. In fact, industrial processes require the large consumption of energy and other resources during products manufacturing.

Thus, having a methodology to assess the impacts from various resources that were used during the production process is useful. Moreover, this approach could be the starting point to evaluate the energy efficiency of industrial parameter processes.

This paper focused on the extrusion process, which is a good example of high energy consumption process.

In the following chapters, we analysed studies from the last decades on sustainable manufacturing, energy efficiency and the methodology applied in industry to monitor and to control processes in order to minimise energy consumption. Then, a new methodology was defined in detail to identify critical areas in the industrial layout and high energy-consuming devices. The conclusions of the paper underline the coming development of the presented methodology in an industrial case study. This industrial application will be the topic of a future work in which LCA (Life Cycle Assessment) and LCC (Life Cycle Costing) analyses are applied.

## 2 STATE OF THE ART

### 2.1 Growing Interest in Energy Efficiency

In recent years, the increasing pressure on material availability, energy prices, and emerging environmental legislation is leading manufacturers to adopt solutions to reduce their material and energy consumption as well as their carbon footprint, thereby becoming more sustainable [3].

For example, the European Commission (EC), whose objective is to reduce the annual consumption of primary energy by 20% within 2020, estimated that an energy saving potential for the manufacturing sector of 25% could be realised by implementing energy-efficient motors, fans and lightings [4].

Major industrial repercussions due to this trend can be observed, especially in high-energy-consuming companies (and consequently large $CO_2$ emitters), such as petroleum refining, primary metal processing, non-metallic minerals processing, chemical production, and paper product manufacturing. These companies are characterised by continuous or semi-continuous processes and energy is the major cost voice. The optimization of these processes has received significant attention in both academic and industrial research environments [5]. Over the last decade, the importance of carbon emissions and energy efficiency has grown exponentially and this has created new economic opportunities. However, there are some risks in manufacturing because of the high competition among the industries [6].

Many industrial companies still lack methods and tools that are able to correctly allocate energy consumption along the production chain. In this case Information and Communication Technologies (ICT) and controlling systems play an important role for improving energy efficiency in manufacturing processes. Several studies have also identified a low status of energy management as a barrier to energy efficiency (see, e.g., [7]). Indeed, the measurement of energy consuming by industrial processes is the basis for deciding about

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improvement measures, for tracking changes and improvements in energy efficiency, and for implementing the process control [8].

Energy used in industry can be classified as direct energy and indirect energy [9]. The first is used in production processes, while the second is used in the supporting processes such as ventilation, lighting, heating and cooling. Indirect energy is often underestimated and in this field there is a wide room for improvement. Measuring energy efficiency is the basis to control the energy consumption in the production processes, to decide the improvement measures and to track the changes and improvements in energy efficiency. The sensor devices are used to measure the energy consumption and the collected data are useful to determine the energy efficiency ('plug and play' information in a machine [8]). Herrmann et al. [10] provided an overview of energy consumption metering procedure and tools and Kara et al. [11] presented an overview of the evolution and the latest developments in power measurement and monitoring systems.

### 2.2 "Sustainability" Measurement

Regarding the environmental impact assessment, the utilisation of the LCA methods to assess the production system footprint requires specific developments in life cycle modelling. Specifically, when the production process is considered during the analysis as a product, the system LCA modelling highlights that to realize a correct and complete analysis are required an amount of data bigger than the number of modules that compose the product itself (more than ten times). Then, the final amount of the information to be collected for the Life Cycle Inventory (LCI) usually becomes prohibitive when it is applied to the whole life cycle of machines and equipment, which compose the production lines [12]. The Centre for Sustainable Manufacturing and Reuse/Recycling Technologies (SMART) at the University of Loughborough has developed a system enables to model the Embodied Product Energy (EPE), that is required during the manufacturing phase of a product (in this system are considered both the direct energy consumption and the indirect energy consumption) . As reported in [13], the EPE allows an approach to reduce the energy consumption during the manufacturing stage of a product.

To resolve the lack of environmental analysis of the manufacturing processes and the corresponding LCI data, the CO2PE! – Initiative (Cooperative Effort on Process Emissions in Manufacturing) was launched. The CO2PE! Initiative has the objective to define and quantify the environmental impact of a wide range of emerging industrial processes and to give the guidelines in order to improve their performances. In 2009, the initiative was officially recognised by CIRP as part of the Collaborative Working Group EREE (Energy and Resource Efficiency & Effectiveness) and IMS as the Manufacturing Technology Platform (MTP) Theme [13]. Herrmann et al. [14] proposed a framework to visualise the environmental impact of the manufacturing processes using virtual reality. Lofgren B. et al, [15] developed a method that combines discrete-event simulation (DES) with life-cycle assessment (LCA), with the aim to capture the dynamic interrelationships between manufacturing processes in order to analyse systemic responses to configuration changes.

The Organization for Economic Cooperation and Development (OECD) Core Environmental Indicators (CEI), [16] include 46 indicators to measure the impact of industrial activities on the environment in industrialised countries. Existing EU projects [17] have focused on the ability to redesign and significantly reduce the power consumption of the machines [18]. Although the energy consumption from 1999 to 2009 by the industrial sector was decreased by 15% [19], more improvements are still necessary.

### 2.3 The Extrusion Process

Over the last decades, plastic production has increased intensively. European plastic production in 2010 was approximately 57 million tons, which represented 21,5% of the global production. In particular, PVC and PE productions (these materials are used in the factory that was considered in this study) represented 29% and 12% of the total production, respectively[20]. Extruders play a major role in processing polymer materials, and the extrusion process is used to produce the commodities in various industrial sectors such as packaging, household, automotive, aerospace, marine, construction, electrical and electronic, and medical applications. Improvements in extrusion-process monitoring are invaluable for advanced process control and troubleshooting, and they will help to increase the process efficiency. The extrusion process is highly complex and variable due to significant interdependencies among material properties, operating conditions, and machine geometry [21].

There are many studies on discrete-part manufacturing and how it can be improved in terms of energy efficiency (see, e.g., [5]), but the study of continuous and semi-continuous processes is limited. Currently this type of processes are better analysed with the aim to improve the product quality. For example, "on-line monitoring" is used to analyse the product faults that occur along the production chain and to reduce the waste production. In fact, these processes are widely used in pressure- and temperature-control systems. The field of quality control and the use of specifically related tools are widely described (see e.g., [22]). At process level there are some focus on the thermal monitoring system [23].

The extrusion process, that we consider in this paper, consists of the gradual melting of solid polymer using thermal conduction and the viscous shearing between a rotating screw and a barrel [23]. Some interesting studies have focused their attention to the energy used by the extruder [25], in particular, to the torque measurement and the related electrical energy required. Other studies (see e.g., [24]) referred to the use of finite element method to determine the required minimal energy or the critical point during the extrusion phase, which can significantly affect the product quality.

However, polymer extrusion is an energy intensive process, that has a wide margin of improvement to seek the optimal process conditions. This paper aimed to present a method that is a joint venture between a monitoring system and an LCA analysis related to the process.

## 3 THE IMPORTANCE TO HAVE A METHOD TO MONITORING AND CONTROLLING OF INDUSTRIAL HIGH-ENERGY-CONSUMING PROCESSES

Because energy consumption calculation in a manufacturing system is difficult to realise with only the help of mathematical models, this paper presented an innovative method to quantify the manufacturing energy efficiency and its related environmental and economic consequences. In this study, the objective is to realize a system capable to monitor and control an extrusion line. This work aimed to combine a monitoring system and a sustainability analysis (LCA and LCC application) to obtain the process LCA analysis, to develop a database with the information that can provide feedback, and to make decisions to improve the process performances in the economic and environmental point of view. To realise this, it is necessary to characterise the volume control because this production line is considered an open system that consumes sources (materials and energy) and produces a continuous output, as shown in Figure 1. The system consists of a finite number of units, each of which is treated as an open system.

Currently, there are many types of controlling systems and techniques to recover energy, but few of these techniques are economically suitable. Thus, it is important to consider greener energy as the saved energy.

The objective of saving energy is clever; however, to realise this objective, it is necessary to study all processes, to monitor the parameters and to evaluate the data based on the boundary conditions. Energy saving has repercussions along the entire energy production chain, and because a great amount of energy in Italy is produced from fossil fuels, the environmental and economic benefits are significants.

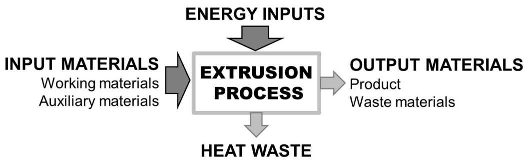


Figure 1: Representation of the extrusion process input/output.

In this case, the aim is to characterise the hotspots of the process, to optimise them and to reduce the energy required at the beginning of the process. If more corrections are conducted downstream of the system, the energy benefits are increased due to the presence of the intermediate yields. It is possible to realise a statistic model prior to the sub processes and then of the major process efficiency, to evaluate and to predict the effect of the changing parameters on the process performances. The LCA analysis will move parallel to this study. In fact, to realise a specific environmental assessment, one must collect a series of data that are not present in the available databases in the literature. Thus, the LCA analysis aims to collect data and their elaboration inside a specific LCA software tool.

Energetic performances are related to many parameters. Therefore, it is important not only to have a system able to monitor the processes in real time but also to develop a database, in which an investigation methodology can be applied to understand which parameters are improvable or not from the energetic and economic point of view. In the Figure 2 is shown an idea of the main relevant parameters that should be investigated to have a realistic value about energetic impact and exploitation of extrusion process.

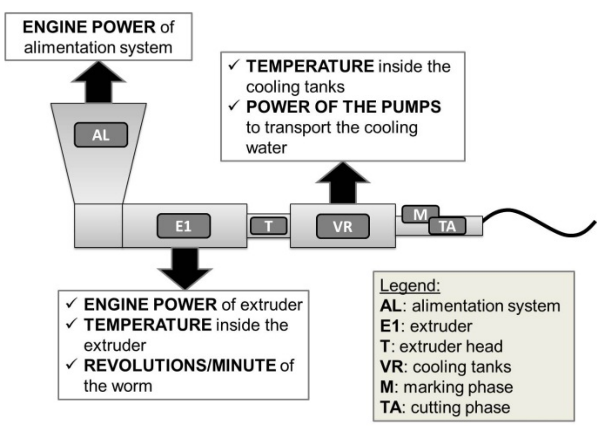


Figure 2: The main relevant parameters of the extrusion process.

In order to achieve the maximum energy efficiency, one should define the quantity of energy required by the modules that form the industrial process, the used type of the energy and the primary energy required. For example, because thermal energy can be produced using electrical resistance or thermal vector fluid, the total primary energy and its related environmental and economic impacts are different. For electrical motors, one should consider the total energy required. Furthermore, one must define and divide the indirect energy and the direct energy. In most cases, one of the major causes of energy inefficiency is the underestimation of the indirect energy consumption. The investigation method will provide a sweep check on the whole process, but the upstream step is to understand the necessary accuracy of this analysis. Not all cases require the maximum degree of accuracy, and the choice will be decided according to the type of energy demanded and the machinery importance inside the process.

During the shaping phase, thermoplastic materials require mechanical energy for the rotating screw and the barrel, and thermal energy is needed for the polymerisation process. Moreover, it is important to quantify the quality of the wasted energy to evaluate the possibility to reuse this type of energy for the auxiliary processes in the major one. The process constraints, such as the production rate, the operating hours, the product quality, the contract types between the factory and the energy suppliers and the available technology, should also be considered. In particular, because industry consumes a lot of electrical energy, due to the presence of some extremely energy consuming motors, it is important to explain the problem related to this type of energy. In fact, one must consider the active energy (Ea, expressed in kWh) and the reactive energy (Er, expressed in kvarh). The first is transformed in work and heat by electrical appliances such as incandescent bulbs. The second is stocked for a few times and then released in the electrical grid instead of being consumed immediately by the user. Reactive energy is related to appliances that operate with a magnetic field, such as motors. Due to its nature, reactive energy off-take is limited because it causes imbalances in the electrical grid, which increases the current flow in the power lines. The current flow increase leads to an increase of the total losses in energy transfer, which reduces the efficiency of the electrical system. In particular, one must pay attention to the ratio between the two types of energy. If this ratio is high, the electrical plant is unbalanced, and there are negative consequences:

- voltage drop;
- energy losses in the conductors;
- energy consumption increases;
- available power decreases.

This ratio, named cosφ, is characterised by Equation (1) shown below:

$$\mathrm{Cos}\varphi = \frac{Ea}{\sqrt{\mathrm{Ea}^2 + \mathrm{Er}^2}} \tag{1}$$

In Italy, this value must be at least 0,9. It is important to maintain this high value because of the penalty that the industry receives if the value is lower than the first one. Thus, beyond the environmental aspect, there is also an important economic implication.

Because the relevance of the economic aspect that determines the industry competitiveness an LCC analysis must be done accurately to evaluate the main cost sources. Considering in the analysis an industrial process instead of a product, the economic risks and the possible improvements must be evaluated in the medium and long period rather than in the short period.

## 4 SUSTAINABILITY OF EXTRUSION PROCESS

The modern enterprise is characterised by a complex system of relationships among various stakeholders (customers, employees, shareholders, regulators, and society in general), and each of them exercises specific pressures; in this context, new opportunities and threats arise. Therefore, it is fundamental to define responsible and forward-looking policies and strategies.

In this context, process monitoring and controlling are the main pillars in modern industrial production to achieve the total quality for the overall control of the production processes and to connect the elements between the environmental impacts and the decision making process.

This paper responded to a general need to have full control on the highly energy-intensive processes, characterised by a high resources exploitation where a small change in the production process can produce a big benefit in terms of process sustainability. Extrusion process is a good example because it involves a several number of machineries (i.e. extrusors) and auxiliary systems (i.e. chillers, shredder, etc.) which consume a lots of energy, water and raw materials each one. Moreover this process is based on rules of thumb and experience of the operators and not on codified knowledge.

Extrusion is a continuous process to realize semi-manufactured products such as pipes, profiles and cable sheaths. Although the design of the mould and some extrusion components are different, each product has the same production method [26]. The plastic material, initially in the solid state in the form of small particles (pellets) or powder, is conveyed using a screw pump and heated by suitable heating bands at a controlled temperature until it becomes a highly viscous liquid to be extruded through a die, which gives it the desired shape. Subsequently, the product thus obtained is cooled and calibrated. When the product has reached the desired length, it is cut to size. The biggest energy consumers in the extrusion process are the motors and the heating units.

Today the environmental and economic impacts affected by the extrusion process are not known due to the lack of a methodology that investigates each process components and its resources consumption. The method proposed in this paper tries to reply to this issue, using a highly flexible system that can be applied to any company that has a continuous production flow, high energy consumption and problems to keep the process under control. In fact, the method that will explain in the next chapters can be applied to other manufacturing companies in order to monitor their process parameters and save the energy consuming during their exploitation phase. It requires to have high energy consuming that justify an investment for a customized infrastructure to capture and to collect the data needed. The constrain about the continuous production flow is necessary in this analysis in order to monitor and control the extrusion process; if we had a discrete manufacturing process, would be difficult compare data and information during time period different and unrelated.

### 4.1 Methodology

The proposed methodology aims to identify the high energy consuming machineries, components, and devices in the company. This study is supported by a hardware and software infrastructure among the machineries and auxiliary systems which appear to be the most impactful in terms of energy consumed.

The hardware infrastructure consists of a several sensors implemented on the chiller cycle, on the main electrical panel plant, and on the extrusors, both inside each component and at the upstream of the production line. The sensor typology varies according to the measurement expected:

- temperature measurement, through temperature probes;
- energy measurement, through a network analyzer;
- chiller pressure, measurement through pressure transducers;
- productivity measurement, in terms of tube meters per minute, through encoders or magnetic sensors.

For the new generation extrusors, some of these data are collected directly by a PLC on board.

The software infrastructure allows the user (e.g. department head, production manager, etc.) the monitoring and controlling of both the production line and the whole plant in term of energy consumptions and environmental impacts. In fact, the real data monitored by the hardware infrastructure are collected and compared with the hypothetical values, measured on the basis of historical data. In fact, to understand and discover the critical process components and auxiliary systems, the enterprise must have a database of several historical data, so that the process designer or the head of the production can compare the real measured data with the collected historical data. When there is an incongruity between real and hypothetical values, user can read in real time this issue and he can intervene as soon as possible.

The main advantage of software infrastructure is the feedback visibility: when user modifies some parameters to include their values in a certain range, he also can verify the result of his modification feedback.

In order to identify only the production lines and the auxiliary system which have an high energy consuming it is necessary to apply a step by step methodology that allows the tracking at first of all macro areas high energy consuming in the plant, and then, for each macro area identified, all high energy consuming processes and devices recognised. In the last step, the critical parameters and the critical values for each machine and device identified are studied and monitored.

The study was conducted with a plastic pipe manufacturer, which had at least three plants where the extrusion process was performed. The plant involved by this new monitoring and controlling process method was affected by the production of polyethylene (PE) pipes. The macro areas identified are:

- raw materials storehouse. This area involves both the plastic powder storehouse and the transporting means through the plant from the raw materials silos to the extruder alimentation zone;
- extrusion lines. This area is the production area, which involved seven extrusion lines, many of which are of the latest generation. Thus, they are supported by a PLC on board. Moreover, the extrusion lines work continuously;
- refrigeration unit (chiller and cooling tower). This area allows an effective cooling of the freshly extruded tubes;
- shredder waste. This machine disposes the production waste. Because it works in discrete time intervals instead of continuously, it is considerably difficult to quantify the real percentage of energy consumption that is involved in the global consumption of the whole plant;
- finished product storage. This area involved the devices and sensors that store the finished product.

Figure 3 shows how the two main macro-areas identified in this specific extrusion enterprises (chiller group and extrusion lines) are interconnected. The blue line represents the ICT connection among the macro-areas and the orange lines represent the set of sensors and devices to collect the process parameters by each components in the macro-area.

After the macro areas in the plant were identified, it is necessary to understand their energy-consuming percentages. To solve this problem, a network of sensors, encoders and appropriate devices was developed and implemented in the industry plant (hardware infrastructure defined before). The purpose is to capture all data that the monitoring and control methodology needs.

These data are:

- the productivity of each line; this value involves the production speed (meters/minutes or kg/hours) and the number of pieces produced;
- the temperature detected along the extrusion line, which is the temperature of the cylinder, the extrusion head and the cooling tanks;
- the temperature measured in the refrigerating circuit, which is the temperature in the evaporator inlet and the chiller outlet;
- the flow rate of the refrigerant circuit.

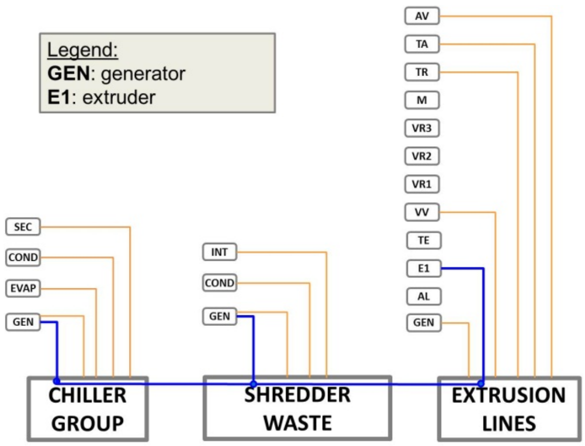


Figure 3: Macro-area and components identification in the extrusion plant.

Regarding the extrusion process, the plant areas most affected by energy consumption are the production area (the extrusion lines) and the refrigerator area. The crushing waste area is critical but unlike the previously mentioned areas, it does not work continuously. In the discussion of monitoring and control, we only refer to processes that operate continuously and difficult to keep under control. Otherwise, it becomes difficult to understand the contribution of a batch process with the proper conditions and working hypotheses.

In the production area, the critical components are the extruder (the main motor), the coextruder, the extrusion head and the vacuum calibration tank. In the refrigerator area, the critical system is the chiller.

At this point, the network to collect all necessary data into an enterprise was defined and built.

The next step in this methodology definition is the evaluation of the LCA analysis, applied to the production process. In this way, all process parameters and critical values are involved.

### 4.2 Sustainable Manufacturing

The measured data during the methodology application were necessary to create also a LCA database, where the environmental impacts related the extrusion process were collected. The using of this tool allowed to involve and merge in the methodology all process parameters and critical values affected by a high-energy-consuming.

In fact, the studied method had to present the promising prospect of a hardware and software system to control and monitor the industrial production processes. This system is promising due to the current needs to increase the productivity and decrease the waste of industrial processes while respecting the environmental sustainability.

In the previous paragraph the hardware system functionalities have been presented in detail; here the software system functionalities will be defined.

The software system is based on a correlation model between the process parameters and the energy consumption, which also considered the related environmental and economic impacts. These values are associated to extrusion process components and devices.

The process parameters and the energy consumption are collected through the network of sensors and devices which compose the hardware infrastructure. The environmental and economic impacts are defined through the LCA and LCC analysis application on the process. This is an innovative way to identify and control the industrial processes.

Figure 4 shows the schematics of the methodology, which was developed in the industrial case of the extrusion process. In the environmental and economic analysis the main concept is to translate the LCA and LCC analysis from product application to process application; this means that the industrial process must be organised in several functional components which have a specific number of input and output. In the extrusion process considered in this paper, these functional components are the same defined during the hardware system design and implementation. This is the reason because the methodology defined is innovative; in fact, it allows to understand where the high and expensive consuming, and the major environmental impacts are located in the industrial plant.

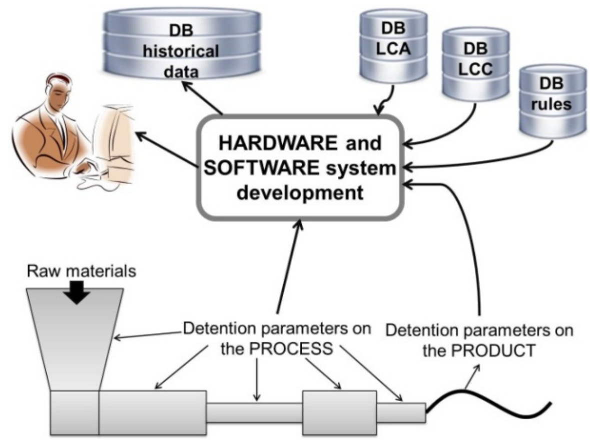


Figure 4: The methodology apply in the industrial case of the extrusion process.

So far, we focused on the network developed in the industrial plant to identify the areas affected by high energy consumption and to measure all parameters of the process and the product. Now, it was essential to understand the connection between the concept of sustainable manufacturing and this proposed method of monitoring and control.

"Sustainable Manufacturing is defined as the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" [27]. In this vision, some reasons to implement the sustainability of the enterprises are:

- rational use of energy and raw materials consumed by the processes through the optimisation of all parameters involved in the production process;
- development of technologies to monitor the processes and the products;
- reduced environmental and economic impacts throughout the whole process life cycle (implementation of LCA and LCC methodologies).

According to this definition and the related guidelines, the methodology proposed in this paper accurately reflects the character of sustainable manufacturing. In fact, the first steps aim to identify the subject of the analysis: factories areas, and for each area, the affected processes and devices are also identified. The next steps aim to define for each subject its parameters, energy consuming, environmental and economic impacts. In this way, it is possible to create a database of real data collected by the process and the product. The last step is the creation of a database of a set of rules to manage the several data and information come from the industrial process.

The process control is implemented through a user interface directly by the user (e.g. the head production).

## 5 CONCLUSIONS

The proposed methodology is a good example to implement the monitoring and controlling in the high-consuming industrial processes. Moreover, it is a great starting point to realize the first example of sustainability manufacturing implementation in the process enterprises.

This paper presented the methodology, its bases and principles, its main modules and its required data. With a thorough understanding of this information, a real case study can be defined and developed.

In order to validate this methodology a case study must be developed. Currently, the hardware infrastructure at the extrusion enterprise has been implemented. Future works will present the process and the product parameter value that were collected by the process. Moreover, process LCA and LCC analyses will be conducted. These steps are necessary to concretise the value of sustainability manufacturing in an extrusion process. It is important to validate also a mobile or tablet application which allows to user to remote control the process and to send it the data feedback in real time.

A further step after these validations is the development of “exergia” concept. In fact, the focus on the LCA analysis, which was applied to the industrial process, will become an interesting starting point to discuss “exergia”. Exergia, which is a significant quantity that is lost and destroyed in any real process, could better emphasize the critical process.

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# Employee Participation for Increasing Energy Efficiency in Factory Operations

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**Abstract**

Changing conditions in the business environment of manufacturing companies lead to new challenges for the operation of factories. Especially, rising energy prices, stricter statutory requirements as well as environmental awareness of customers, cause higher requirements in terms of energy efficiency. Among other, the behaviour of employees and their environmental awareness have an impact on energy consumption within the factory. This paper shows an approach to increase energy efficiency in factory operations by consideration of employee behaviour. The approach includes basic requirements for stimulating energy-efficient behaviour and presents ways of improved employee participation in process of increasing energy efficiency.

**Keywords:**

Sustainable Production; Employee Participation; Energy Efficiency

## 1 INTRODUCTION

Energy efficiency in manufacturing companies is getting more and more important in the last years. A survey of the German Energy Agency detected in 2005 that 56% of the participating enterprises assess the value of energy efficiency to “very important” and further 41% to “important” [1].The importance is based on the following three external factors [2]:

1. **Rising energy costs:** The statistical office of the European Union is collecting the prices for electricity of industrial consumers in the 27 countries of European Union (see figure 1). Although in Germany the price almost stagnated in the last four years, there was an increase of about 33% between 2001 and 2012. The price increase in other countries was even higher. For example, the price in Spain rose by 120% in the same period. Furthermore, a significant increase in electricity prices is predicted for the future. [3] The development of gas prices from 2001 to 2012 is even more dramatic for manufacturing companies. Compared to the year 2000 a rise in prices of about 142% can be determined. [4] For these reasons, energy efficiency is subsequently rising in importance to ensure the competitiveness of manufacturing enterprises. [5] Thereby, production costs can be reduced without negative consequences to the quality of products [6].
2. **Limited $CO_2$ certificates:** The second factor is a political driver for better energy efficiency. In 2005 the so-called European Union Emission Trading System as an instrument for the reduction of $CO_2$-emission in energy-intensive branches came into force. Content of this regulation is the restricted allocation of $CO_2$-emission rights, and the commitment to a price for $CO_2$-emissions. Enterprises need to hold certificates, which are bought and charged off according to the occurred emissions. [7] This financial aspect of emission trading is an important motivation for enterprises to increase their energy efficiency efforts [8]. The German Federal Government plans to double the energy productiveness (GDP per energy consumption) by 2020 in comparison to 1990. [9] Consequently, a considerable increase in energy efficiency is inevitable.

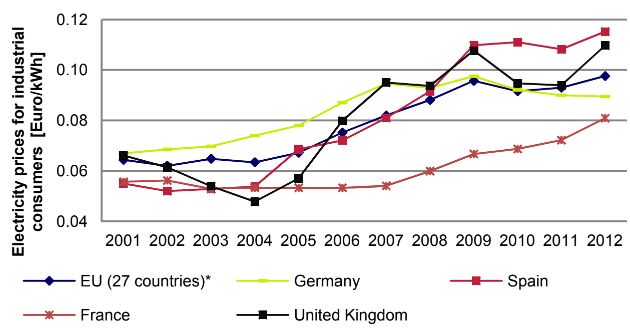


Figure 1: Electricity prices for industrial consumers [3].

3. **Environmental consciousness of consumers**: An increasing number of people are aware of environmental problems like climate change and they are aspiring a more sustainable life style. Nevertheless, people often do not change their way of life. At the same time they regard industrial companies as the primary environmental sinners. Companies must invest in ecologically friendly actions [10]. Improved energy efficiency is an essential aspect to adapt to the "green" consumption desire of their (potential) customers [11].

Beside these external factors also internal factors can be determined. Rising expenses for energy do not only have their origins in higher prices, but also in increasing energy demand due to automation of the production. The growing demand is caused by the application of modern energy-intensive production processes, for example, by laser welding. Traditional rationalisation fields like lead times or inventories are considered as almost exhausted, while optimisation of energy efficiency seems as a field with high potential for improvements in the focus of rationalisation [2]. If latest technologies would be strictly used in factories, 25% of the energy could be saved. If enterprise conditions, like amortisation times, are considered a saving potential of 14% can be realised. [12]

The internal and external factors are showing the increasing importance of energy efficiency in factories. For increasing the energy efficiency all areas of the factory need to be taken into account.

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## 2 OVERVIEW AND PROBLEM STATEMENT

In the following, the connection between energy efficiency, factory operations and employee participation will be described . As a result, an approach will be presented, that uses employee participation to increase energy efficiency in manufacturing.

### 2.1 Factory Operations and Energy Efficiency

The factory can be described as a socio-technical system [13] with the components technical equipment, human factors and organisation (see figure 2). [14] The cooperation and synchronisation of these components determines the factory's efficiency in ecological, economic and social issues. In the case of energy consumption, each part has to contribute to a high efficiency. Usually, the main focus is on the technical equipment, because it has the highest potential for improvements. [2] The second part are the human factors including behaviour, skills and ecological awareness. For example, it is a wasteful behaviour when employees airing with opened doors or windows and heating in the same time. Hence, the thermal energy of the heater flows into the environment. Another example is the use of compressed air for cleaning the workplace due to ignorance or missing knowledge about the expensive and energy-intensive production of compressed air. The behaviour of employees influences their willing to switch off machines, lightning or other energy users while they are not in use. Thirdly, the organisation of a factory with its leadership and hierarchy is affecting the efficiency. Many companies and research institutions are doing a lot of research about these three elements; nevertheless, there is just little research about the influence of human factors on the energy efficiency of processes and technical equipment.

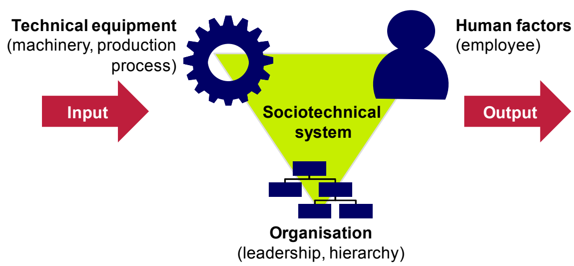


Figure 2: Factory as socio-technical system [14].

Typical approaches for enhancing energy efficiency are centralised and expert-driven. The number of experts is very small compared to the workers on the shop floor. In contrast, the decentralised and layman-driven approach deals with employee participation. The general aims of employee participation are the use of tacit knowledge, use and advancement of specific employee qualifications, an increase in acceptance and the comprehensive consideration of employee's needs. [15] There are some initial statements and concepts about the effect of employee participation for improving energy efficiency. Meyer et al. describe some measures to save energy by employee participation, like trainings, controlling of energy consumption or idea competition. [16] Doty et al. describe employee participation as the "greatest untapped resource in an energy management program." [17] An OECD analysis characterises employee participation as a very important part of energy saving programs which is used seldom. [18] The concepts of these authors are lacking an industrial application and a consideration of employees motivation. Energy saving measures require a deep knowledge about production processes for a comprehensive analysis. Therefore, involved employees need to meet some basic requirements like occupational competence, qualifications and skills about energy saving tools that are described later on.

### 2.2 Behaviour, Motivation and Participation

As shown before, the **behaviour of employees** has an essential influence on energy consumption within a factory. The term productive behaviour summarises all activities that contribute positively to the objectives of an organisation. There are three types of productive employee behaviour: the first form states that employees act exactly according to their job description. The second form describes that employees, for example, cooperate and help each other. This goes beyond the formal job description. The third form of behaviour is called innovative. It refers to the creativity level of employees which supports the competitive position of the enterprise. The most common part of productive behaviour within an organisation is job performance. The individual's job performance is determined by a complex set of factors, e.g. motivation. [19] With reference to Ryan and Deci, a person who "is moved to do something", is motivated. However, there has to be distinguished between intrinsic and extrinsic motivation. Intrinsic motivation "refers to doing something because it is inherently interesting or enjoyable", extrinsic motivation "to doing something because it leads to a separable outcome" [20]. For example, an employee switching off the light to save energy because he considers it as simply important is intrinsically motivated. An employee only saving energy for the reason of a financial reward, is mostly motivated by the expectation of the extra-money which means: extrinsically. [20]

A popular theory of human motivation is Herzberg's **two factor theory**. Herzberg and his colleagues identified two sets of factors being responsible for human motivation: on the one hand, there are the so-called motivation factors referring to an individual's psychological growth like achievements, recognition of achievements, the work itself, responsibilities, advancements, salary (bonuses) and growth. They are related to motivation. On the other hand, there are the hygiene factors, e.g. company policy and administration, interpersonal relations, supervision, working conditions, salary, status and security, being responsible for feelings of discomfort if not realised in a satisfactory manner. They lead to dissatisfaction. So, motivation can only be reached by the combination of the two factors: a comfortable work environment alone only leads to not dissatisfied employees. But, in combination with an interesting, challenging work task and the opportunity to personal growth motivation can be stimulated. [21] Herzberg's two factor theory points at the importance of self-actualisation, a challenging work task, certain responsibilities and recognition for one's achievements at the work place for human motivation. An involvement of employees in a company's energy saving efforts could exactly meet these demands.

With reference to Gonzalez, **participation** of employees can be divided into two components: on the one hand, participation through representatives, e.g. within co-management or shop committee. This is an indirect form of participation. On the other hand, participation can be direct so that employees themselves have an influence on a decision. [22] Wegge distinguishes five different levels of participation (see figure 3). At the lowest level, enterprises do not involve their employees at all. On the second level, employees get information about their company and decisions that have been made, but this level of participation is a passive one. A more active way of participation is level three, the "consultation". On this level employees are asked about their opinion. However, the management makes the final decisions. The level "involvement" is reached when there exist rules for the consideration of employee's opinions. The fifth level describes a form of participation in which the worker's vote is considered equally to the management's opinion. [23] [24]

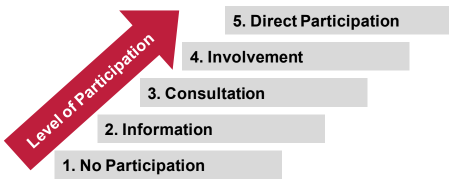


Figure 3: Levels of participation [23] [24].

Figure 4 presents an overview of common forms of employee participation. The different types are either assigned to direct or indirect participation and analysed to the level of participation they provide. Due to legal or collective regulation there must be implemented certain forms of a representation of interests, e.g. a shop committee. It correlates with an indirect participation and the participation level "involvement", because there are regulations how the vote of a shop committee has to be considered. By means of a company information system, employees get informed passively about decisions and activities within an enterprise. This goes together with the participation level 2 "information". Employees get actively involved by participation in problem solving groups (level 3), the opportunity to continuously improve processes during daily work (level 5) or a work suggestion system (level 3). Enterprises can reward commitment or proposals for improvements in a financial way, e.g. with a share of profit or stock options as a part of a financial reward system. [25] [26]

| Forms of Participation | Participation: direct | Participation: indirect | Level of employee participation |
|---|---|---|---|
| Opportunity for continuous improvement processes (CIP) in daily | X | | |
| Legally or collectively regulated representation (e.g. shop committee) | | X | |
| Work suggestion system (individual or proposal groups) | X | | |
| Complaint and articulation opportunities (e.g. complaint boxes, | X | | |
| Participation in problem solving groups (e.g. quality-circle) | X | | |
| Employee interview, staff meetings, consultation hours | X | | |
| Company information system | X | | |
| Profit sharing (e.g. stock options) | X | | |

Figure 4: Forms of employee participation [25] [26].

The correlation between motivation, participation and productive employee behaviour is summarized in figure 5. How the different forms of employee participation can be practically involved in the respect of energy efficiency will be discussed in the following.

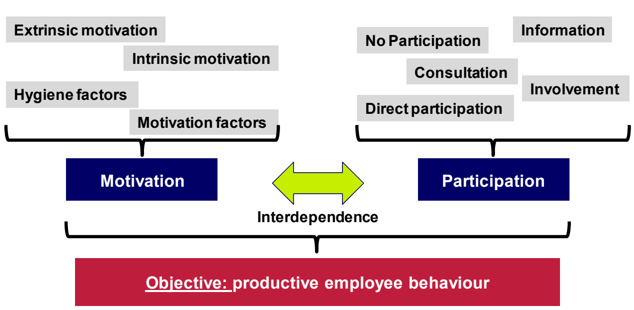


Figure 5: Interdependence between motivation and participation.

## 3 APPROACH

The approach of this paper is to improve energy efficiency by increasing employee participation. Figure 6 shows the three steps of the approach. Firstly, the aspired behaviour of employees with regard to energy efficiency and ecological awareness has to be defined (see 3.1). Afterwards, the basic requirements for sustainable employee behaviour: ability and willingness need to be fulfilled. They are described in paragraph 3.2. The requirements can be called occupational competence. An actual analysis needs to be carried out for determining the starting point of the company in terms of the employees' capability for participation, qualification and the current motivation. The occupational competence is needed for the next step. The implementation of measures and activities according to the motivation factors are realised subsequently (see 3.3). Thereby, involved employees are improving their qualification and motivation. The success of the measures is depending on the level of participation. The higher the participation levels, the higher is the awareness resulting in it. Within the process the awareness is increasing continuously. The "finish" of the approach is achieved, when the employee behaviour corresponds with the target behaviour. In this case employees have the appropriate qualification and the competence for an autonomous and an independent energy efficiency improvement.

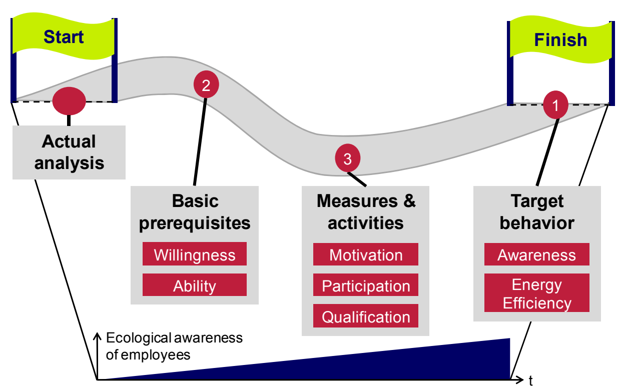


Figure 6: The approach to energy efficient employee behaviour.

### 3.1 Target Behaviour of Employees and their Awareness

In context of the three types of productive employee behaviour (see paragraph 2.2), the aspired behaviour of employees goes beyond the formal job description. Nevertheless, the job description and target agreements should include aspects of energy efficiency like energy saving objectives. The aspired behaviour comprises the second type of cooperative and creative behaviour and the third type performance behaviour. As described earlier, this includes high motivation that is examined later. The aimed behaviour requires different individual skills. First of all, employees should work in a responsible and open-minded way. They should identify energy saving potentials by themselves and continuously solve problems. Another important element of the behaviour is the suitable and autonomous involvement in the continuous improvement process. Also, they should be communicative to share best practice solutions. Employees use energy sparingly and are aware of the environmental consequences of the behaviour. The prerequisites for the behaviour are explained in the following section.

### 3.2 Prerequisites for Increasing Participation in Energy Savings

Employees need to have occupational competence for participation. Occupational competence is the employee's capability for proper reaction in various situations in business, social or private environment. The occupational competence of employees is a valuable asset for companies. It can be decomposed in ability, willingness as well as companies' culture (see figure 7). The employee's **ability** is the sum of all skills combined with information. [27] The employee's personal skills consist of technical, methodical and social competence. The expertise comprises technical expertise, knowledge and specific experience. [28] [29] Especially, knowledge about waste of energy, energy measurement methods and basic knowledge about types of energy (e.g. compressed air, process heat and electrical energy) are important. Furthermore, employees need to have knowledge about the continuous improvement process in the context of lean production systems. Its aim is to reduce waste within manufacturing processes. The following seven kinds of energy waste [30] are derived from seven kinds of waste of the lean production [31]:

1. Overproduction
2. Waiting time
3. Transport
4. Inventory
5. Reject part
6. Movement
7. Unused creativity of employees

For example, the kind of energy waste "transport" demands energy for forklift transport. Methodical competence is characterised by qualifications that enable employees to participate and to bring their own and external technical and social knowledge into energy-saving projects. The social competence describes human factors, such as teamwork and communication. [29]

The second pillar of occupational competence is **willingness** that is the combination of wish, permission and time. [27] The employee's wish is a highly individual aspect that is depending on his satisfaction with job and company [32]. The motivation of an employee can be derived by his wish and his satisfaction, which are considered by Herzberg's theory. However, hygiene as well as motivation factors are rarely taken into account with the consequence that employees may be discouraged from participating. The enterprise has to grant the permission to take an active part in energy efficiency activities. These permissions include the job description or job task and the breakdown of corporate sustainability objectives to individual objectives, e.g. energy saving by 10 % for a workplace. Also employees need time to participate. The required time is depending on the participation level.

The **company's culture** contains the specific rules and ethical values of the company. Based on the described elements, three aspects for an employee oriented improvement of energy efficiency can be assigned: qualification, motivation and participation. [27]

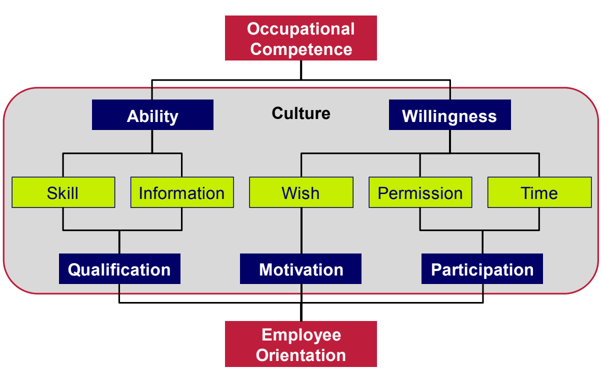


Figure 7: Decomposition of occupational competence [27].

### 3.3 Implementation of Energy Efficiency Measures and Activities

The successful participation of employees requires a high motivation on the employee side. However, the opportunity to participate itself can create motivation. There is an interdependency between motivation and participation which makes it even more important to enable active employee participation. As described earlier, different activities for improving the energy efficiency by involving employees interact with Herzberg's motivation and hygiene factors. Figure 8 illustrates the impact of some measures on all factors of motivation and hygiene factors. The chosen factors are identifed by Herzberg's theory for job satisfaction.

The first column of the chart contains an expemplary listing of possible **measures** for energy efficiency that are used by industry partners of the Insitute for Advanced Industrial Management (IFU). These partners have implemented several of the measures to use the employees' potential for energy saving that is basically associated with the forms of participation in figure 4. Nevertheless, the effectiveness of the measures is depending on the three aspects of employee orientation.

The recommanded **level of employee participation** for each measure is shown in the column on the right side. The highest level of participation is not suitable for every measure, nevertheless the level should be as high as possible, because participation leads to awareness and qualification. However, if the actual analysis carries out low occupational competence of the employees, it limits the number of possible levels of participation. For example, if the culture of a company is characterised by low trust between employees and management, it is not appropriate to implement measures with the level "involvement" or "direct participation". The level of participation has to be adapted to the specific circumstances of an enterprise and the degree of former participation opportunities [15].

The results of the **impact evaluation** between measures and hygiene/ motivation factors are presented in the middle of the chart. The evaluation was carried out by an expert survey at the Institute for Advanced Industrial Management. The questioned experts have a research background in the field of factory planning. The results will be verified by a larger company survey. Strong impact implies a high influence of one measure on a specific factor that means there might be a high motivation for this measure. Low impact characterises missing dependance between measure and hygiene/ motivation factor. The following three examples (see figure 8) show the connection between measures and motivation:

1. The first example is the adaption of the business objectives to the aspect of energy efficiency like maximum limit of total energy consumption per anno. The measure is influenced by the company's culture. The adaption has a strong impact on the hygiene factor "company policy and administration", because it connects the sustainable acting to the company's target system and business objectives. The adaption has a strong impact on the motivation factors "achievement", "recognition of achievement" and "responsibility", because the adaption of business objectives to energy efficiency makes the progress measurable. Nevertheless, the level of employee participation for this measure is low. There is no participation of employees required, because the top management typically defines the target system.
2. When the measure "energy efficiency training" is implemented, employees are attending on training courses. The topic of the course is basic knowledge about energy saving. It has a strong impact to the factor "interpersonal relations" due to the exchange with colleagues. There is also a strong impact on the motivation factors "achievement", "work itself" and

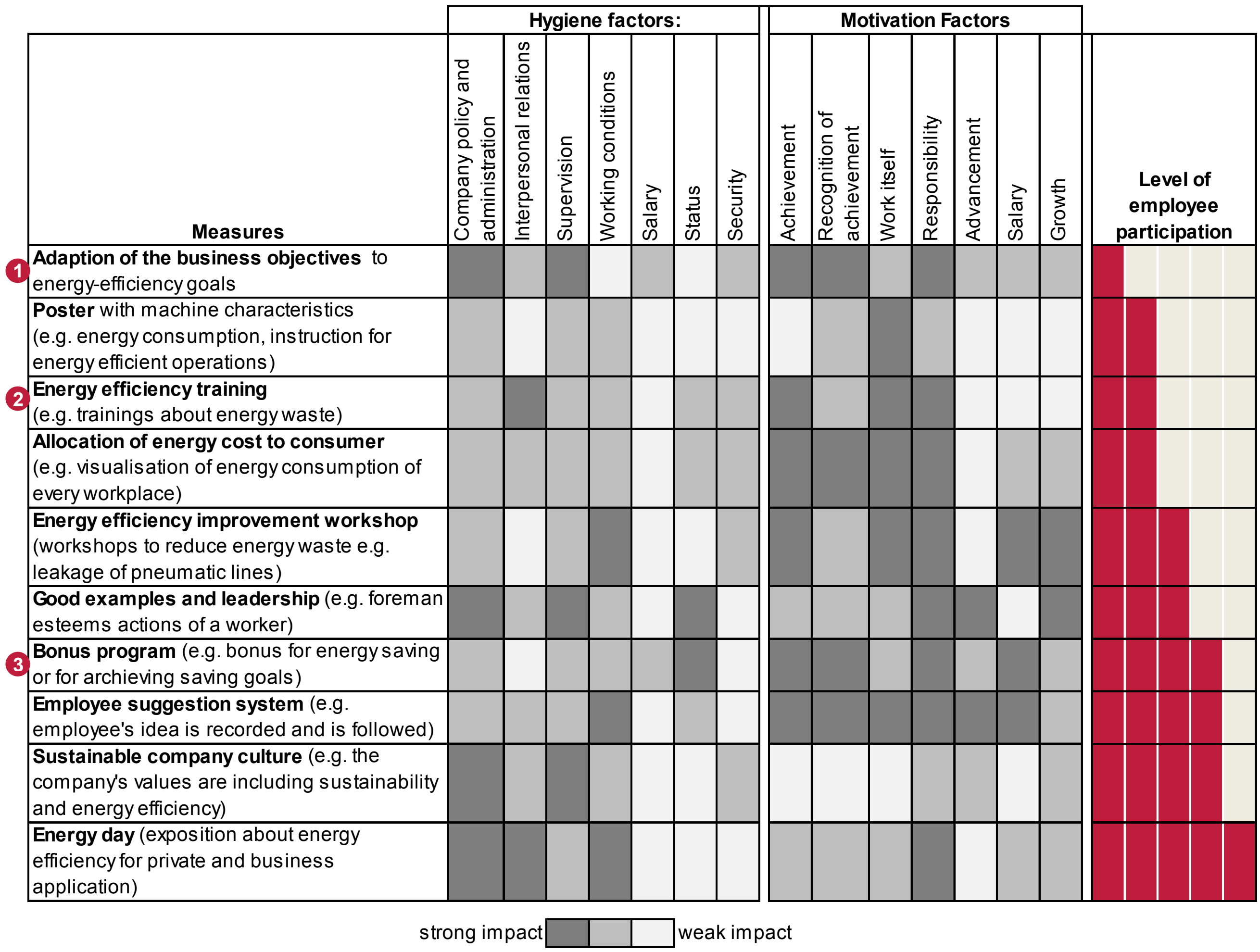


Figure 8: Impact of measures on motivation factors.

"responsibility", because participants are developing their abilities in terms of saving energy. The recommended level of participation is information, because the aim of trainings is basically the transfer of knowledge.

3. Another example is the bonus program that rewards energy savings. This program has a strong impact on the motivation factor "salary", "achievement", "recognition of achievement" and "responsibility", because individual performance is honoured. The bonus program has a low impact on the hygiene factor "interpersonal relations", because it regards individuals exclusively. It finally has a participation level of "involvement" that supports the energy efficiency-oriented behaviour in a proper way.

If a measure is implemented, it has an effect on the hygiene and motivation factors, which may lead to higher motivation. Also the involved employees are improving their qualification in terms of energy efficiency. Furthermore, based on the impact matrix, enterprises can evaluate measures and they can implement these measures that fit most their requirements. After measures are implemented, awareness for energy efficiency will increase. The result is a continuous change of the employee's behaviour and employees are starting measures by their own without an impulse from the management.

### 3.4 Suggestions for Industrial Implementation

The previous chapter has exemplarily described different measures. Based on this, various suggestions can be identified for industrial application. Before a company starts implementing specific measures, it should carry out an actual analysis to identify the starting point of the company. For example, some companies need to develop the occupational competence of their employees for a successful participation. Others can start immediately. For developing occupational competence, the elements of ability and willingness need to be considered. Employees' willingness for participation is depending on their wish, which has a direct connection to motivation. If a company has highly motivated employees, the effect of employee participation is much higher. The impact matrix is helpful for considering specific motivation factors. When the activities for energy efficiency are starting, they should start with simple measures and not with the highest level of participation. Also employees should be addressed by measures with different participation levels to increase the awareness. For example, lightning is suitable for a start, because every employee can participate by switching lights off and has ideas about the lightning [33]. The involvement of employees for increasing the energy efficiency in factory operations needs a comprehensive consideration of motivation, qualification and participation. By implementing different measures, the selection and the sequence of measures are crucial for the success. Hence, the impact matrix provides an evaluation that allows a specific analysis of hygiene and motivation factors.

## 4 CONCLUSION

Rising energy costs, new governmental restrictions like $CO_2$-certificates and growing environmental consciousness of consumers are new challenges for manufacturing companies. Thus, energy efficiency in planning and operating factories is getting more and more important for remaining competitive. The behaviour of employees within the factory has an impact on the overall energy consumption of the factory. Energy-efficiency-oriented employee behaviour goes beyond the job description and requires motivation, qualification and participation. The prerequisite for these aspects is the occupational competence of employees. Occupational competence combines willingness and ability with the enterprise culture. The approach of the paper applies Herzberg's two factor theory for analysing measures according to hygiene factors, motivation factors and employee participation. Every measure has an impact on hygiene and motivation factors. If the motivation can be increased and the occupational competence is considered, the employees can develop ecological awareness and an energy-efficiency-oriented behaviour can be established. This is resulting in higher energy efficiency in factory operations.

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# Energy Value-Stream Mapping – A Method to Optimize Value-Streams in Respect of Time and Energy Consumption

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**Abstract**

In the industry, Lean Production Systems have been successfully used for years to reduce inventories and lead times. The Value-Stream Mapping Method (VSM) has proven itself to be the best practice tool for this purpose. With this method process steps can easily be divided into value-adding and non value-adding ones. However, the VSM does not provide any information about the process energy consumption and, as a consequence, it does not give any hint at how much of the energy used actually serves value-adding purposes. Would it be known how much energy is used for value-adding and for non value-adding process steps, then it would be possible to optimize value-streams in a holistic way, simultaneously considering time and energy consumption. This paper describes how the VSM can be extended to an Energy Value-Stream Mapping Method (EVSM) while maintaining its original character and its inner logic.

**Keywords:**

Energy Value-Stream Mapping; Energy efficient production and logistics; Lean and Green Manufacturing

## 1 INTRODUCTION

While the manufacturing industry is one of the main energy consumers, it is at the same time also the key factor for our prosperity. Considering the continuously rising energy cost and an increasing public awareness of the need for a sustainable economic activity, many branches of industry have in the meantime declared energy efficiency their strategic business objective.

During the second half of the last century, labour productivity has increased almost fourfold, while energy productivity has not even doubled during the same period of time [1]. In the past, the industry's rationalizing efforts have focused on increasing the degrees of automation while simultaneously cutting down the cycle times.

When in the nineties of the last century the methods of the Toyota Production System (TPS) came to be known in the Western world, numerous companies tried to adopt them for their own use. At that time the TPS was considered, and today still is, a benchmark for designing highly efficient value-streams and very often it is also described as a lean production system.

## 2 THE TOYOTA PRODUCTION SYSTEM

Taiichi Ohno, who is one of the TPS's architects, describes its essence as follows: ‚All we are doing is looking at the time line from the moment the customer gives us an order to the moment when we collect the cash. And we are reducing that time line by removing the non value-added wastes' [2]. So, the point in the TPS is to keep the time interval between the placement of an order and the payment of the product as short as possible. Therefore, the creation of value should be as efficient as possible, in other words it should be achieved while avoiding waste. To accomplish this, non value-adding processes (waste) should be eliminated wherever possible. If complete elimination is not possible waste should be at least reduced to a minimum. To identify non value-adding processes systematically, Ohno classified the types of waste as follows [2]:

- Waste of overproduction
- Waste of time on hand (waiting)
- Waste in transportation
- Waste of processing itself
- Waste of stock on hand (inventory)
- Waste of movement
- Waste of making defective products

That means, waste is everything that is not immediately value-adding [2] or, as Masaaki Imai puts it: ‚In gemba, only two types of activities go on: value-adding and non value-adding‘ [3]. He thereby makes it quite clear that a process step is either value-adding or non value-adding. This dualistic view has proven itself to be the best practice tool to achieve high efficient value-streams.

Usually, the creation of value requires an input of time and energy – however the creation of waste needs the same two input factors, too. Waste in the meaning of the TPS is thus in many cases not only a waste of time but also and in addition a waste of energy [4]. The types of waste listed above seen from an energy-related perspective are:

- Waste of overproduction

Overproduction requires time and it usually generates additional energy costs. It also causes inventories and unnecessary transport and that, too, entails additional energy inputs.

- Waste of time on hand (waiting)

During the time machines stand ready for operation, most of them require energy. Their energy consumption in the stand-by mode or in the ready to operate state often reaches levels that are similar to those found in productive operation.

- Waste in transportation

Transport by its nature does not increase the value of the product. For the most part, however, it involves an necessary input of energy.

- Waste of processing itself

Designs, manufacturing technologies and process flows not suited for their intended purpose as well as tools of poor quality entail an energy input that is needlessly high.

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- Waste of stock on hand (inventory)

Unnecessary stocks waste energy by the additional transport and the storage area they require, by air conditioning, warehouse management, etc.

- Waste of movement

Every type of movement sequences in machinery and equipment requires energy. Every movement that does not bring about a manufacturing progress in the product is non value-adding.

- Waste of making defective products

Reworking itself as well as the processes required for reworking need energy. When rejects have been produced, the whole energy used thus far is waste and must be spent anew. In addition the disposal or recycling of such products also requires energy.

It may therefore be taken for granted that as a rule lean production systems are usually more energy-efficient than the usual mass production systems because they have shorter lead times and so they provide less time to waste energy [5]. A lesser input of time has a direct impact on the energy consumption due to the simple fact, that energy is a function of electrical power and time.

## 3 VALUE-STREAM MAPPING AND ENERGY VALUE-STREAM MAPPING

With their value-stream mapping that Rother and Shook [6] presented in 1999, for the first time a method appeared on the scene which was apt for practical use and made it possible to look at the cycle times separately from the non value-adding lead time. With this method they followed the inner logic of the TPS, namely to differentiate the processes of a value-stream into the two categories 'value-adding' and 'non value-adding', only. In their approach, minimizing the lead time was in the focus of their interest. They contrasted the production lead time with the sum of the cycle times – which they called processing time. This shows clearly the lead time extending effect of a batch-oriented production (see Fig. 1 above).

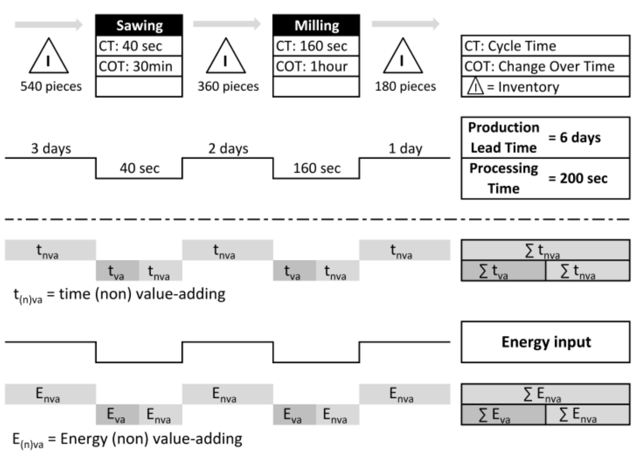


Figure 1: Value-stream mapping according to [6] and schematic representation of value-adding and non value-adding input of time and energy.

Though Rother and Shook did make a distinction between value-creating time and cycle time, in their value-stream mapping graphics the processing time is consistently represented as the sum of the cycle times (Fig. 1 above). This may convey the impression that the process sequences within the cycle times are, as a matter of principle, free from waste. However, this is not so. When taking a closer look, one can see almost always that the cycle time, in other words the manufacturing process itself, is composed of value-adding ($t_{va}$ = time value-adding) and non value-adding ($t_{nva}$ = time non value-adding) amounts of time [7]. The same applies to the energy input of the manufacturing processes. This is represented schematically in Fig. 1 below. The processes outside the cycle time are classified as non value-adding.

There are several proposals in order to extend the VSM to an EVSM [8-14]. But none of them is built on an exclusively dual assessment of the time and energy input only referring to the criteria value-adding or not.

If a VSM has to show the non value-adding elements of the process within the cycle time, then it is indispensable to use a dual approach for looking at the cycle times. In other words the cycle times has to be separated into the two categories 'value-adding' and 'non value-adding'. After this has been made the energy consumption can also be looked at in a dual approach, and it is only then that the manufacturing process itself can be differentiated into a value-adding and a non value-adding energy input.

In cooperation with the Chemnitz University of Technology, Aalen University of Applied Sciences has developed a method allowing for appraising the process-related input of energy using the criteria 'value-adding' and 'non value-adding'. This dual approach allows for the first time to extend the proven VSM method to an EVSM, in concordance with the principles of the TPS.

## 4 CREATING DUAL ENERGY SIGNATURES, USING THE EXAMPLE OF A CHIP REMOVAL PROCESS

In the Aalen University's chip removal laboratory power measurements were taken on a 3-axis vertical machining centre, Hermle Type C 30 V. The machining process consisted in successively milling three grooves of different widths into a component made from heat-treated steel C45. Chip removal was done in full cut, with an infeed of 7.5mm over a distance of 60mm and using three HSS end mill cutters with diameters 8, 12, and 16mm. In parallel, a power measurement was taken using a portable wattmeter [15].

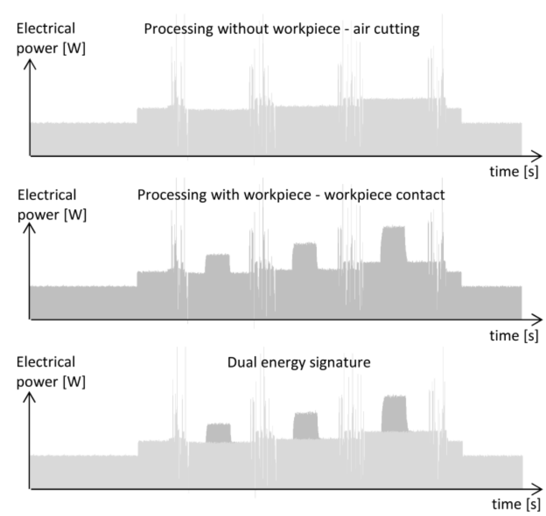


Figure 2: Chip removal - air cutting vs. cutting with workpiece contact; representation of the dual energy signature.

The test set-up had a distinctive feature insofar as the first pass took place using an air cut, in other words processing without a workpiece (Fig. 2, top). This made it possible to see what the energy signature of the process looked like without a workpiece contact. The second pass took place with workpiece contact (Fig. 2, centre).

When both signatures are overlaid you get the dual energy signature (Fig. 2, bottom). In this signature the value-adding elements of the process are clearly distinguishable, with regard to their duration as well as with regard to the input of energy, and can be differentiated unmistakably from the non value-adding elements of the process.

Details of these measurements are shown in Fig. 3. The light grey signature shows the electrical power consumption during air cutting, while the dark grey signature shows the additional power consumption during chip removal. Only the actual chip removal process is value-adding. The value-adding times are marked by means of dark grey bars at the bottom.

The value-adding energy directly required for chip removal is 10 Wh, the value-adding time needed is 25 seconds in total. The non value-adding input of energy is 116 Wh, while the non value-adding input of time is 135 seconds [16].

## 5 DUAL RESOLUTION OF CYCLE TIME AND ENERGY INPUT

The value-adding efficiency of the process in terms of energy, $\eta_{Eva}$, as well as the value-adding efficiency in terms of time, $\eta_{tva}$, can now be defined.

$$\eta_{Eva} = \frac{E_{va}}{(E_{va} + E_{nva})} \qquad \eta_{Eva} = \frac{10Wh}{(10Wh + 116Wh)} = 8\% \tag{1}$$

$$\eta_{tva} = \frac{t_{va}}{(t_{va} + t_{nva})} \qquad \eta_{tva} = \frac{25s}{(25s + 135s)} = 16\% \tag{2}$$

Equation 1 : Value-adding efficiencies and calculation example

The use of dual signatures makes it possible to shine a bright light on the production process as regards the time used and the energy input.

The cycle time itself as well as the energy input within the cycle time are thereby consequently subdivided into value-adding and non value-adding portions. In the extended data box of the milling process under consideration, (Fig. 4) the measuring results are shown nominally, in the form of figures, as well as proportionally in the form of the bars beneath.

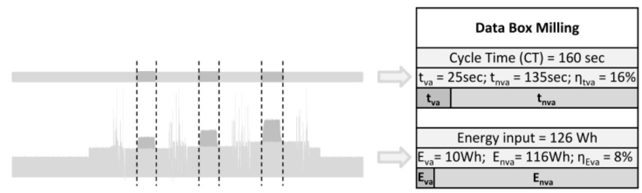


Figure 4: Dual signatures and extended data box.

The hypothesis that the entire cycle time is value-adding, which up to now has been considered valid, must be abandoned as not being correct. In addition the low efficiencies to be seen in Fig. 4 also indicate that the dual approach can help uncover substantial improvement potentials.

## 6 EXTENDED VALUE-STREAM MAPPING AND ENERGY VALUE-STREAM MAPPING

Reducing inventories is one significant field of action of the VSM. However, a typical functional chain does not consist of inventories and processing, only, but also involves transport (Fig. 4). For the EVSM it is therefore necessary to integrate the input of energy caused by transport, as the in-plant logistics has quite a significant share in the total energy consumption of the factory [17], [18].

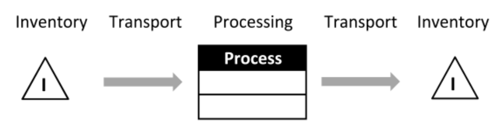


Figure 5: Typical functional chain.

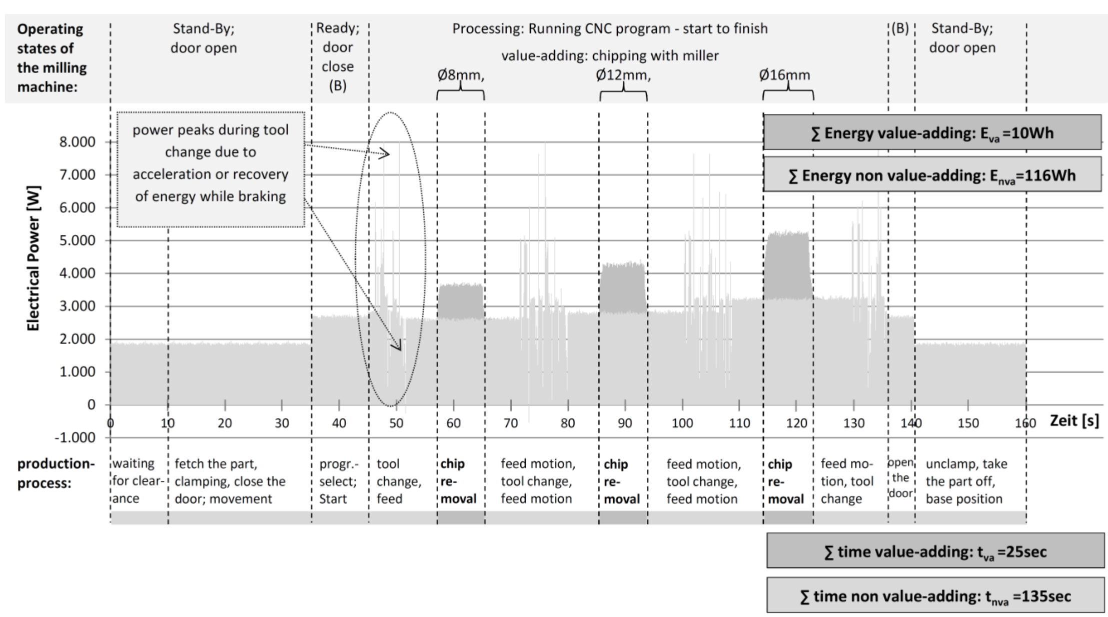


Figure 3: Dual energy and time signature of a chip removal process.

The time used for in-plant transport has so far hardly been taken into account in VSMs although it has a lead time-extending effect. In addition, the transport-related energy input, apart from not being value-adding, also occasions cost. From an economic point of view it is therefore reasonable to minimize this cost factor. To this effect the very first thing to do is to provide for transparency as regards the energy requirements of the means of transport used, such as fork-lift trucks, conveyor belts, tugger trains, etc. The EVSM can help provide for this transparency.

If the energies needed for transport $E_i$ ($E_1$, ... , $E_n$) are to be integrated into an EVSM, then first all transport processes $T_i$ ($T_1$,… , $T_n$) must be entered (Fig. 6). In keeping with the rectangular function of the time line, a rectangular function of the energy line must be mapped in the graph. This way, by analogy with the type of waste Inventories $I_i$, also the Transports $T_i$ and the energy inputs $E_i$ associated to them can be visualized. Also the transport times which up to now have not been taken into account in the VSM can thus systematically be made transparent. It is therefore recommended to also integrate the transport times $T_i$ into the classical VSM in the future.

## 7 PERIPHERALS MODEL AND ENERGY VALUE-STREAM MAPPING

In addition to the main processes and the transport processes, a number of peripheral auxiliary processes contribute to the overall energy requirement of a factory. Schenk & Wirth's Model of Peripheral Order [19] is particularly suited to visualize the energy consumption, with the main processes in the centre and the numerous auxiliary processes at the peripheries. By means of this model the energy requirement in an organization is subdivided into that of the main processes and that of three peripheries [20]. While a manufacturing or assembly progress is brought about on the workpiece by the main processes, the peripheral auxiliary processes ensure that the main processes can work properly [21].

The EVSM with its associated in-plant transport processes presented in this essay can be linked easily with the Peripherals Model (Fig. 7).

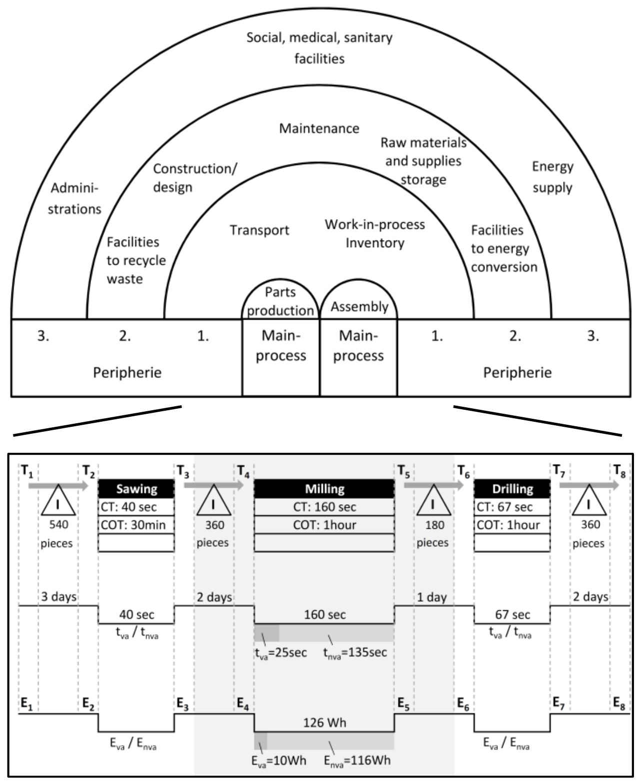


Figure 7: Peripherals model and energy value-stream mapping.

## 8 USING ENERGY VALUE-STREAM MAPPING TO LOOK AT GLOBAL SUPPLY CHAINS

When the VSM is extended and becomes an EVSM, not only the in-plant production and logistics processes should be taken into account but also external processes. Globalisation entails the formation of worldwide and in part highly complex supply chains and, as a result, leads to an enormous increase in the worldwide flows of commodities.

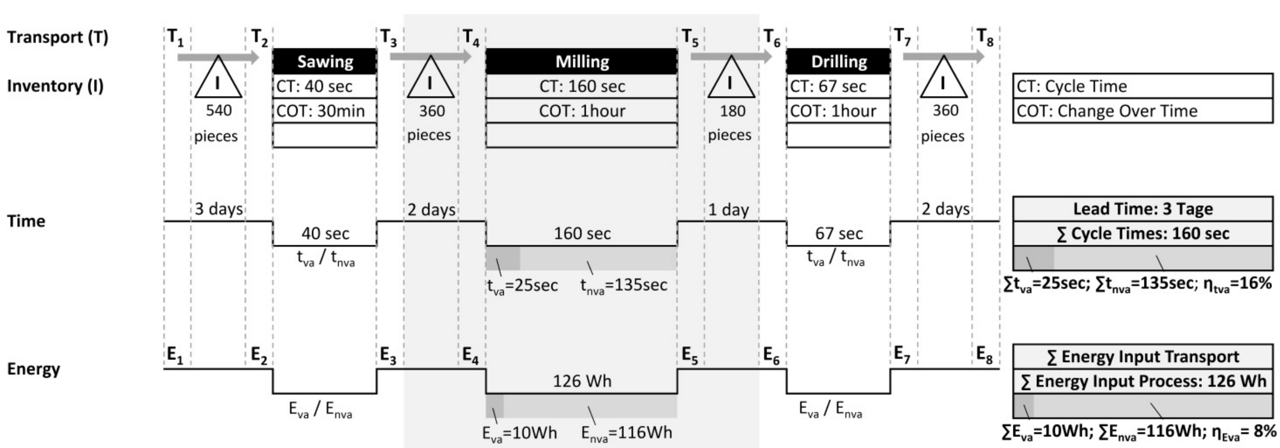


Figure 6: Extended value-stream mapping and energy value-stream mapping.

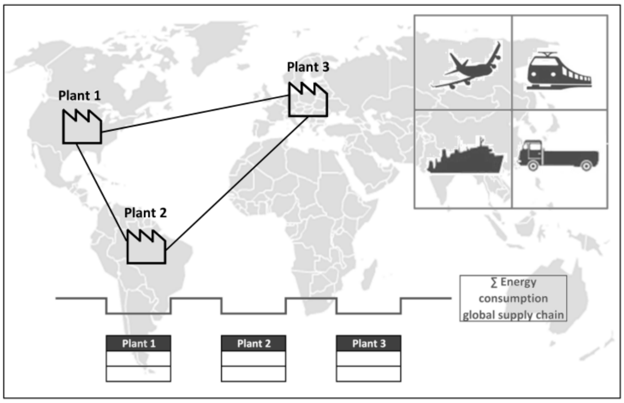


Figure 8: Drawing an energy balance of the global value-streams by means of energy value-stream mapping.

It has to be expected, that in the medium term, the overall energy footprint of a product will become a competitive factor that should be taken very seriously. At that time at the latest it will be necessary to draw an energy balance of the entire value-stream, beginning at the raw material and ending at the disposal of a product. The life cycle carbon footprint of a product would then become an integral part of its specification, which means that airfreight, rail transport, navigation, and truck transport will have to be integrated into the energy value-stream mapping, too. As shown in Fig. 8, EVSM is also ideally suited to look at global interplant transports.

Fig. 9 shows this matter in some more detail. The exemplary logistics chain shown at the top is composed as follows: Transport $T_{A1}$ from Plant 1 to the warehouse of an area freight forwarder, then Transport $T_{A2}$ across a bigger distance to the next warehouse, then $T_{A3}$ to Plant 2.

The rectangular function for transport and storage between plants is offset upwards, meaning that these two types of processes are non value-adding. The lead times in the plants are offset downwards as they are, at least partially, value-adding. In the energy line beneath, the energy requirements $E_{A1}$ ,…, $E_{A6}$ of external transport and storage are also represented schematically. Both types of processes require energy, and according to the TPS both are classical types of waste. Therefore, as far as storage and transport of the products are concerned, the energy line is offset upwards, very much like the time line. The central part of Fig. 9 represents a schematic view of the processes that take place in Plant 2. Here, too, the transport and storage processes are considered non value-adding. Only the time and the energy of the manufacturing processes themselves are offset downwards, as they are, at least partially, value-adding. This is shown by the signatures in the bottom part of Fig. 9.

Using the suggested EVSM method, complex value-streams can be investigated in their entirety. One and the same logic can be used to analyse in-plant as well as external process chains time-wise and energy-wise. If all sub-processes are investigated with regard to the value-adding and the non value-adding inputs of time and energy (Fig. 9, bottom), then it is possible to make up a dual balance for complex value-streams by contrasting the sum of the value-adding time and energy demand with the sum of the non value-adding demand.

## 9 SUMMARY

Designing time- and energy-efficient value-streams is becoming more and more important in the manufacturing industry. With the help of dual energy signatures the value-adding and the non value-adding inputs of time and energy can be determined.

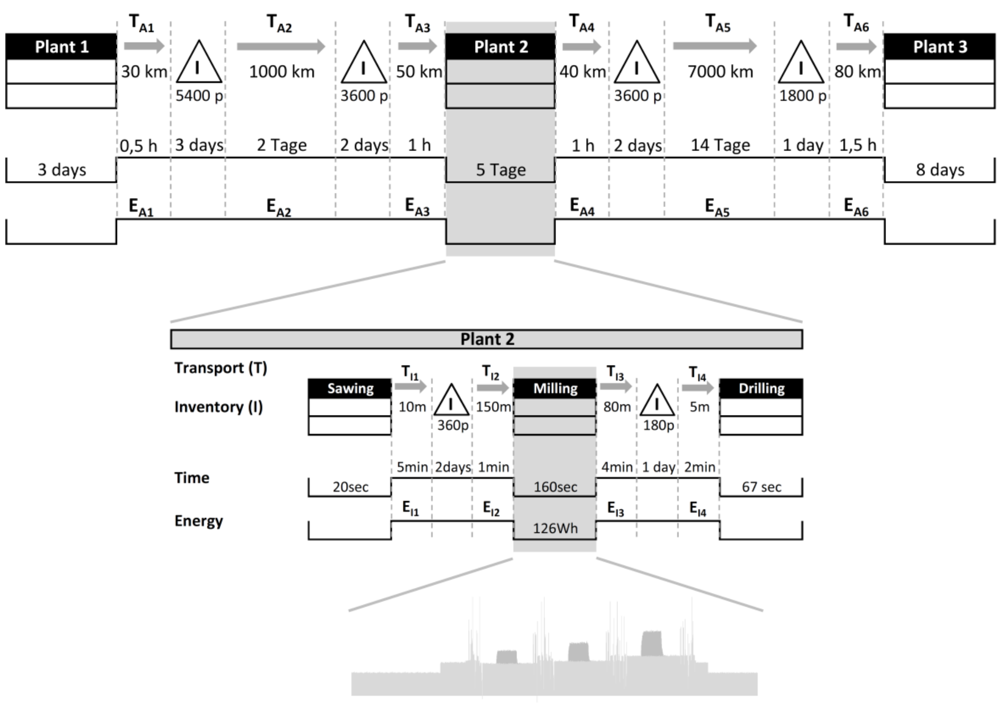


Figure 9: EVSM overall view – from the global flow of commodities to a detailed view on processes.

This is shown using the example of a chip removal process, in which the energy requirement during air cutting is contrasted with the energy requirement for a cutting operation with workpiece contact. This distinction makes it possible to extend a VSM, for a start, by adding a detailed dual temporal view on the processing and transport processes. Then, with this analysis a dual energetic view is possible, too. Only a consistent reduction to a dual approach will make it possible to subject the technology used to critical analysis in respect of its time and energy balances.

Including transport in the EVSM offers the opportunity of visualizing not only its lead time-extending effect but also its non value-adding energy requirement. The transport-related input of energy is not only non value-adding: what is more, it also occasions cost and has quite a significant share in the overall energy requirement of the factory.

The VSM which has become common practice in the industry is, in consequence and while maintaining its inner logic, extended by adding the representation of the energy input in production and logistics processes to it. This methodical procedure provides a practical tool to process designers for a comprehensive analysis and improvement of value-streams.

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# Increasing Competitiveness of Egyptian Industrial SMEs via Technology Transfer

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**Abstract**

Throughout the last century, the world has witnessed a major paradigm shift migrating from traditional mass production concept to agile, lean and reconfigurable manufacturing systems; Concepts that are believed to become major enablers for economic growth of developing countries. Example of which was China, one of the fastest growing giants that capitalized on these technologies in order to achieve leapfrogging steps and compete at the economic frontier. This brings into focus more challenging questions: what are the key factors that should exist in industrial SMEs in developing countries in order for them to guarantee a successful transfer of these industrial technologies? And what is the ideal ecosystem that should exist in order to sustain the adoption of such new concepts? This paper contributes to the literature of industrial engineering by studying all key factors that should exist in the Egyptian SMEs in order to guarantee a successful transfer of latest industrial technologies. Those key factors are determined and validated through industrial and academic experts, then categorized into a hierarchal structure according to their characteristics. Technological appropriateness, Government & Economy and External factors are three main categories on top of the hierarchy in which multiple factor exist. These factors are relatively evaluated using the AHP technique and simple rank order, in order to determine the value of each factor or group. The developed model will assist mangers and policy makers to successfully plan for more competitive and efficient manufacturing systems for the Egyptian SMEs.

**Keywords:**

Technology Transfer; Industrial SMEs; Competitiveness

## 1 INTRODUCTION

The last century has witnessed the inception of multiple production technologies which had tremendously affected the growth of nowadays advanced economies. Japan and China are two prominent examples of such rapid economic growth [1]. It can also be said that such technological advancement industrial technologies was originated at its very beginning from the transfer of technology. Thus, many developing countries have recently realized that industrialization would constitute their only way to reach socio economic parity with advanced economies in Europe and the United States [2].

As a result of that realization, the international technology transfer initiatives have significantly increased. On the other hand, as one of the most important characteristics of agile manufacturing is the high responsiveness to the market ; The high capability of industrial SMEs to transfer state of art-technologies would necessarily enable them to satisfy new market needs which accordingly will increase responsiveness to the market.

Saagi argued that the movement of technology transfer has steadily increased since the mid-1980s[3]. Through statistical data, he showed that this increase reflects the important role of technology in international production [4]. Silva, R. C. da, Junior, M. V., & Lucato, W. C. clarified that SMEs are motivated towards technology transfer through which they can reduce their expenditure on research and development and cope with technological changes with high rate of responsiveness. [5]

Yet, Freeman and Hagedoorn, indicated that the majority of these technological acquisitions took place in developed economies; Which might be due to lack of indigenous capabilities allowing developing countries to capitalize on the learning process associated with the technology transfer process [4].

Kondo argued that “an entity to acquire technology from abroad first needs to know where to seek candidates of technology to be imported. Then, it must assess each technology and compare those candidates. This kind of capability is often lacking in the firms of developing countries” [8].

However, many developed countries facilitated the transfer of technologies to developing countries by adopting direct and indirect measures, including financing, training, etc. [9]; this provides evidence to the importance of technology transfer to both developing and developed countries.

The role of this paper is to provide a clear interpretation about the factors that industrial SMEs in the Egyptian context should focus on in order to acquire new industrial technologies.

An extensive research was done in order to extract most factors argued by scholars to have influence on the technology transfer process; these factors were then categorized into groups according to their perceived nature, and then filtered through experts opinion in order to allocate the most influential factors that have significance in the Egyptian context and to adapt the eco-system of factors to match the Egyptian circumstances.

## 2 LITERATURE REVIEW

The process of technology transfer can never be considered new. Donald, Mathews and Roussel have dated the origin of the technology transfer process back to the pre-history of human species, when tacit knowledge was the only mean of knowledge creation and transfer.[10] On the other hand, Segman (1989) argued that the TT process was developed during the Neolithic times.[10]

However, studies on the nature of technology transfer have not started till last century. Ramanathan indicated that six decades ago, interest in technology transfer were initiated by colonial power that had their main focus on extracting resources from their colonies at that time.[11]

During the last fifty years, research on the topic of technology transfer has been vastly accumulating. N. Reddy, L. Zhao indicated

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that the main focus of the research was on three main aspects; namely, "international political dimension, commercial transactions and issues of operational relevance", where the international dimension is mainly concerned with the nation level and how cooperation between nations affects the technology transfer process, while the commercial transaction focuses on the firm level, studying the outcome of the transfer projects.[12]

Hypothetically, enabling technology transfer factors might vary due to discrepancies between countries' circumstances. This paper is mainly concerned with studying the enabling factors in the Egyptian context by which industrial SMEs would implement a successful technology transfer process.

## 3 CONSTRUCTING A TECHNOLOGY TRANSFER ECOSYSTEM

In order to construct an ecosystem in which most key factors that influence the technology transfer process are contained, three main inputs were taken into consideration; first, the literature of technology transfer which includes lots of studies discussing the effect of multiple factors on international technology transfer; secondly, experts who were able to implement successful technology transfer processes. Since this paper is concerned with the Egyptian context of technology transfer implementation; the role of experts in this study is considered the most significant. The third and last input in constructing this ecosystem was academic experts that have done research in the field of technology management, and have been practically exposed to the industrial sector in Egypt. All factors that were from literature were referenced. Others were extracted from expert opinions.

### 3.1 Primary Technology Transfer Ecosystem

This ecosystem is concerned only with the transferee's environment, with disregard of the transferor environment. Based on similarities in characteristics and environments of some factors, the preliminary ecosystem was divided into main six groups. The first is related to the "transferred technology" under which six factors lies, these are: technological appropriateness, the technical gap between the technology transferred and the recipient (transferee), the degree of complexity of the transferred technology, the level of maturity of this technology and finally the protection of this technology by the transferor (seller).

The second group of the ecosystem is related to the "internal management" of the company, in which four factors are included, these are; Research & Development, Innovation Policy, Knowledge Absorption of the corporate personnel, and the availability of adequate training system.

The third group is related to the National scale, called "Government & Economy". Four factors lies under this group; these are: Governmental Support offered to the transferee, the laws related to the technological issues and the transferor company as a whole, the political stability of the nation and the economic situation.

The fourth group is concerned with the "relations" of the transferee, containing only two main factors, one is the relationship between the transferor and the transferee and the second is the domestic relation between the transferee and the national entities, including government, suppliers and competing corporations.

The fifth group is related to the "resources" of the transferee; including four main resources: infrastructure of the company, human resources, capital resources and information resources about the market.

The final group is concerned with entities external to the transferee and the government, called "external factors". Three main factors are included in this group: the quality of local suppliers, the culture and value system within the society, and the exposure of the transferee internationally.

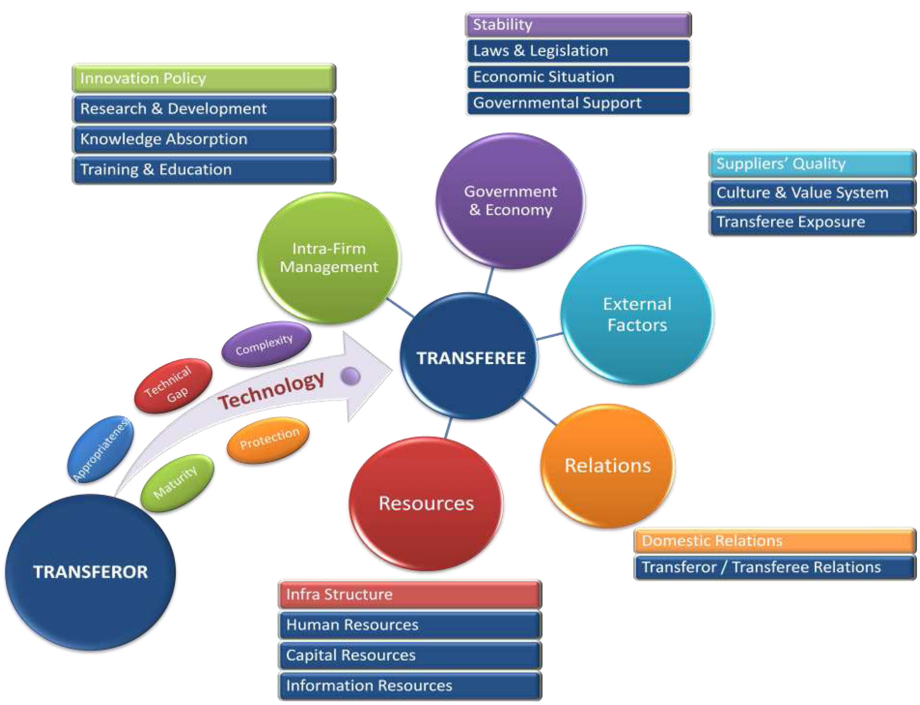


Figure 1: Technology transfer general ecosystem.

### 3.2 Ecosystem Qualitative Modifications

Environmental circumstances and factors certainly differ not only between different countries, but also between different industrial sectors in the same country; thus, it is of high importance to determine Technology Transfer key success factors in each industrial sector separately. However, this paper aims at evaluating the factors affecting TT process taking place in Egypt to local industrial SMEs in general. In order achieve that, the above mentioned eco-system – which is considered very generic – was modified according to qualitative expert opinions obtained from interviews with 10 experts from different industrial companies in which they implemented a successful TT process. Each expert was asked to explain the TT experiences he witnessed, focusing on the essential elements that had the major effect on the success of these experiences. Secondly, each expert was asked more specifically about the certain factors that should exist internally within the company and externally in order to guarantee a successful technology transfer process, finally the general model in Figure 1 was shown to each expert in order to get their feedback upon each factor contained in the model. Accordingly, the above mentioned (TIGER) model was modified to match the qualitative data collected through experts' interviews.

Experts indicated that when governmental stability is not existent it would be nearly impossible for the technology transfer process to take place. Investors will necessarily lose interest in expanding their investments in such a turbulent environment. Accordingly, political stability was put as an assumption that should be existent already before expanding companies' technological portfolio. It was also recognized that local manufacturers do not consider culture difference as a significant factor affecting the TT process. Some experts also indicated that the functions of innovation policy, Research & Development, training & education and knowledge absorption are aiming at closing the technical and knowledge gap between the transferor and transferee. Accordingly, these factors were all embedded in "knowledge and technical gap". Also, it was recognized that most of the transferred technologies are already in a high maturity phase and are protected already from the transferor. Which eliminates the importance of having a factor called "maturity" or "protection". It was also found that the level of complexity of the transferred technology is not the main issue as long as the resources needed were assigned and the technical & knowledge gap is not too large between the transferor and the transferee. On the other hand, the transferee should have already implemented a feasibility study to make sure that the technology has a market need. However, as technology transfer processes might take long time, it is important for the transferee to keep monitoring the fluctuations that might occur in the market.

The resultant model depicted in figure 2, consists of three main categories; "Technological Appropriateness" which indicates whether the choice of technology is suitable or not, the second group is "Government & Economy" indicating the effect of the government policy and the economic conditions on the technology transfer (TT) process, and finally the "External" group in which some other essential factors - external to both government and the transferee - are included. Stewart and Komoda argued that technological appropriateness is considered the most important aspect of technology. [13] If choice of technology was not suitable to the market, the whole process of technology transfer – according to some experts – will be endangered. Thus, Ladman claims that the ability of determining a suitable technology is critical. [13]

We here assume that the transferee has already studied market conditions and has properly implemented tact feasibility study. Still, a continual "Market Monitoring" process should be undergoing along with the transfer process.

Three main factors determine the appropriateness of the transferred Technology; the first is the "Resources" owned by the transferee, including infrastructure, capital, and human resources. Technology transfer - as Chen stipulated - "is not just acquiring of knowledge in production, but also a building of the nation's technological capability". [14] However, the company to which the transfer will happen should have certain level of enabling capabilities; these capabilities consists of human resources, capital, natural resources and land resources. [13]

The second key factor that lies under "Technological Appropriateness" group is the "Technical and Knowledge Gap" between the two parties - the transferor and the transferee. Although there should be a certain gap between the transferor and the transferee in order to have an effective learning process [15], this gap should not be too great, or else, the learning process – as Hamel indicated – would be impossible. Cummings referred this to the fact that "too many learning steps will be required if the knowledge gap (or distance) is significant."

The last factor in this group is the "Market Monitoring" process that goes in parallel with the transfer process itself, in order to observe any market changes.

The second group, namely "Government & Economy" constitutes elements that are influenced by the government and the economical system. The role of government in accelerating technology transfer is very crucial, otherwise, "lack of government support may cause the failure of technology and the company or create barriers to further development" [16]

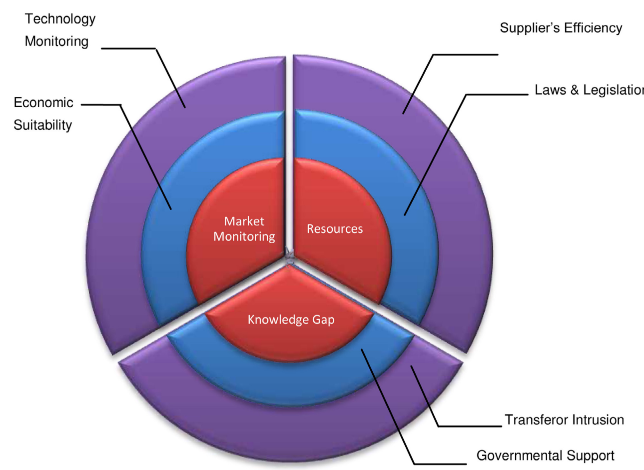


Figure 2: Key factors affecting the TT process to the indistrial SMEs.

Three main factors lie under this group; "Laws & Legislation", specifically the laws concerned with technological and intellectual property rights, as well as the easiness of starting and doing new businesses. The second is the "Governmental Support" policy directed towards the transferee such as tax incentives, R&D funds, etc. and the last is "Economic Suitability" of the country.

Some other key factors are considered "External" to both the transferee and the government; these are; "Suppliers Efficiency" which indicates the level of quality that local suppliers provide, and the level of "Transferor Intrusion" in the internal policy of the transferee, finally, since disruptive technological changes could affect technology market, "Technology Monitoring" process is essential to watch for these probable changes. The main difference between market monitoring and technology monitoring is that while the former is mainly concerned with the market need of the transferred technology, the latter is only concerned with the technical evolution of new technologies that might constitute a replacement for the transferred one.

### 3.3 Quantitative Analysis

Father elucidation of the modified ecosystem was done by evaluating all factors using two main techniques. The first was the Analytical Hierarchy Process (AHP) developed by Saaty; and the second was simple ranking. Saaty argued that “Using judgments has been considered to be a questionable practice when objectivity is the norm” [17]. Thus, he developed a tool by which each two factors of the same level of hierarchy lying under the same group are compared relative to each other.

In order to use the AHP technique, clear number of steps should be followed. Firstly, the problem should be clearly defined; which in our case is “Evaluating the Effect of Multiple Factors on the Success of TT process to the Egyptian Industrial SMEs”.

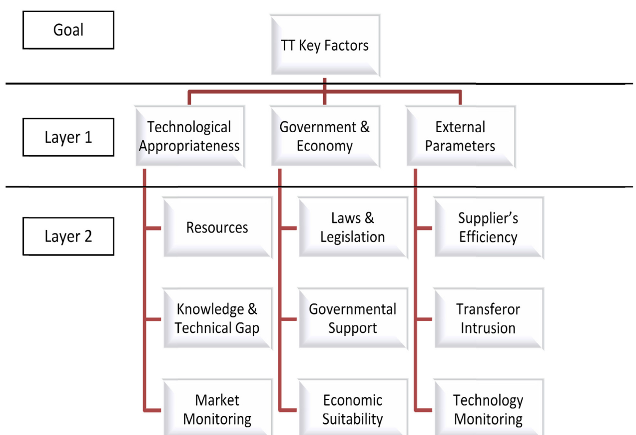


Figure 3: The AHP hierarchal structure.

Secondly, the complete hierarchy is built from top to bottom as depicted in figure 3; then a set of pairwise decision matrices are built. After that, judgments of pairwise comparisons are recorded (according to each expert) in the comparison matrices. Finally, weights are calculated by getting the normalized eigenvector of the specially constructed decision matrix.

In order to extract experts’ opinion using the AHP tool, questionnaires - containing pariwise analysis between factors In the same group - were submitted to them. The sample size was 10 experts of different industrial backgrounds that witnessed a successful TT process, and academic experts who have done research in the field of technology management and were quit exposed to the practical Egyptian environment. Due to space limitations, the procedure for each expert will not be reported here.

Results clearly indicated that the top three major factors were Resource, Knowledge & Technical Gap, and Economic Suitability respectively. Ironically, though experts have indicated high evaluation of local suppliers’ efficiency, this factor came last on the list of priorities. The figure below shows the result of using the AHP technique.

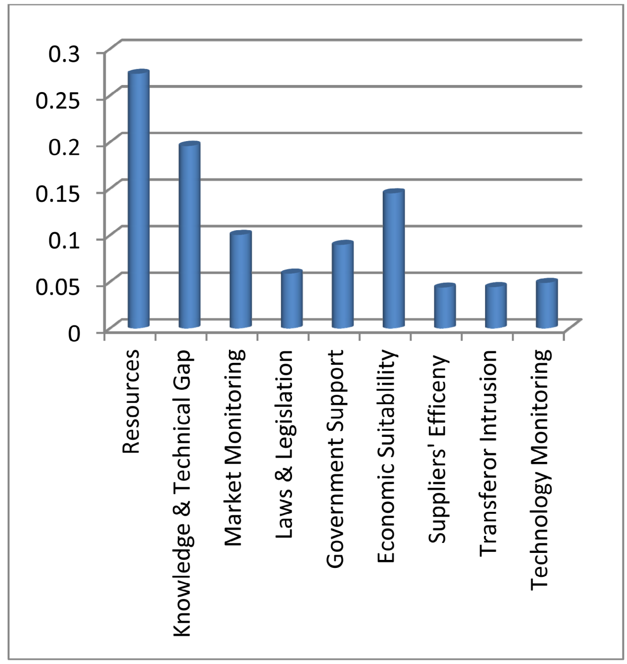


Figure 4: Resultant weights using the AHP tool.

On the other hand, experts were also asked to list the top three factors in terms of their influence on the technology transfer process, and then total counts were added for each factor. It was notable to find that although a totally different methodology were used, the top three factors were the same as it is in using the AHP.

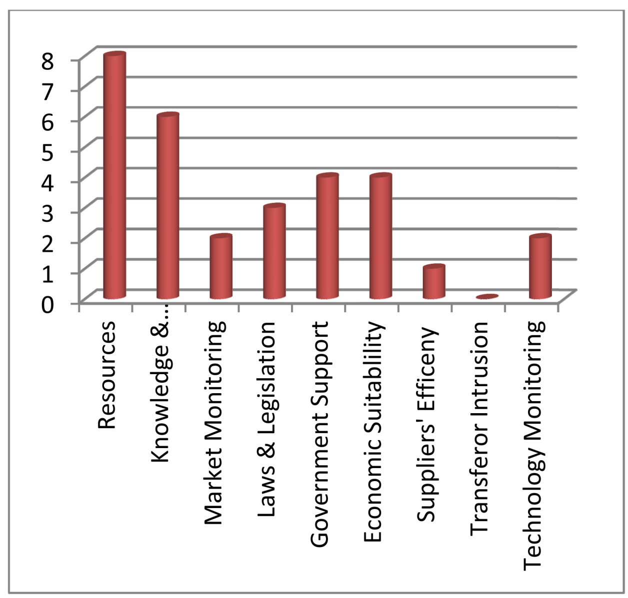


Figure 5: Results of simple ranking technique.

In order to compare between results of the two methodologies, resultant counts were normalized in order to limit the two methodologies in the same range. The figure below show the comparison between the two sets of results using both the AHP and Simple Ranking methods.

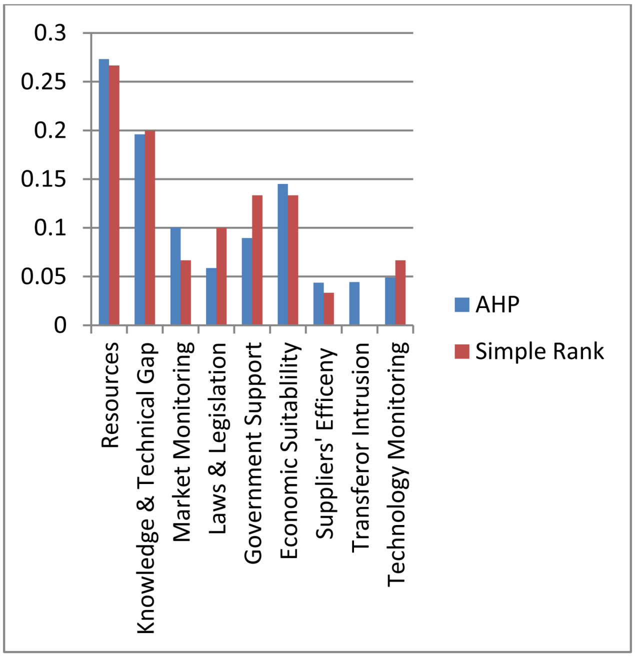


Figure 6: Results of both methodologies (AHP and simple ranking technique).

## 4 CONCLUSIONS

Investigating the influence of several factors on the technology transfer process to the industrial small and medium enterprises in Egypt was done by reviewing the literature of technology transfer and perceived opinions of several experts. A broad model of key factors was developed consisting of six groups. A further step was taken by adapting such a generic model to match the requirements of the Egyptian industrial sector. Finally, using both the AHP and simple ranking order technique, weights of all factors were determined. Results indicated that the top three factors were "Resources" of the transferee, "Knowledge and Technical Gap" between the transferor and the transferee, and finally "Economic Suitability" of the country. This should constitute a guideline for government officials, investors and supporting institutions in order for them to concentrate on the most influencing factors that facilitate the technology transfer process. Also, it was clear from the result that lack capital, human resources are the most problematic issues that hinder growth of the Egyptian SMEs by means of technology transfer. Further research is required to identify the key performance indicators through which assessments of industrial SMEs can be implemented, enabling decision makers to identify the odds of implementing a successful TT process by each case.

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# Planning Approach for Designing and Evaluating Product and Production Adaptations to Local Market Conditions

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**Abstract**
A company's success depends more than ever on its strategic, international dimension and its global presence. Another key factor for the success of a company lies in the extent to which the product portfolios take account of the demands of local markets. Growing prosperity, demographic change as well as increasing international competitive pressure urge companies to adapt products and its production systems. The advantages of the planning approach depicted in this paper are to be found in shorter planning times, shorter time-to-market and the opportunity to suggest a decision at the beginning of the product engineering process regarding a product and production system alternative. The consideration of local production capacities, the analysis of possible production costs of different production systems and the consideration of factors of uncertainty (number of units, costs, etc.) of future planning periods present a huge challenge.

**Keywords:**
Global Production Systems; Production Networks; Production Adaptation

## 1 INTRODUCTION

For some years now, a worldwide trend towards internationalization of companies has been observed. At first, this international orientation was motivated by costs, but now this motivation is increasingly being replaced by the opening of new markets. The development of the nominal gross domestic product worldwide indicates a significant increase in the next decades. It can be concluded that the percentage of Western Europe in terms of regional distribution of the worldwide nominal GDP will decrease from 25% in 2010 to 13% in 2030. In contrast, the share of developing Asia will increase from 18% to 40%. Consequently, the trend of the international tapping of new markets will continue to increase. The central question for the companies will be whether the local markets can be satisfied with the existing product portfolio or whether the product portfolios as well as the production portfolios have to be adapted to secure the market share.

## 2 OBJECTIVE

The purpose of the presented planning approach for designing and evaluating the product and production adaptation to local market conditions is to provide an answer to this question. The aim is to create a planning approach and a decision support system that enable companies to control cause-effect relationships between the product and the production system and to evaluate the resulting adaptation alternatives according to economic aspects. The added value of a planning approach and a decision support system is provided by the strategic planning of product and production system adaptations. This includes aspects of value creating network planning, factory planning, quality assurance and site-specific product design.

## 3 LITERATURE REVIEW

The following paragraphs introduce the state of the art regarding frameworks of integrative product and production system development, approaches for global product and production system adaptation and evaluation methods of solution alternatives.

### 3.1 Frameworks of Integrative Product and Production System Development

In the literature several frameworks that deal with integrative product and production system development can be found. Besides the integrative development of products and production systems, these approaches also focus on the persistent trend of globalization and thus the formation of international value-added networks and production structures that cope well with globalization.

Systems engineering concentrates on the "definition and documentation of system requirements in the early stage of development, composition of a system design and checking the system for compliance with requirements by taking into consideration the overall problem" [1].

One of the first approaches emphasizes in particular an integrative view of product and process design (production system development is simultaneous engineering or respectively concurrent engineering). Eversheim regards simultaneous engineering as "integrated and in parallel designed products and processes with the aim to shorten the time-to-market, to reduce development and manufacturing costs and to improve the quality of products in a comprehensive sense" [1]. Simultaneous engineering comprises the design of the process, the product and the production goods for the entire product life cycle in combination with an integrated project management [2].

A process model of product development was spelled out by Gausemeier [3] [4]. According to Gausemeier, the process of product development entails the areas of "strategic product planning", "product development" and "production system development". However, these areas are not regarded as a stringent order of process steps and mile stones. Moreover, they are depicted as three cycles where different tasks are carried out.

### 3.2 Approaches for Global Product and Production System Adaptation

The adaptation of renowned products, developed in the home country, leads to the opening of new markets and the satisfaction of local customer needs. Besides the adaptation of product design, Abele also points to the adaptation of production technology since only a simultaneous adaptation in these two categories results in

M.F. Zaeh (ed.), *5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013), Munich, Germany 2013*,
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ultimate success. Above all, these adaptations affect the degree of automation of the material flow, the workpiece handling and the assembly. Consequently, completely different manufacturing technologies may be applied. In this context, changes in the design relate to the product structure, the individual product components or the entire product. In order to adapt to different local conditions, trying to avoid complex component geometries to decrease capital intensity is appropriate. The aim is to make automated tests with Poka Yoke unnecessary and using simple connection technologies instead of capital intensive ones. Production technologies shall be oriented towards the degree of automation and labour costs, capital costs, technical know-how and the number of variants. [5]

Hurschler deduces the design modifications from the factors that cause product adaptation. These factors are to be found in the procurement or the sales market. Global products may be distributed worldwide without any modifications. Merely the packaging and language must be adapted. Adaptations are caused by the procurement market stem from material availability, process availability in local production or an altered process selection that allows meeting the product requirements despite the different understanding of quality. [6]

Reinecke presents a method for adapting products to the conditions of global competition. Therefore, product and production flexibility are regarded as key factors of global product adaptation. The objectives of this method are the identification of improvement potential, the provision of recommendations for redesigning, a virtual product revision and a benchmark of design alternatives. The model is based on an integrated product data model. The functional structure comprises functions from the marketing and development perspective. The process structure comprises the attributes production location, material, manufacturing and transportation costs as well as manufacturing and transportation time. The component structure is made up of an assembly-oriented parts list. [7]

Große-Heitmeier presents a tool for supporting the globalized product development for small and medium sized companies. The depicted method focuses on a product structuring that corresponds well to globalization considering core competencies. Here, structuring occurs based on common design criteria, such as whether it will satisfy manufacturing or assembly requirements. In order to support the systematic process performance under this aspect, the method of product structuring is presented here. This method corresponds well to globalization and it is based on technological core competencies. [8]

Lanza illustrates the challenges and opportunities of the design for low-cost country sourcing. To seize the opportunities of a construction that fulfils low wage and procurement requirements, the research objective is to support the construction with the development and allocation of suitable tools. [9]

Fallböhmer introduces an integrated technology planning methodology. By means of feature based matchings' of product and technology characteristics, production technologies could be chosen already in the early phases of product development and combined to technology chains. [10]

Trommer expands the methodology of Fallböhmer, aiming at generating the best suited production alternative with corresponding production equipment. In addition, another objective is the multicriteria assessment of those production alternatives by means of company specific criteria. [11]

Müller develops a methodology for process planning by integrated design and evaluation of technology chains. Based on defined product elements, existing and potential technologies are assigned and evaluated regarding the optimal product and production costs. [12]

### 3.3 Evaluation of Solution Alternatives

The alternatives must be evaluated regarding functionality as well as economic benefit in order to reach the best solution. When it comes to evaluating the solution, it is important to look at the solution in its entirety and to consider evaluation criteria such as functionality, profitability and design.

Generally, a differentiation is made between two principles. On the one hand, the solutions are compared to one another. On the other hand, it is defined to which degree the identified solutions have reached the intended ideal solution. The evaluation process has to follow an approach that requires little effort and that is transparent as well as reconstructable. [13]

Conrad's method aims at analysing and evaluating risks and effects of solution alternatives of change requests of technical products [14]. The evaluation approach leads to a selection of those solution alternatives that present the lowest risk and that additionally have the least impact on other product components and processes. Köhler supplements Conrad's approach by a procedure to evaluate and select solution alternatives correctly for product adaptation. Additional evaluation criteria, such as the effects on costs and deadlines, are included as well. In addition, change propagations are taken more into consideration. The CIRA approach developed by Köhler is referred to as Property-Driven Change Impact and Risk Analysis (PD/CIRA). [15] The PD/CIRA approach evaluates solution alternatives according to various criteria to implement product adaptation in order to define the solution quality of each solution alternative. It results from the summation of the individual adaption effects, based on Köhler's evaluation scales and probabilities. The higher the solution quality, the better suited the solution alternative for implementing the presented product adaptation.

De facto, the capital value method is one of the most frequently used methods. It pursues the objective of defining the added value of a certain investment project, provided that the capital value to be calculated is a positive one [16]. Most evaluation methods, including the capital value method, are based on the assumption that the future expectations will surely be reached. Consequently, this evaluation method only determines the added value of an investment based on quasi reliable expectations [17]. Risk indicators may be determined and sensitivity and scenario analysis may be carried out in order to define uncertainties during the product development process and the assessment of solution alternatives [18] [19]. By using specific evaluation procedures, these forecasting and analytical methods may explicitly be taken into consideration when it comes to solving decision-making problems [20] or they may be integrated in the evaluation with Monte Carlo simulations [16] [21].

## 4 PLANNING APPROACH FOR DESIGNING AND EVALUATING PRODUCT AND PRODUCTION ADAPTATIONS

In order to reach the objective, the work program has been divided into three phases (see Figure 1). Phase 1 determines the potential need for adaptation. It creates the basis for the strategic orientation of the company since it states whether the local market will be supplied with adapted products or the existing product portfolio. Initially, the factors that cause and drive the adaptation of products and production systems are identified. They may both be internally (innovation) as well as externally (customer wishes in the form of altered product characteristics) be determined. The difference between the existing and the new product characteristics represents the need for adaptation. Furthermore, the existing product structure is analyzed in phase 1, whereas the cost structure is determined on the one hand and the list of parts on the other. This information serves as a first indication whether the measures of adaptation will influence the entire product structure or merely specific components. The list of parts indicates the adaptation measures' scope and effort. Finally, phase 1 evaluates the qualitative and quantitative production capabilities of local sites.

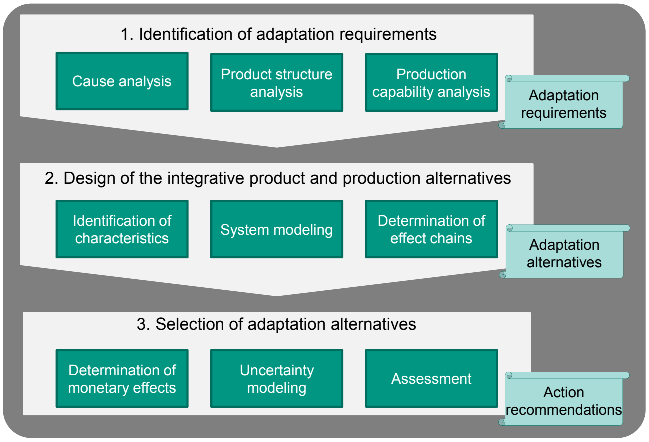



Figure 1 : Planning Approach for Designing and Evaluating Product and Production Adaptations.

Phase 2 aims at shaping integrative product and production system alternatives. First of all, the product and production characteristics are determined. The operator might consider these characteristics when dealing with the consequences of adaptation. The following system modelling serves the purpose of determining the relationship between product and production system characteristics. Afterwards, event chains are created based on the results of the modelling of the dependencies between the characteristics. These event chains entail precise characteristics in order to realize adaptation of the products and the production system. Phase 3 serves the purpose of selecting adaptation alternatives. Firstly, the monetary consequences of adaptation are defined. Subsequently, a Monte Carlo simulation is carried out in order to illustrate uncertainty factors (among others the quantity of sales, labour costs, material costs etc.). The evaluation is performed with the capital value method. Since the Monte Carlo simulation leads to a probability distribution of capital values per adaptation alternative, a sensitivity analysis is carried out to determine the robustness of the respective alternative compared to the changes of an uncertainty factor. This calculation is also executed for the existing product and production system since it might be an option for offering the existing product locally.

### 4.1 Identification of Adaptation Requirements

The basic condition for the identification of adaptation requirements is the determination of the strategic orientation of the company in global competition. In the process, both external and internal causes can influence the companies' decisions how to position themselves on the local markets. External causes are, for instance, new regional customer demands, external innovations and new legal framework concerning regulations, norms and laws. Internal causes are, for example, in-house product or process developments or failures in different divisions. Thus, the analysis of these drivers leads to an influence of the product portfolio planning and price differentiation in local markets as well as to the determination and selection of the markets that are affected by the causes.

The product structure analysis is used to describe the product to be examined in view of globalization. On the basis of the analyzed product structure, primary characteristic dependencies of the product structure elements can be identified and therefore, a control and reduction of the complexity can be achieved. The objective of the product structure analysis is the generation of a production/assembly oriented and a function oriented product classification (see Figure 2). Product characteristics are used for product definition and can therefore act as interface between the description models of the product structure.

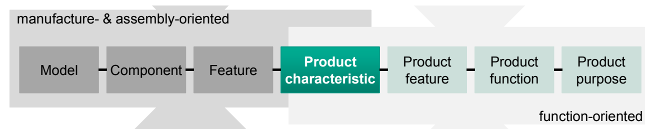



Figure 2: Product characteristics as interface in the product structure.

Following the deterministic product analysis according to Rapp, products or product variants are divided into product components which are, in turn, separated into modules, components, single parts and features. Thus, the determination of the adaptation area is carried out with the product structure analysis. It is the basis for the identification and specification of product characteristics and the determination and analysis of product-related dependencies. Besides, the product structure analysis is the basis for evaluating prospective adaptation effects in phase 2.

The analysis of the manufacturing capabilities is used to collect the strengths of existing locations to adapt production processes to the different local requirements. Primarily, manufacturing capabilities aim at the production process in order to manufacture the products in the required quality, within the intended time and at the desired cost. However, that does not only include the operative design of the production processes but also the production technologies, production infrastructure (organizational structure and information systems) as well as the production equipment and all needed resources. By the structured analysis of the qualitative criteria regarding lot size variations, occupational safety, protection of the environment, documentation and operability, a first classification of the company locations is carried out. The cost-based comparison of locations considers direct and indirect material costs, direct and indirect production costs, special direct costs of production as well as administrative expenses. An extended value benefit analysis allows for a quantitative comparison of locations by taking into account the competence- and cost-based comparison of locations of the manufacturing capabilities (see Figure 3). On the basis of an MS Excel® VBA tool, companies get the opportunity to evaluate and weight the single criteria in groups of criteria so that finally a location index can be calculated. This index with the corresponding visualizations is used to compare the competencies of the locations and to derive potential measures for improvement. Afterwards, the manufacturing costs for each component at each location are determined and also the manufacturing costs for alternative process steps are assessed on the basis of the value benefit analysis and the product structure.

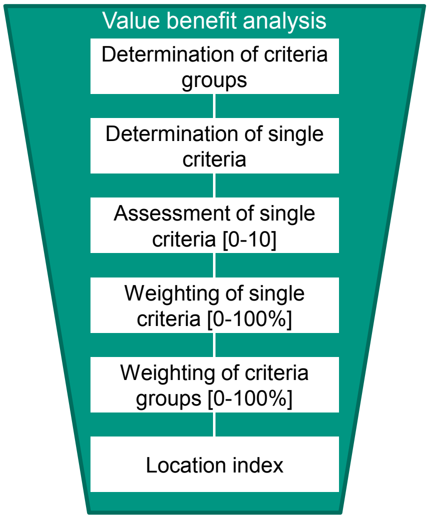



Figure 3 : Extended value benefit analysis for the cost-based comparison of global manufacturing capabilities.

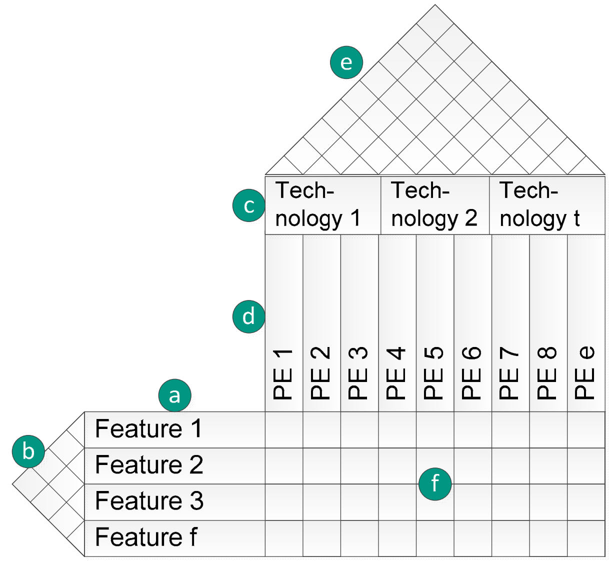
### 4.2 Design of Integrative Product and Production Alternatives

The integrated adaption of product and production systems can be changed by various influencing factors. Therefore, it is necessary to find and categorize a list with potential characteristics. The categorization of the characteristics is effected with the help of geometrical, functional, technological and economic-organizational groupings.

The generation of the integrated product and production system adaptation is done following the House of Quality [22] in the House of Product and Production Alternatives (see Figure 4). With this tool the system modeling is done. In the course of the system modeling it is assumed that different constructive solutions (here product alternatives) exist and also that some of the features of these solutions are different. The system modeling aims to generate several process chains and to prioritize them on the basis of product features, production features and customer requirements. As first step (a) of the system modeling process the status quo of the product alternatives is derived by specifying their features. Afterwards (b) correlations between features are developed using Boolean operands in order to model the product alternatives as composition of various features. The specification of a correlation between two features can be stated as follows:

- AND = „++“: Both features are considered in the production alternative
- NOT = „--“„: The two features must not be part of one product alternative
- OR = „+“: Either one or the other feature or both together can be considered in the product alternative
- XOR: „-“ : Only one of two considered features is chosen

In the next step (c) the eligible technology options for the modeling of production alternatives are determined. By means of data bases regarding technologies and production equipment those production equipment are chosen which fulfill the basic criteria of feature requirements (d). The correlations between the production equipment (e) are described as Boolean operands as well, so the outcomes of this are realizable production alternatives. In this context production alternatives are understood as value-added process chains.




PE: Production equipment
f ∈ F: feature from the sum of the potential features
t ∈ T: technology from the sum of the potential technologies
e ∈ E: equipment from the sum of the potential equipment

Figure 4: House of the Product and Production Alternatives.

Finally the relation matrix (f) is built in order to assign the production equipment to the features by which they can be created. Therefore following algebraic characteristics are distinguished:

- 1 = MUST: Feature has to be produced by the production equipment XY
- 2 = OPTIONAL: Feature can be produced by the production equipment XY or YX
- 3 = MUST under boundary conditions: Feature has to be produced by the production equipment XY. Boundary conditions must be considered
- 4 = OPTIONAL under boundary conditions: Feature can be produced by the production equipment XY or YX. Boundary conditions must be considered

Consequently two different solutions arise from the House of Product and Production Alternatives:

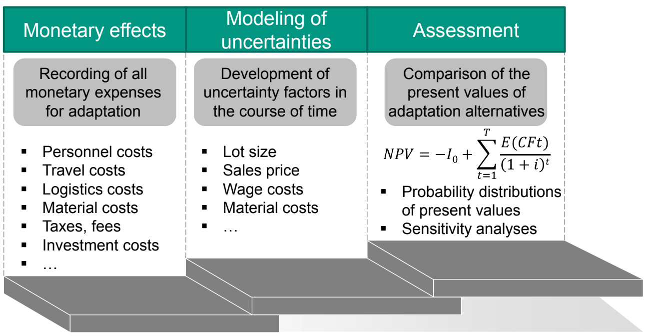
- The composition of different features to product alternatives
- The production alternatives as process chain by linking production equipment

So as to be able to determine the correlation between the product alternatives and the production alternatives, a matrix is used to state if the product alternative can be manufactured by the found production alternatives or not.

These product and production allocations are assessed in terms of selecting product and production characteristics and then collated to customer requirements or internal guidelines. The aim is to eliminate possible combinations in order to get adaption options as a result of system modeling. The product alternatives are linked to the production equipment and assessed with regard to process time, process efficiency and flexibility in relation to item quantity for example. If the production alternatives are linked to the features, the evaluation is done for example on the basis of the product characteristics such as tolerance, finish quality and material indicators. At this point the user takes all features that may lead to an elimination of product and production alternatives into consideration.

### 4.3 Selection of Adaptation Alternatives

Adaptation alternatives are selected based on dynamically changeable factors and during the entire life cycle of the product. Thus, the structured selection of the adaptation alternatives is subdivided into the calculation of monetary effects, the modeling of uncertainty factors and the assessment by means of a present value method (see Figure 5).




NPV: Net Present Value | $I_t$: Investment expenditure in period t | E( ): Expected value | T: Evaluation duration | $CF_t$: Cash flow or savings in period t | i: Discount rate

Figure 5: Approach for the determination of action recommendations.

Given that both, personal costs and investment costs, can incur due to adaptation measures, all monetary influences are determined. In addition to the costs for personnel, travel, material and investment, also the effects on quality and date are determined in monetary terms. Date-related effects can be quantified in monetary terms by the costs of production downtimes or production delays. Concerning the quality effects, the costs for rework are determined and the recycling costs are calculated by means of the quality rate.

During a product life cycle various uncertainty factors occur (e.g. lot size, sales price, wage costs, material costs). For this reason, it is difficult to predict and assess the course of the product life cycle at the beginning of the product development process and therefore it should be modeled. Uncertainty factors can comprise different sales volumes and consequently unstable production numbers as well as the unstable expense patterns concerning the costs for transport, wages, energy and material. To be able to make statements regarding the future developments and to deduce action recommendations on this basis, distribution functions are assumed for these uncertainty factors. Furthermore, the operator specifies standard deviations and expectation values so that the factors are simulated by means of random experiments during the planning period. It is appropriate to model different prospective developments of dynamical factors by using the geometric Brownian motion, which is a continuous-time stochastic process [22] [23]. The general differential equation of the geometric Brownian motion is of the form:

$$dX_t = \mu X_t dt + \sigma X_t dtz_t \qquad (1)$$

With

$dX_t$ Change of variable *X* in time period *dt*

$\mu$ Expected drift rate of variable *X*

$\sigma$ Volatility of variable *X*

$dtz_t$ Wiener process

The linearization of a discrete point of interest can be written as

$$\Delta X_t = \mu X_t \Delta t + \sigma X_t \varepsilon \sqrt{\Delta t} \qquad (2)$$

$$X_{t+\Delta t} = X_t \left(1 + \mu \Delta t + \sigma \varepsilon \sqrt{\Delta t}\right) \qquad (3)$$

With

$\Delta X_t$ Change of variable *X* in time period $\Delta t$

$\mu$ Expected drift rate per time unit

$\sigma$ Volatility of variable *X*

$\varepsilon$ Random value of the standardised normal distribution

The first term $\mu X_t \Delta t$ implies the expected drift rate per time unit, which is equivalent to the expected in- or decrease of the dynamic variable. Using the Brownian motion in order to simulate prospective wage cost developments $WC_{t+1}$, the drift rate is multiplied with the wage costs of the prior time period, assuming the volatility equals zero.

$$WC_{t+1} = WC_t + \mu WC_t = WC_t(1+\mu) \qquad (4)$$

Assuming a consistent drift rate and the volatility equals zero, the prospective wage cost is of the form:

$$WC_T = WC_0 e^{\mu T} \qquad (5)$$

In the third step, the calculation of the net present value, the results of the simulation runs are included. The basic structure of the net present value does not change. The takings and spendings in the considered planning period are discounted to the present time of investment. Provided that the net present value shows a positive value, the alternative is in general economically reasonable and profitable. A negative net present value would lead to the rejection of the selected alternative. The alternative with the highest net present value is to prefer to all other alternatives. Nevertheless, the robustness of the chosen alternative can be tested on the basis of different courses of the influencing factors by means of sensitivity analyses and insensitive diagrams.

## 5 SUMMARY

The benefit of the planning approach for the companies is the systematic adaptation development of product and production systems in order to achieve shorter development cycles and to be able to make preemptively statements regarding the profitability of the adaptation alternatives. Thus, the expected results produce an immediate saving of time and costs when realizing the planning approach. The planning approach reduces the risk of companies to make wrong decisions with long-term implications concerning the positioning in local markets. By adapting the products, the optimal satisfaction of customer needs is achieved and cost transparency is guaranteed by the structured recording of data and the analysis by the software evaluation models. By including international locations and their capabilities, it is possible to identify quality problems at an early stage and to avoid them sustainably when designing the production system.

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# A Petri-net Based Approach for Evaluating Energy Flexibility of Production Machines

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**Abstract**
Nowadays production systems are faced with new turbulences in energy-markets due to the increasing use of renewable energy sources. Therefore, production systems and their machines have to be energy flexible. This paper provides an approach for evaluating energy flexibility of production machines based on a Petri-net modelling of machine behaviour. Furthermore, an application of the evaluation on two different machines is given.

**Keywords:**
Three most representative keywords; energy; flexibility; Petri-net

## 1 INTRODUCTION

Production systems are working in an environment that is characterized by a distinctive complexity and uncertainty [1]. This complexity and uncertainty derive e. g. from the globalization of the economy, the rising speed of information transfer and the rapid emergence of new technologies [2; 3]. To cope with these market uncertainties, production systems have to be flexible [4]. Flexibility in this context is understood as the ability of a system to adapt itself with little penalty in time, effort, cost and performance to changes in market environment [5]. Nowadays, production systems are faced with new turbulences in energy-markets. Due to the increasing use of renewable energy sources – especially wind power – prices for electrical energy are not fixed during the day. They are changing every 15 minutes on energy-markets depending on the current energy demand and the energy generation as a consequence of weather conditions. Based on these uncertainties utilities are designing new energy-contracts that force production systems to adapt their energy consumption to the actual energy availability in the energy grid. Therefore, production systems and in particular its production machines have to be energy-flexible.

This paper gives an introduction to the topic energy flexibility and presents an approach for evaluating energy flexibility of single production machines. Thus a Petri-net based modelling of the machine behaviour is given.

## 2 ENERGY FLEXIBILITY

The power demand of a production system stays within a lower and an upper boarder. The lower boarder represents the baseload of the production system, i. e. the power demand of the production system when all machines are switched off or not in use. The upper boarder is given by the sum of the maximal power demands of the machines of the production system. Within these boarders the power demand can vary depending on the state of the production system and its machines. Hence, the energy demand of a production machine also depends on process parameters e. g. cutting forces of milling machines.

This leads to the opportunity for production systems to generate economical benefits out of volatile energy prices. As explained before, prices for electrical energy can change every 15 minutes. Fig. 1 shows an energy price curve as it appears on energy markets like EEX and the corresponding power demand of a production system.

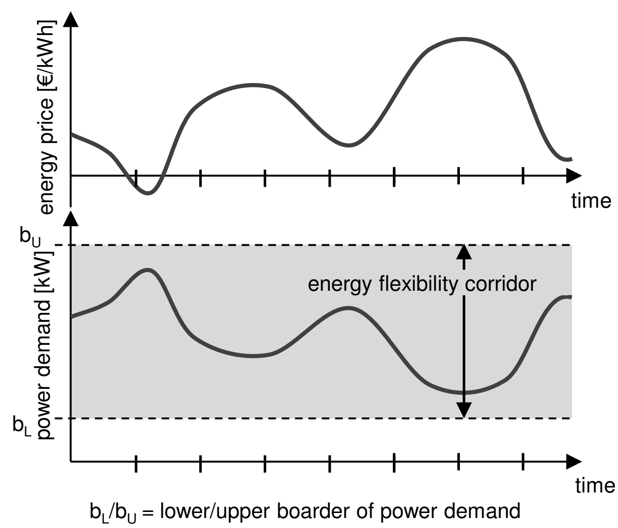


Figure 1: Volatile energy price and corresponding power demand.

An energy price tariff with varying components and an adapted behaviour of the production system can lead to significant energy cost savings [6]. An important requirement for that is, that production systems know their energy demand and know how to adapt the energy demand within the described boarders [7]. This capability is called energy flexibility [8]. Referring to classical flexibility definitions, energy flexibility in this context can be defined as the ability of a production system to adapt itself fast and without remarkable costs to changes in energy markets. The range of the power demand of the production system, within the lower and upper power demand boarder, can be defined as the energy flexibility corridor.

While the energy demand and therefore the energy flexibility of a production system depends on the behaviour of the production

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system's machines, an approach for evaluating the energy flexibility of single production machines is presented in the following section.

## 3 EVALUATION OF ENERGY FLEXIBILITY

### 3.1 Petri Net Based Modelling of Machine Behaviour

In this work, a model is required that enables both a sensible modulation of machine behaviour and provides the necessary inputs for the investigation of energy flexibility. First of all, flexibility can be regarded as a function of variability, cost and time [1]. Therefore, a suitable model has to enable the consideration of these three variables. From a machine point of view, variability is regarded as the number of states that the machine can adopt. Time and cost can be thought upon as the penalty for changing states, so the definition of machine states is of key essence. [9] recommend the use of Petri-nets for the modelling of machine states, since it enables manageability of complex systems with several states. The possibility to assign each state with upper and lower time boundaries as well as power demands to each state make Petri-nets suitable for the task of this work. Other authors also use Petri-nets for modelling machine states in their works regarding the described topic [10]. Petri-nets are widespread in literature coping with flexible manufacturing systems [11-14]. For this reasons, Petri-nets are suitable for this work. By adding time to the Petri-nets, the flexibility of a machine can be regarded as a function of the time needed to reach a certain state [12]. Hence, using Petri-nets as modelling tool requires unambiguous an understanding of machine state and transition. Following definitions for this work are given.

*Definition of Machine State*

A machine state is defined through its average power demand P, its non-zero time duration (existence of a minimal and maximal time stay $t_{min}$ and $t_{max}$) and its triggering and terminating events. The terminating event of one state is the triggering event of a succeeding state. The triggering event also defines the task of the following machine state. Machine states performing similar tasks can be grouped together into one state, if their average power demand does not deviate from one another with more than a defined tolerance of the maximum power demand of the machine. A machine can only adopt one state at any given moment.

*Definition of Transition and Event*

Transitions illustrate the direct connections between machine states. The transitions are executed by events e. g. turning on the machine. Neither the transitions nor the events can be assigned any power demand or time duration in the Petri-net model. A transition from one state to another is always triggered by an event. However, whether a transition can occur, depends on whether the requirements for leaving the previous state have been fulfilled. The requirement for leaving a state is remaining there for at least the time corresponding to its lower time boundary.

Below follows an example of a Petri-net modelling of a simple grinding machine with three machine states: "Off", "production state 1" and "production state 2". First the power demand of the grinding machine is measured. A picture of the investigated machine and results of the measuring can be seen in fig. 2.

The measuring of the machine starts in state "Off", where power demand is 0 W. A change of state from "Off" to "Production state 2" is executed at t ≈ 40 s. Power demand then rises and stabilizes at 1.89 kW. At t ≈ 135 s a new change of state slowly is carried out, from "Production state 2" over "Off" to "Production state 1". Power demand then stabilizes at 1.52 kW. None of the grinding machine's

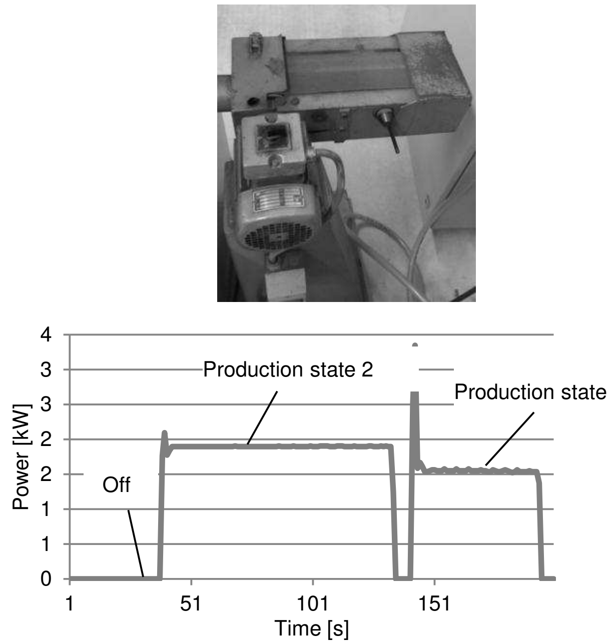


Figure 2: Grinding machine and its power demand.

three states have any lower or upper time boundaries, which enables very fast state changes. Transferring the data gained in the power demand measure to the Petri-net, gives the model shown in fig. 3.

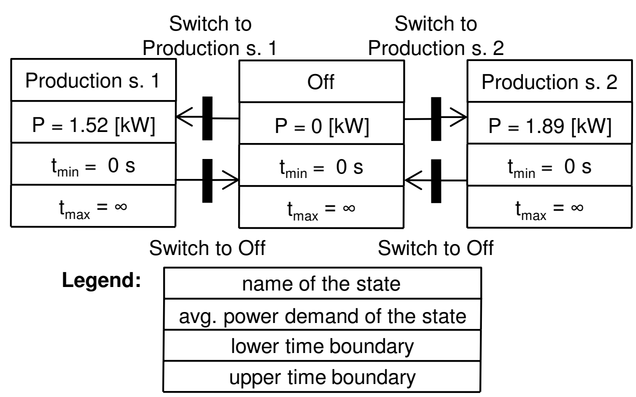


Figure 3: Petri-net of the grinding machine.

More complex machine states showing non constant power demand can be modelled as a sequence of different machine states when required.

### 3.2 Axioms of Energy Flexibility

In order to improve the understanding of energy flexibility of machines some basic properties of energy flexibility need to be discussed first. Fig. 4 visualizes the numbers of states Z and the distribution of these states in relation to their power demands P of three different machines.

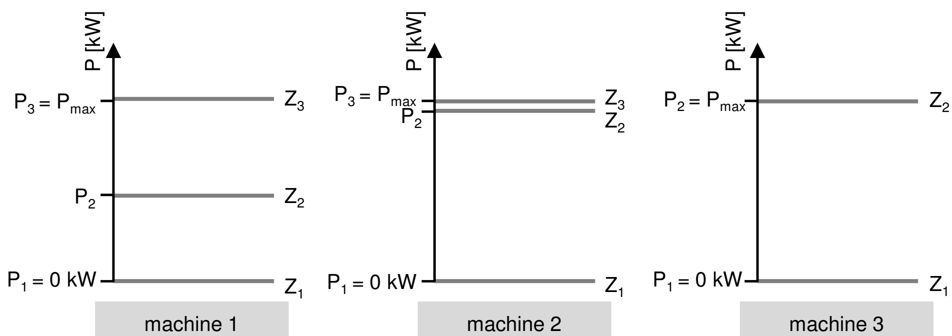


Figure 4: Machines with different adoptable states.

Since flexibility is a function of variability, a machine displaying more adoptable states should be more energy flexible than a machine with fewer adoptable states. Therefore, machine 1 in fig. 4 has to be more energy flexible than machine 3. Machine 2 has – as machine 1 – three adoptable states and therefore has to be more energy flexible than machine 3, which has only two adoptable states. Yet the difference between the power demands of the states $Z_2$ and $Z_3$ of machine 2 is so small that the adoptable states of machine 2 are almost like the ones of machine 3. This leads to the conclusion that a more even distribution of the machine states should increase energy flexibility since it increases variability. Therefore machine 1 is more energy flexible than machine 2 which again is more energy flexible than machine 3.

The next property under investigation is the influence of time on changes of states and how this affects the energy flexibility of a machine. As established in section 3.1, only machine states can be assigned time duration. However, the presence of lower time boundaries brings inertia in to the system and can make momentary state changes due to energy price changes impossible. In fig. 5 there are two similar systems illustrated. They have the same number of machine states and the distribution of the machine states is equal. The only difference is the lower time boundary of the machine state $Z_2$. Flexibility is considered as a function of the penalty of changing state. Regarding machine 1, the time penalty of changing from $Z_1$ to $Z_3$ and back is lower than the penalty of the corresponding change of machine 2. Hence, machine 1 is more energy flexible than machine 2.

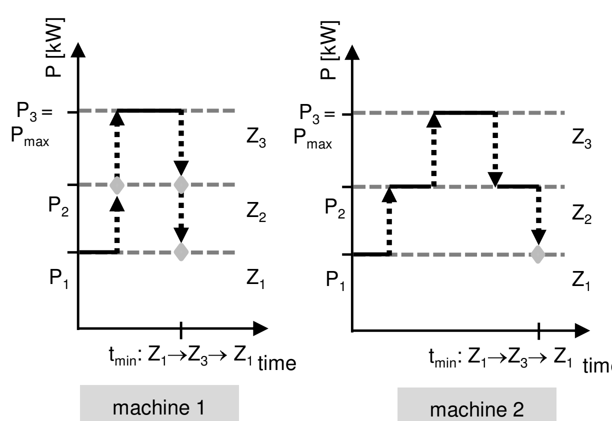


Figure 5: Systems with the same machine states but different lower time boundaries.

The influence of lower and upper time boundaries in machine states on the energy flexibility of a machine is displayed in fig. 6. A low positioned lower time boundary $t_{min}$, ensures fast machine state changes, and is therefore positive for the energy flexibility of a machine. A high positioned upper time boundary $t_{max}$ also has a positive influence on the energy flexibility, since it allows long stays in machine states. Therefore, machine 1 is more energy flexible than machine 2.

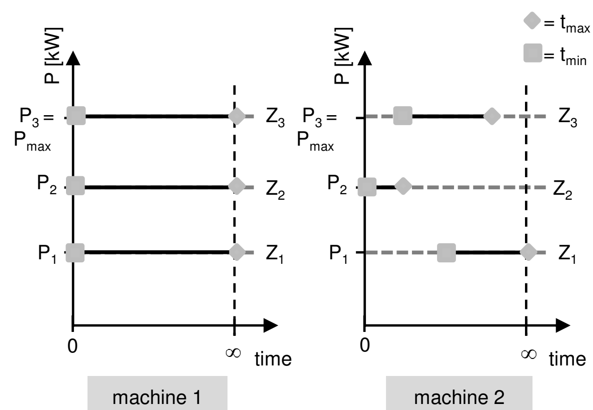


Figure 6: Machines with different lower und upper time boundaries.

Referring to the conclusions made in this section, five essential axioms to enable evaluation of energy flexibility of an arbitrary machine are made:

1. The energy flexibility of a machine increases/decreases with an increase/decrease of adoptable machine states $Z_i$.
2. The energy flexibility of a machine increases when the distribution of the power demand of the adoptable machine states is more even.
3. The energy flexibility of a machine increases/decreases when the required time $t_{ij}$ for a change of state decreases/increases.
4. The energy flexibility of a machine decreases when there exists a lower time boundary $t_{min}$ in one or more of the adoptable machine states. A decrease of the lower time boundary increases the energy flexibility.
5. The energy flexibility of a machine decreases when there exists an upper time boundary $t_{max}$ in one or more of the adoptable machine states. An increase of the upper time boundary increases the energy flexibility.

### 3.3 Evaluation of Energy Flexibility

Based upon the 5 axioms defined in section 3.2 an equation for evaluating energy flexibility of an arbitrary production machine has been developed. The resulting equation given from this work is:

$$E_{machine} = \frac{1}{2P_{max}^2}\Big(\sum_{i=1}^{n^+-1}\alpha_i\Big(\sum_{j=1}^{i}\Delta P_j-\sum_{j=1}^{i-1}\Delta P'_j\Big)\Big(P_{max}-\alpha_i\Big(\sum_{j=1}^{i}\Delta P_j-\sum_{j=1}^{i-1}\Delta P'_j\Big)\Big)+\alpha_{n^+}P_{max}\sum_{i=1}^{n^+}\Delta P_i$$
$$+\Big(\sum_{i=1}^{n^--1}\alpha_i\Big(\sum_{j=1}^{i}\Delta P_j-\sum_{j=1}^{i-1}\Delta P'_j\Big)\Big(P_{max}-\alpha_i\Big(\sum_{j=1}^{i}\Delta P_j-\sum_{j=1}^{i-1}\Delta P'_j\Big)\Big)+\alpha_{n^-}P_{max}\sum_{i=1}^{n^-}\Delta P_i \quad (1)$$

with

$$\Delta P'_j = \alpha_j\left(\sum_{k=1}^{j}\Delta P_k-\sum_{k=1}^{j-1}\Delta P'_k\right) \quad (2)$$

**Parameters**

$E_{machine}$ = Energy flexibility of the machine

$P_{max}$ = Maximal power demand of the machine

$\alpha_i$ = Weighting factor of state i

$\Delta P_i$ = Power demand difference between the states $Z_i$ and $Z_{i-1}$

$\Delta P'_i$ = Weighted power demand difference between the states $Z_i$ and $Z_{i-1}$

$n^+$ = Number of machine states with a higher power demand than the base state

$n^-$ = Number of machine states with a lower power demand than the base state

The equation is applicable to all machines with at least two machine states and it returns dimensionless values between 0 and 1, where 0 means that the machine has no energy flexibility and 1 is the maximum possible energy flexibility. Referring to the axioms number 1 and 2 the more machine states the machine has and the more evenly distributed they are, the higher the value the formula returns.

First of all a base state $Z_B$ has to be selected. The base state is the state, which usually is the origin for changes of state. It normally has no lower or upper time boundary. For the example with the grinding machine, the natural choice would be to set machine state "Off" as base state since the machine has neither a stand-by state nor any ramp-up time. Next, the differences between the power demands of two states $\Delta P_i$ and the weighted state differences $\Delta P'_i$ have to be calculated. Therefore, starting at the base state every state gets weighted step by step. It should also be noticed that the choice of base state affects the end result of the value of the energy flexibility $E_{machine}$.

The reason for weighing the machine states is to describe their importance for the energy flexibility of the machine more accurate in accordance to the axioms number 3-5. The weighting of each $\Delta P_i$ is done by the factor $\alpha_i$ and it is defined by equation 3.

$$\alpha_i = \frac{1}{1+\frac{t_{iZB}+t_{ZBi}}{t_{ref}}}\int_{t_{min,i}}^{t_{max,i}}\frac{1}{q}*e^{\frac{-t}{q}}\,dt \quad (3)$$

The times $t_{iZB}$ and $t_{ZBi}$ are the transition times from machine state $Z_i$ to the base state $Z_B$ and back. The time $t_{ref}$ is a reference time that depends, as well as the fitting parameter q on the speed with which the energy prices changes. The integral part of $\alpha_i$ manages the influence of time boundaries in machine states. A lower time boundary, $t_{min}$, is of high significance since it means that a state can be adopted fast as a reaction to quickly changing energy prices. A high upper boundary, $t_{max}$, enables a long stay in a state. This is up to a certain limit important because energy prices usually stay for at least 15 minutes at the same price-level. However, regardless of the machine, the importance of being able to stay in a state declines when $t_{max}$ moves against infinity since changing energy prices makes a longer stay of non interest. Fig. 7 gives a visualisation with a random example of the parameters used in the given equation.

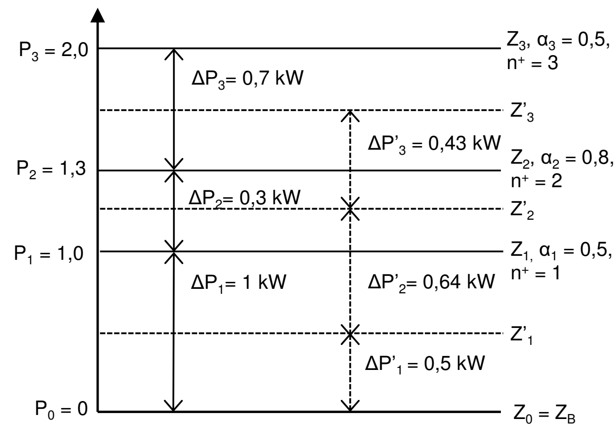


Figure 7: Visualisation of the given equation.

## 4 CASE STUDY

For the evaluation of the equation given in section 3.3 a case study was carried out. The case study was conducted on two different machines. The first machine is the grinding machine described in section 3.2 and the second machine is a Laser Sintering machine (MTT SLM 250). The laser sinter machine has eight main systems, a SPS, a computer (GUI), a heating system, an inert gas system providing the essential protecting atmosphere in the workspace, a metal powder delivering and filtering system, an automatically lowering construction table, a water based cooling system and a laser.

Turning on the main power switch starts the Laser Sintering machine. With main power on, the SPS automatically starts up and the GUI can manually be turned on. When GUI is accessible, the heating system of the construction table can be switched on. The use of the heating system is optional and the temperature is infinitely variable between room temperature and 200 °C. To reach the maximal construction table temperature from room temperature takes 20 minutes and is the most time consuming preparation. Before the production of a defined part can start, the inert gas system has to be turned on. The inert gas system sucks the air out of the workspace and replaces it with Argon. This system has a ramp-up time of 3 to 5 minutes and simultaneously as this is being done, the water-cooling system is turned on, without any ramp-up time. After these operations the machine is ready for production. The ramp-up of the laser takes only a few seconds and is therefore regarded as a part of the production state in this work. Lower and upper time boundaries of the machine state "Production" can hardly be sharply defined. The lower time boundary is set to one hour because process times less than one hour lead to parts with only a few millimetres thickness, which normally is not achievable. Upper time boundary is in practice defined by the size of the workspace of the machine. When the machine is done with its part it automatically turns off every system except the SPS and the GUI.

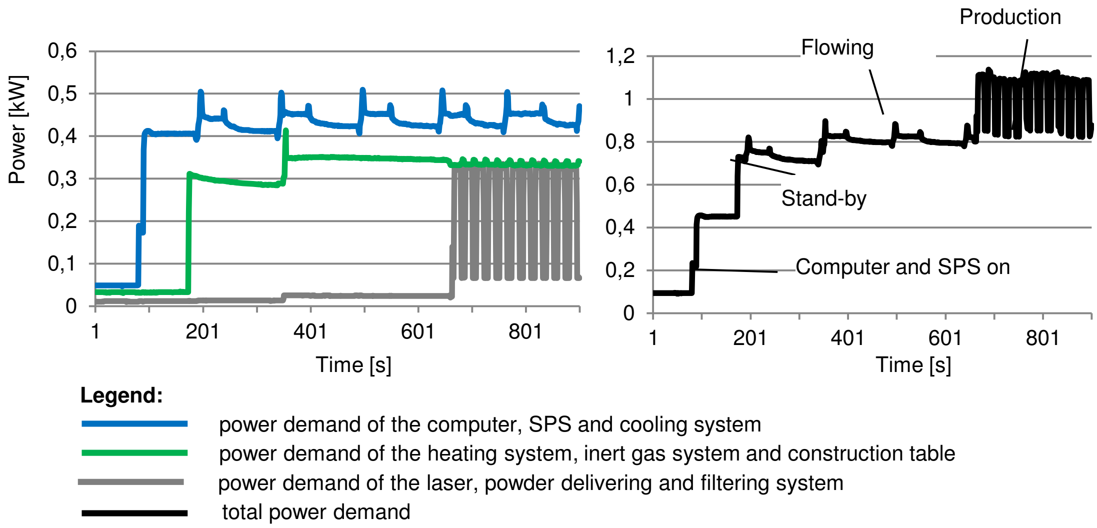


Figure 8: Left: Power demand measured in the three conductors in order to determine the individual power demand of the machine sub-systems. Right: Total power demand of the machine.

To be able to create a Petri-net for the laser sinter machine, power demand of the machine was measured. The results are displayed in the two graphs in fig. 8.

In fig. 8 on the left, the power demand of the three conductors can be seen and combining this information with the time for the switch on of the different systems enables the determination of their individual power demand. In fig. 8 on the right, the total power demand of the machine can be determined. Using the data from fig. 8 the Petri-net of the laser sinter machine is constructed. Notably is the power demand appearing as range in the machine states “Stand-by”, “Flowing” and “Production”. The reason for this is the heating system, which depending on setup uses between 0 and 260 W and the laser which also depending on setup has a power demand between 0 and 380 W. Fig. 9 shows the Petri-net of the described machine.

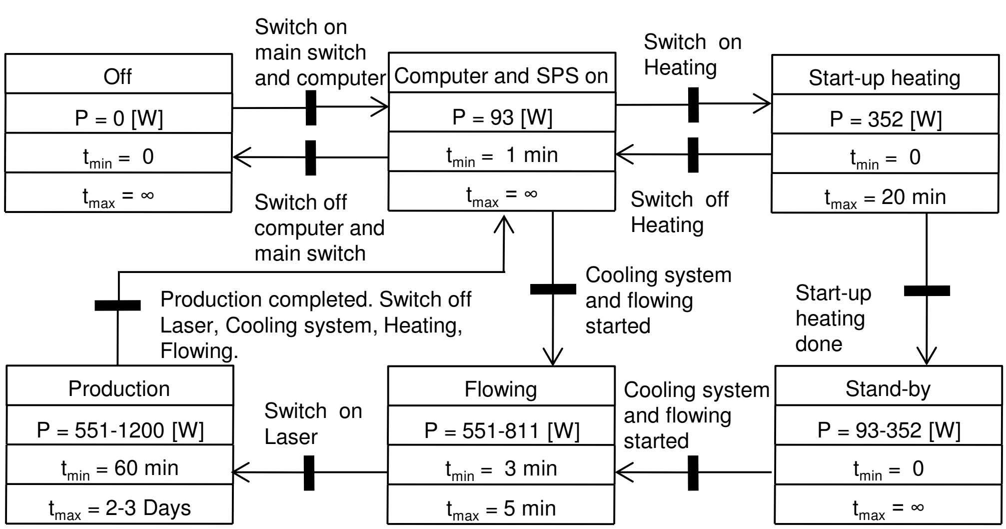


Figure 9: Petri-net of the laser sinter machine.

*Evaluation of Energy Flexibility*

Equation 1 has been implemented in MATLAB®. Calculating the energy flexibility of the grinding machine and the laser sinter machine using equation 1 gives the results represented in table 1.

| Machine | Basic machine state | Energy flexibility |
|---|---|---|
| Grinding machine | "Off" | 0,5786 |
| Laser sinter machine | "Computer and SPS on" | 0,5778 |

Table 1: Energy flexibility of the grinding machine and the Laser sinter machine.

The values of $t_{ref}$ and have been set to $t_{ref}$ = 15 min and q = 60 min. The machines exhibit energy flexibility values very close to each other although these are two very different machines. The grinding machine has a disadvantage in few adoptable machine states and an advantage in very wide time boundaries in its states. The laser sinter machine has a big variability and also in general low lower time boundaries in its states. According to the definition of a machine state given in section 3.1, a machine state has to have a power demand that differs from an already defined state with at least 5 % of the maximum power demand of the machine to be defined as a new state. Using this definition, a total of 11 different production states can be defined. The laser has a stepless power demand between 0 and 380 W. A lower laser power reduces production speed and vice versa. This ability offers great benefits for the energy flexibility of the machine, if the production program enables its utilization. The same applies on the machine state "Standby", where by setting a lower temperature than 200 °C for the table heating and hence, not constantly using 260 W, at least 5 different stand-by states can be defined. This provides a very high variability of the Laser Sinter machine. The combination of inability to interrupt production, a lower time boundary of the machine state "Production" of 1 hour and long lead times for big parts highly restricts its energy flexibility at times. However, the time boundaries set here for the production state are primarily defined by the product the machine produces and not by itself. With a lower time boundary of 3 minutes in machine state "Production", the energy flexibility formula returns the value $E_{machine}$ = 0,8514. This highlights the problem with defining the border between energy flexibility of a machine and its production program. One way to handle this issue could be ignoring the restrictive influences that products have on the machine and regarding the energy flexibility value that is received as the theoretical highest possible value.

## 5 CONCLUSION AND OUTLOOK

This paper gives an introduction to energy flexibility. While the energy demand and also the energy flexibility of a production system depends on the behaviour of the production system's machines, an approach for evaluating energy flexibility of production machines is presented. Based on a Petri-net modelling of machine behaviour an equation is given that meets the requirements of five axioms of energy flexibility. An application of the equation to two different machines shows how the number of machine states, its distribution and time constrain affect energy flexibility. Based on the presented equation, future work has to take in concept actions that can lead to changes of the states of the production machines to adapt the energy demand and the corresponding costs of these actions.

## 6 ACKNOWLEDGMENTS

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# Introduction of a Quality Oriented Production Theory for Product Realization Processes

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**Abstract**

The paper reviews the development of quality management and production theory in the industrial revolution. It is shown that existing production theories focus and explain the logistical transformation processes while leaving the notion of customer satisfaction and requirements transformation open. In the following chapters a concept for a new quality oriented production theory is presented which explains structure and behaviour of product realization processes. It is shown that the time weighted requirements/ specification and their completion level can serve as the central parameter in order to model product realization processes and to provide suggestions for the realization process management.

**Keywords:**

Production Theory; Quality Management; Systems Theory

## 1 INTRODUCTION

### 1.1 Industry 4.0 – The Industrial Revolution and Development of Quality Management

Production companies are experiencing a disruptive change in the industry today. After the automating of production processes, the intelligent application of cyber-physical systems plays an increasing role thanks to the considerably development of interaction possibilities and integrated sensors and actuators in products and production processes [1].

While the second and third industrial revolution took place, quality management has faced a continuous evolution and development of quality management concepts and philosophy (see Figure 1).

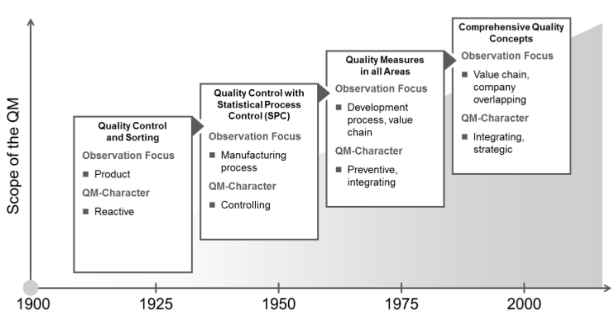


Figure 1: The Development of Quality Management.

Together with Japanese companies Deming introduced the concept of continuous improvement and Kaizen which meant a disruptive paradigm shift in the field of quality management. The established mindset which had been focused on the cost optimization was shifted towards a zero-defect policy. Successful quality and production management concepts such as the Toyota Production System respectively lean management which target the minimization of waste and also Six Sigma which main focus is to reduce variation, were the results. Ever since the successful introduction of these principles for an optimized production the scope of quality management was extended to the entire organization. After the expansion of the zero defect philosophy to product development, total quality management concepts address issues within the entire organization today. [2] [3]

### 1.2 The Development of Production Theory

During the industrial revolutions and the development of quality management philosophy and concepts, production theory has tried to give answer how transformation processes are conducted and to provide suggestions for the management how to evolve the production system.

First attempts to develop a production theory emerged in the 18th century when Turgot developed his law of diminishing returns. Ever since, production theory has been matter of various scientists developing quantitative models in order to describe the transformation processes in manufacturing enterprises. Production theories became more powerful and complex, releasing the models' constraints and adding various aspects such as dynamic production functions, or production planning and scheduling [4] [5].

Nowadays production managers are using these theories to optimize production systems and to make the right decisions especially in case of changes and internal or external disturbances. Mathematical models and heuristics have been implemented and are operating inside ERP and PPC systems.

### 1.3 The Need for a Quality Oriented Production Theory

As for the older history of quality management production theory has developed taking emphasis on the logistical point of view. That is, production theories put focus on the description and optimization of production processes describing the transformation of producer and industrial goods to products, by products or wastage [6] [7] [8]. For modern quality concepts and philosophies such as total quality management, the Kano-Model, or the loss function introduced by Taguchi, production theories are rather insufficient since they are hardly connected with the customer satisfaction but with the logistical transition of products. While the aspect of the efficient transformation of materials via technologies to products is covered by production theory the question about a quantitative model describing the transformation of requirements is left open. Therefore current decisions of quality managers are often based on heuristic models and personal experience. A quantitative model showing the direct impact of successful quality management methods such as QFD, FMEA, SPC, complaint and failure processes is essential for a successful product realization.

Despite existing theories in production engineering a quality oriented theory has to give answer to the central question:

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- ***How can a quality oriented production theory support the structural decisions and quality policies of management in product realization processes?***

In order to answer the research question a quality oriented production theory has to consider both – structure and behavior – of a realization system. Hence it will contain an organizational and systemic concept approach.

## 2 STRUCTURAL CONCEPT OF A QUALITY ORIENTED PRODUCTION THEORY

Instead of highlighting the value chain which examines the flow of the value stream the framework model of a quality oriented production theory has to be developed based on the flow of customer requirements through the transformation processes to ensure the customer orientation of products. Schmitt discusses the differences and commonality of modern quality management models in [9]. With its constituting elements based on the philosophy of entrepreneurial quality the Aachen Quality Management Model serves as a perfect framework for the description of requirement transformation processes.

### 2.1 The Aachen Quality Management Model as a Framework for the Process Structure

The Aachen Quality Management Model shown in Fig. 2 provides a scope of action, which allows the design of entrepreneurial quality management for a company by considering strategic objectives, entrepreneurial conditions, resources and product life cycles [10]. The constituting elements of the Aachen Quality Management Model are Market, Management, Quality Stream and Resources & Services.

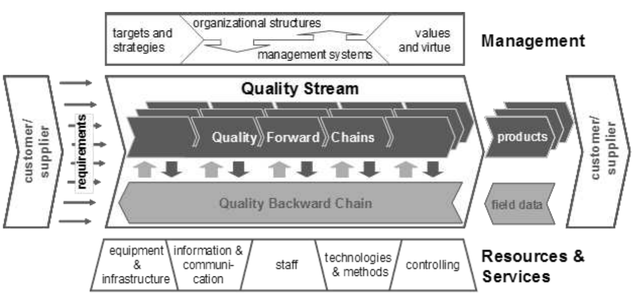


Figure 2: The Aachen Quality Management Model.

Referring to the transformation processes of a company the Quality Stream serves as core element of the model. The unique outline of the Quality Stream consists of two structural elements: the Quality Forward Chains and the Quality Backward Chain.

The Quality Forward Chains describe the transition of requirements over verifiable specifications to develop and produce products in product realization processes. Hence, they should not only be interpreted as the value chain, but also reflect the different states of the products within the product development and production processes.

The Quality Backward Chain works as the central feedback mechanism organizing reactive and corrective actions for all processes and product groups. Hence the Backward Chain combines four major quality management processes which are also highlighted in the ISO 9001 model (chapter 8) and are often referred to as quality (control) loops [11]:

- complaint process
- failure and problem management process
- technical change management
- continuous improvement process

### 2.2 The Cybernetic Concept of Production Systems as a Framework for the Organization Structure

While the Aachen Quality Management Model puts focus on the structure of horizontal process integration a suitable management model for the organization structure has to be defined to consider the vertical process integration. The field of cybernetics and control theory can provide these models. The detailed structure which is invariant of control mechanisms is based on the architecture of cascading and recursive control loops [12] [11] [14].

This structure is always characterized by the operative system. The operations are controlled by a meta system giving plans and policies to the operative units while receiving data and extracted information. These systems are hierarchical meaning the meta system has authority to give directives [12].

Figure 3 provides illustrates a framework model using a cybernetic approach. According to Dyckhoff production theory provides the management a model in order to plan and control the operative transformation system [6].

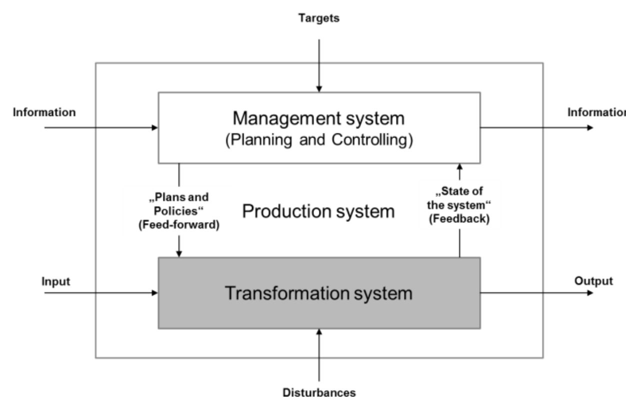


Figure 3: Cybernetic concept of a production systems [6].

### 2.3 The Generic Structure of the Organization Concept

In order to define an organizational concept for the quality oriented production theory the horizontal and vertical framework are merged. That is, the Aachen Quality Management Model is used to describe the process structures and cause-and-effect chains, while the cybernetic control system will help to differentiate managerial from operational processes. Hence, a generic process model for the description of the quality oriented production theory is developed first. Second, the tasks of the meta system are designed.

#### A GENERIC MODEL FOR PRODUCT REALIZATION PROCESS

As the Quality Forward Chains contain by definition all quality oriented processes of an organization (e.g. also human resources, strategy planning, budgeting) the scope of the model has to be focused towards the processes connected to the transformation of customer requirements to productsproduct characteristics. These product realization processes typically combines the major business processes of producing companies – product development purchasing and production – often containing many of the companies' core competencies. The four processes of the Quality Backward Chain are highly connected to the product realization processes causing changes and iterations within the process model.

Hence the architecture and structural interaction of these processes have to be defined.

In order to define processes in product realization reference models (e.g. SCOR model in supply chain management and purchasing, V-Model in Software- and Systems Engineering, Value Chain and Value Stream Mapping in production management, spiral model and the stage-gate model for product development processes) were introduced and can be mapped to the specific processes of a company. Nevertheless the models are reductionist by focusing the matter of their correspondent domain and are therefore hard to integrate: While the V-Model for example is an agile and highly iterative approach the stage-gate process model is a rather plan oriented model putting activities into formalized process steps. Hence a concept for the integration of the models is needed.

A generic reference model for the description of product realization for customer satisfaction can be derived using the essence and selected aspects of existing models. Especially the V-Model could serve as a basic element if rescinded from software and system development to the entire product realization. As Figure 4 shows, the processes for each level of the product contain a specification and verification phase. The implementation happens right between these steps meaning the verification/ validation of each level is based on the written specification of that level.

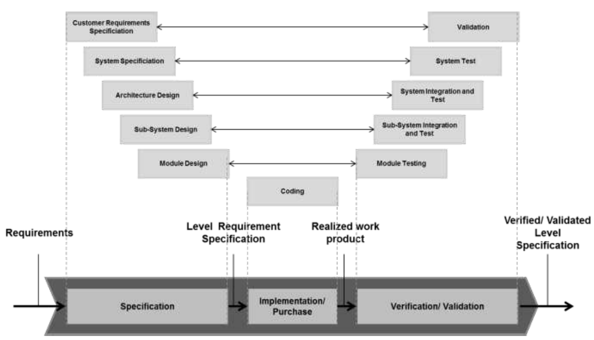


Figure 4: Rescinding the V-Model shape to a reference model for product realization processes.

Reviewing the tasks within the product realization they always contain

- a specification phase where requirements are collected evaluated and specified,
- an implementation phase where the requirements are realized either in-house or via purchasing and
- a verification/ validation step where the specifications are tested according to the test strategies on different levels and for each involved discipline.

Being a generic model for the entire product realization this model has to be applicable to product development, purchasing and production processes:

The milestones and quality gates of stage-gate processes have to be defined referring to the level of the prototypes. Each level prototype release will mark the synchronization point of the iterative product and system development process. The iteration itself should not be intercepted by further quality gates.

Moreover the model can be also employed in production: Within the given philosophy of the transformation of requirements over specifications to tested products a production process alters a product, components or parts according to its defined set of specifications: To give an example, an assembly process integrates a product/ system/ subsystem according to its specified architecture. The verification takes place in the on- and offline assembly tests where the success of the alteration of the product according to its specification is tested.

In the sense of the spiral model the iterative character of the V-Model is a concept of great importance. These iterations within a product realization system can be explained by the quality loops.

## THE QUALITY LOOP PROCESS

All the reactive quality processes – technical complaint, failure and change – and the continuous improvement process can be described using the model of quality control loops [15] [16] [17] [18] [19]:

All control loops contain three phases:

- the sensor: where changes/ problems or complaints are recorded and analyzed,
- the controller: where the proposals are approved/ rejected and prioritized and
- the actuator: where the adaption within the product realization is described

## INTEGRATION OF THE PROCESSES

The three quality loop processes have in common that they are directly linked to the product realization. While the trigger of the failure and problem process is located in the focused product realization process element itself, the other processes are triggering from upstream (change) or downstream (complaint). Each process is causing an adaption of the specifications. Repair and claim processes shall not be considered here since they do not give direct feedback to the product realization. Note that these aspects are critical for logistical process models and production theories since the logistical transition of goods is effected.

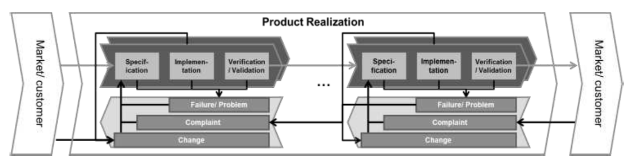


Figure 5: The architecture of a product realization system in the in the framework of the Aachen Quality Management Model.

## MODELING THE METASYSTEM

Cybernetic models such as the Viable Systems Model (VSM) give a detailed design of the different management functions within the meta system [20]. The model contains a normative, strategic and tactical management level.

Tactical management (management of reality): While the tactical level describes the management of each of the process steps within the architecture of product realization and feedback processes the meta systems' architecture can again be designed using the structure of control loops as blueprints.

Strategic management (management of capability): The tasks of the strategic management is the control, decision-making and adaption of the focused operative system – the product realization system. Hence, the strategic management defines the policies and distributes capital within its means in order to keep the realization process working or improve their performance.

Normative Management (management of potentiality): The normative management executes the planning of the strategic management processes. That is, it provides additional capital and resources in case of disturbances and is responsible for the long term development of the product realization activities (potentiality).

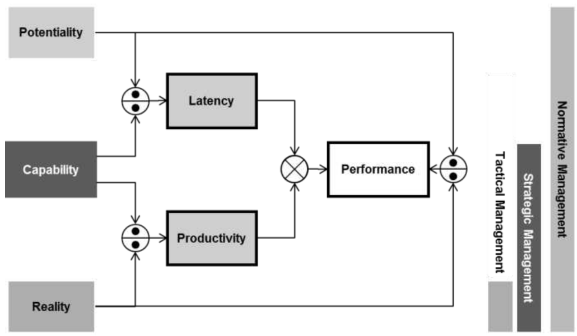


Figure 6: Three measures of achievement for the three levels of management [20].

## 3 BEHAVIORAL CONCEPT OF A QUALITY ORIENTED PRODUCTION THEORY

After the structure of the product realization system has been set up, the behavior of these processes has to be modeled. Following a system and control theoretical approach a central control parameter needs to be identified which can integrate the process flows of the model before the simulation model is constructed.

### 3.1 Identification of the Central Control Parameter

While existing logistical production theories are describing the flow within the value-chains using countable parts/ components and products referring to the bill-of-material (or other material oriented parameters such as volume or weight for process and chemical engineering description) a new central control variable for customer satisfaction has to be defined.

Quality management models like the ISO 9001 and the Aachen Quality Management Model define the customer satisfaction being the overlap of customer requirements with realized product characteristics (influenced by operations and management according to the extended philosophy of entrepreneurial quality) [19]. Hence, from the perspective of customer oriented quality management the requirements are flowing through the transformation processes instead of focusing the physical product transformation as shown in Fig.4.

In order to define the requirements flow as an elementary variable for product realization processes and quality control loops has to be normalized to a common unit which allows the calculation of the contribution and interactions of the processes for the simulation model of the production theory. To count requirements within the unit of logistical production theories (in pieces) does not contribute to the fact that requirements can severely differ from each other and are not equal in complexity. Hence we suggest “time units” as the central unit for the control variable giving

1) the opportunity to weight requirements/ specifications according to their complexity, and
2) providing an ideal interface for cost models where costs can be calculated in dependence of operating time units.

Therefore the time weighted requirements/ specifications will serve as the new central controlled value of the product realization system.

The new variable has to be reflected considering the reality of realization processes:

In product development, project managers are generating project plans where they plan the length of the tasks according to the time consumption of the activities and the available capacity. That is, the project managers are already estimating the time consumption of characteristics/ specifications in the defined tasks.

In production the time for the implementation and verification (testing) of a product can be calculated as the process throughput time, being the time a process needs to alter a part to a given set of specifications.

Following a deductive research methodology two hypothesis can be conducted for the validity of the system parameter:

- Time weighted requirements/ specifications can serve as the central variable for product realization process simulation!
- The time consumption of requirements/ specifications implementation and validation can be calculated analytically!

### 3.2 Simulation of Product Realization Processes

In earlier publications concerning the analysis of the dynamic behavior of realization processes quality control loops were frequently modeled as the controller of the controlled system itself [15] [18]. For the new designed system of the production theory the quality control loops are part of the control system itself. Due to their feedback character they are creating additional dynamics and oscillation in the product realization.

**BUILDING THE SIMULATION ENVIRONMENT**

In order to simulate the systems behavior the method of system dynamics is used [21]. The elementary architecture of the model is based on the model of the rework cycle [22].

**The Product Realization Process Module**

Fig. 7 illustrates the architecture of the model. The transformation process is shown in light grey. All parameters in rectangles are representing stocks (the integral of the run in and run off flows) while the bold dark arrows illustrate the flow.

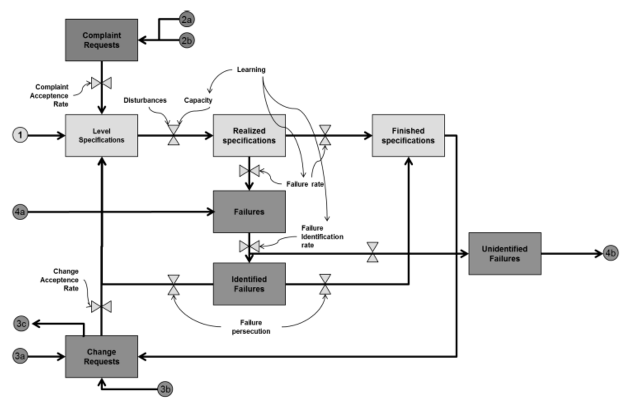


Figure 7: Product Realization System Module.

The system variables are controlling control the flow rates and reduce or an increase the level of stocks. The model assumes that in connector 1 level specifications enter the realization process step (the transformation of requirement specifications to level specifications can either be understood as part of the stock itself or be modeled as a separate realization system module). The overall capacity of the realization is influenced by learning and occurring process disturbances. Once the specifications are realized they tentatively enter the failure loop.

**The Failure Process Module**

First a fraction of failures is set to the stock of realized specifications. The elementary failure model assumes the alpha error to be zero (correct realized specifications are never recognized as defects) while beta errors are either identified or unidentified depending on the failure identification rate. All identified failures pass a decision step where the rate of failure persecution decides about the fraction of failures that have to be reworked. The model does not contain a separate process for the specifications which need to be reworked (this would mean to construct another realization system model recursively, integrating the elementary model in itself). Instead the defect specification reenters the stock of level specifications and thereafter the flow of the realization.

**The Complaint Process Module**

Complaints can arrive from external customers (2a) or from downstream processes which may find a fraction of the undiscovered failures. The complaint management decides about the acceptance of complaints. Accepted complaints enter the system as additional level specifications which have to be realized (again).

**The Change Process Module**

Change Requests can enter the model via three possible triggers 3a – change request coming from the customer – and 3b – change requests arriving from downstream process elements and change requests according to finished specifications. The change acceptance takes credit to the decision of the complaint process management to accept the change requests and let them enter the system or to deny the change requests. It can also happen that a change request is sent to an upstream process (connector 3c): The change request will enter the upstream element where the decision of the acceptance is made.

**Integration of Realization Systems**

With the help of the connectors different realization process steps can be connected in a modular way. The sequence of the processes can be controlled using a switch for the initiation of the second process. The value of the switch can be set between zero and one which is a measure for the overlap rate of the two processes. If the switch is set to 0,2 the resulting overlap rate between the processes is 80%. That is the second process can start simultaneously to the first after the finished specification of the first step have reached a value of 20% of the overall level specification

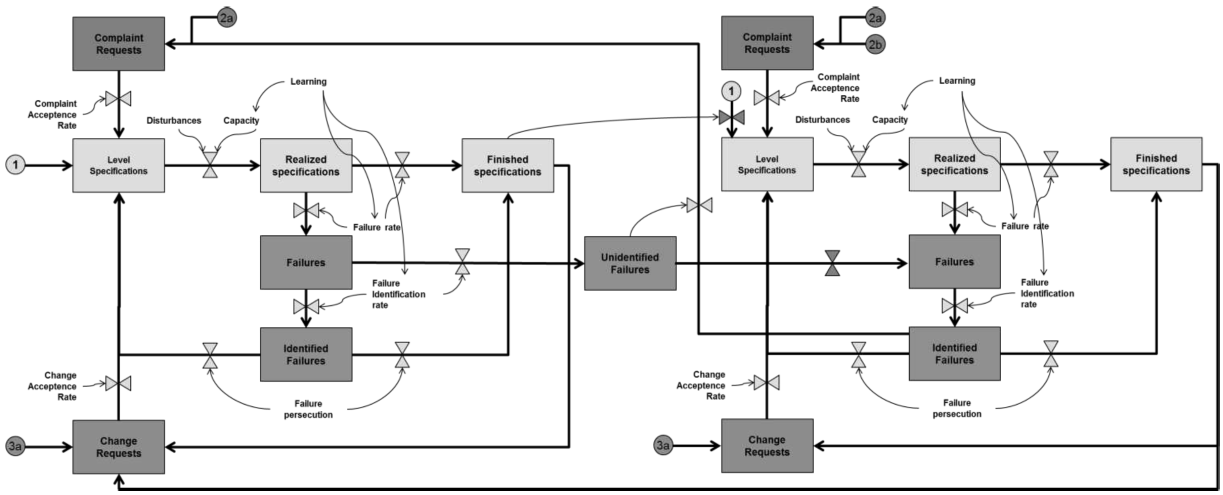


Figure 8: Two-stage Realization Process Model.

**THE SYSTEM BEAHVIOR**

The behavior of the system can be estimated using the structure of the model shown in the causal loop diagram in Figure 9.

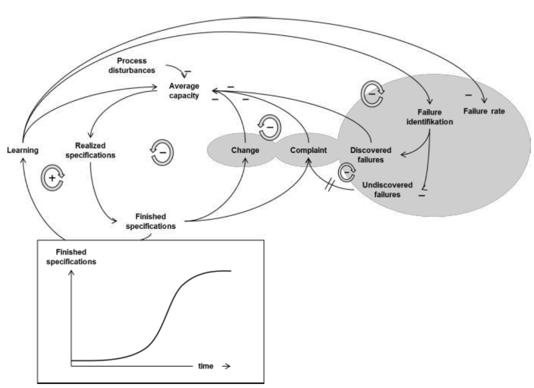


Figure 9: Causal loop diagram of a Product Realization System.

According to the defined fundamental modes in system dynamics [21] shown in Figure 10 the model has a non-linear behavior and can be characterized by an s-shaped growth.

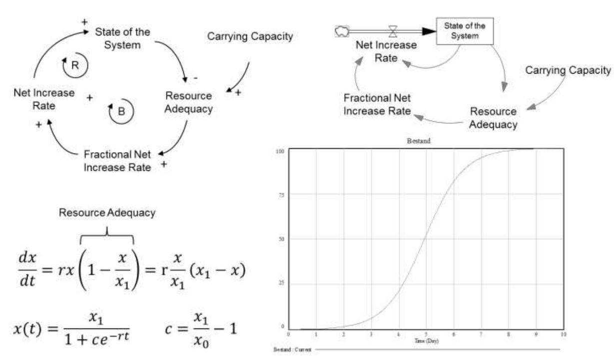


Figure 10: S-shaped growth: structure and behavior [21].

Depending on the severance of the delay by returning undiscovered failures the pattern can also have an oscillating overshot.

The parameterization with realistic data from product realization confirms the pattern. According to the sensitivity of the parameters the strategic and tactical management can decide where to improve the process in order guarantee the efficient allocation of resources for process optimization.

The alteration of the parameters show the effect on the s-curve of finished specifications. If learning or capacity is increased the function is shifted to the left, while the increase in failure rate, failure identification rate, failure persecution, change and complaint acceptance rate, are causing additional delays.

## 4 CONCLUSION

A quality oriented production theory can give answers to the managers of realization processes where to invest for a more effective and efficient transformation of customer requirements.

Using a deductive analytical approach the structure and behaviour of a quality oriented production theory was developed and has proven feasibility to the first parameterization.

The further implementation of the model will proof the feasibility of the theory. Therefore a standard methodology has to be developed in order to estimate the time consumption of the specification, implementation and verification/ validation in advance.

Moreover the development of the product realization system model shall be continued. The differentiation of alpha and beta errors will be introduced and the parameters will be connected to given quality management methods such as QFD, FMEA, or SPC.

## 5 ACKNOWLEDGMENTS

The support of the German National Science Foundation (Deutsche Forschungsgemeinschaft DFG) through the funding of the graduate program “Ramp-Up Management – Development of Decision Models for the Production Ramp-Up” and the Cluster of Excellence “Integrative Production Technology for High-Wage Countries” is gratefully acknowledged.

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# A Mathematical Model for Supply Chain Planning in a Build-to-Order Environment

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**Abstract**

Since the earliest attempts of addressing the problem of developing a coordinated link in a supply chain (SC) in 1959, managing SC performance has been a main challenge among enterprises. Supply chain planning (SCP), as one of the most important processes within the supply chain management (SCM) concept, has a great impact on firms' success or failure. In this paper, a mathematical model for planning a SC of a computer accessory manufacturing company operating in a build-to-order (BTO) environment is developed. The developed multi-product, multi-period, multi-echelon mixed-integer linear programming model is then solved using CPLEX optimization studio and guidance related to future areas of research is given.

**Keywords:**

Build-to-order; Mixed-integer programming; Supply chain planning

## 1 INTRODUCTION

A supply chain (SC) is an integrated process in which a group of several organizations, such as suppliers, manufacturers, distributors and retailers, work together with both a forward flow of materials and a backward flow of information, to acquire raw materials with a view of converting them into final products, and deliver the final products to the customers [1]. Today, individual firms compete as an integral part of supply chain link rather than independent entities with unique brand names [2]. Thus, a firm's success is greatly influenced by its managerial ability to integrate and coordinate the complicated network of its business relationship among SC members.

One of the most important processes within the supply chain management (SCM) concept is the supply chain planning (SCP) process which is about the coordination and integration of key business activities undertaken by an enterprise, from the procurement of raw materials to the distribution of final products to the customers [3]. In today's competitive environment, manufacturing companies are facing with rapidly changing market condition and customer expectation, which leads the build-to-order (BTO) supply chain strategy to receive more attention. BTO supply chain is a productions' strategy in which production activities are not performed until orders are received from customers. This characteristic helps companies to effectively reduce the cost of demand prediction while keeping product inventory holding cost and delivery lead time at the lowest possible amount.

Agility is an emerging term which implies a certain relation between a company and its market. Indeed, agility is a set of abilities for meeting widely varied customer requirements in terms of price, specification, quality, quantity and delivery [4]. Thus, agile manufacturing relates to companies coping with volatile market demand by allowing changes to be made in an economically viable and timely manner [5]. Although a significant amount of research has been conducted in the area of SCP, the literature is largely lacking in providing an analytical model to solve the problem of agile manufacturing operating in a BTO environment. Moreover, it lacks the consideration of different echelons in a whole supply chain.

In an attempt to fill this gap, a mathematical model for mid-term supply chain planning of an agile manufacturing company operating in a BTO environment is developed. The main aim of this study is to formulate an innovative mathematical model for multi-product, multi-period, multi-echelon supply chain planning of a BTO system which integrates suppliers, manufacturers, distribution centers, and customer zones using the mixed integer linear programming (MILP) approach. According to the literatures, this is one of the first research conducted on SCP problems of agile manufacturing in a BTO environment.

The structure of this paper is described as follows. Literature review of SCP and BTO supply chain is presented in section 2. Section 3 provides the mathematical model for BTO supply chain problems. An illustrative case study related to the proposed model and the optimal results obtained are provided in section 4. Conclusions and future research avenues are drawn in section 5.

## 2 LITERATURE REVIEW

In this section, previous literature of SCP for make-to-stock (MTS) systems and BTO supply chains is reviewed.

### 2.1 Supply chain planning (SCP)

Successful SCM requires an integrated and coordinated process planning among different stages. There are various studies in the area of SCP. One of the first attempts on developing an integrated production plan and schedule for a manufacturing chain was conducted by [6]. The authors determined the optimal amount of assets that should be allocated to the particular production tasks through formulating a mixed-integer linear programming model, dealing with both mid-term tactical and short-term operational decision levels. Authors in [7] developed a fuzzy mathematical programming model to solve a multi-product, multi-echelon, and multi-period SC problem with fuzzy parameters considering the objective of minimizing total SC cost. A mixed integer linear goal programming (MILGP) model for an integrated multi-objective procurement, production and distribution problem was developed by [8]. The authors proposed different time-grids and planning horizons for aggregate and detailed planning with the objective of minimizing the total cost deviation. In [9], the authors developed a fuzzy multi-objective, multi-product, and multi-period linear programming model to deal with collaborative production-distribution planning problems with the aim of minimizing retailing cost, while maximizing total profit. However, models proposed by the above authors are exploited for supply chains operating in a MTS environment.

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DOI: 10.1007/978-3-319-02054-9_53, 

### 2.2 BTO Supply Chain

Adoption of build-to-order (BTO) manufacturing strategies in the marketing function has been increasingly applied in a large variety of industries, from car manufacturing to computer accessories to furniture. Authors in [4] conducted a survey on examining the concepts of agility, adaptability and leanness in terms of their relationship overall purpose and characteristic in the Japanese manufacturing industry. Researchers in [10] investigated the impact of reducing the lot size and developing a communication system in a furniture manufacturing company considering the concept of agile manufacturing. In [11], the authors presented a mathematical model to investigate the effect of integrating different supply chain strategies, namely build-to-stock (BTS) and build-to-order (BTO) on the actual business environment. Researchers in [12] studied the influence of adopting the BTO strategy on manufacturing and marketing cycle. The authors identified the most adaptable industries in which the BTO strategy can be successfully adopted.

Examining the relationship between buyer and supplier in a BTO supply chain, [13] conducted a survey on different reaction strategies undertaken by suppliers in response to short-term schedule changes in a microcomputer manufacturing company. An empirical investigation on significant differences between MTS and BTO environments was conducted by [14]. The authors also made a comparison between BTO environments in developed countries and those in the developing world. Authors in [15] developed a fuzzy mathematical programming model of integrated production-distribution planning for a multi-echelon, multi-plant and multi-product SC operating in a BTO environment. They considered the objective of minimizing the total operating cost, while improving the level of customer service through providing the possibility of product customization and on-time delivery. Researchers in [16] developed a multi-objective mathematical formulation to model SCP in a BTO environment, with the aim of minimizing total cost and time, while maximizing product quality as evaluation criteria. Authors in [17] formulated a two-phase mixed integer linear programming (MILP) model for a procurement, production, and distribution scheduling problem of a SC operating in a BTO environment. With the objective of minimizing the total operating cost, the authors presented a modified genetic algorithm (GA) approach to solve the proposed model. As illustrated in the literature review, researchers employed various methods and techniques to solve the SCP problem over different planning horizons, although some of them have not completely considered the problems encountered by agile manufacturing in a BTO environment. Making a trade-off among different conflicting objectives such as minimizing the overall operating cost, while maintaining customer service performance was completely ignored by some of the previous researchers. In this paper a multi-product, multi-period, multi-echelon BTO supply chain is considered for analysis. We propose a MILP model for an integrated procurement, production, and distribution plan of customized products in an agile BTO manufacturing system.

## 3 MODEL FORMULATION

In this paper, a SC network consisting of suppliers, manufacturing plants, distribution centers, and customer zones is considered. In general, the BTO supply chain operates as a demand satisfying strategy of supply chains that are involved in assembling customized products. In the proposed BTO system, common component parts are fabricated based on a short term forecast of customer demands, while final customized products are produced after receiving confirmed demand orders. The main aim of the proposed model is to determine the procurement plan, production plan, inventory level, transportation plan, and backorder amounts in each time period of the planning horizon for each echelon included in the supply chain. The objective of the developed model is to minimize the overall operating cost while maintaining the desired customer service level. The model is developed for companies that benefit from the advantages of being agile to the diversified customer preferences for products. Agility, which is a combination of flexibility and responsiveness, is a vital need for those manufacturing companies that want to increase their market share and survive over their competitors. Satisfying various customer demands at the shortest possible time while showing quick responses to changing market conditions cause manufacturing plants to produce standard parts and components based on anticipated demands of historical data. However, customized products will not be produced until the final demands are revealed with certainty.

### 3.1 Nomenclature

The following notations and parameters are used in the formulation of the model.

### 3.2 Objective Function

In this research, a single-objective function of minimizing the total SC operating cost is developed, while maintaining the desired customer service level.

$$RC = \sum_t \sum_r \sum_v \sum_f RC_{rvt} \cdot RTQ_{rvft}$$

$$PC = \sum_t \sum_n \sum_p \sum_f \left(NGC_{nft} \cdot NGQ_{nft} + NOC_{nft} \cdot NOQ_{nft} + GC_{pft} \cdot GPQ_{pft} + OC_{pft} \cdot OPQ_{pft}\right)$$

$$T_sC = \sum_t \sum_r \sum_v \sum_f RTC_{rvft} \cdot RTQ_{rvft}$$

$$I_rC = \sum_t \sum_r \sum_f RHC_{rft} \cdot RIL_{rft}$$

$$I_nC = \sum_t \sum_n \sum_f NHC_{nft} \cdot NIL_{nft}$$

$$T_pC = \sum_t \sum_p \sum_f \sum_w WTC_{fwt} \cdot WTQ_{pfwt}$$

$$I_pC = \sum_t \sum_p \sum_w PHC_{pwt} \cdot PIB_{pwt}$$

$$T_wC = \sum_t \sum_p \sum_c \sum_w PTC_{cwt} \cdot PTQ_{pcwt}$$

$$BC = \sum_t \sum_p \sum_c BC_{pct} \cdot BQ_{pct}$$

$$Min\ Total\ Cost = Min\ Z = Min \sum \left(RC + PC + T_sC + I_rC + I_nC + T_pC + I_pC + T_wC + BC\right) \quad (1)$$

The total operating cost $Z$ shown in (1) consists of nine aggregate cost components that exist in each of the supply chain actors such as raw material supply, transportation, and storage costs, regular time and overtime cost of production, product inventory holding cost, transportation cost, and shortage penalty cost.

**Indices**

v suppliers, $v = 1,2,\ldots,V$

r raw materials, $r = 1,2,\ldots,R$

f plants, $f = 1,2,\ldots,F$

n component parts, $n = 1,2,\ldots,N$

p final products, $p = 1,2,\ldots,P$

w distribution centers, $w = 1,2,\ldots,W$

c customer zones, $c = 1,2,\ldots,C$

t time periods, $t = 1,2,\ldots,T$

**Parameters**

$D_{pct}$ Demand of product p in CZ c in period t.

$RC_{rvt}$ Cost of purchasing raw material r from supplier v in period t.

$\gamma_{nr}$ Quantity of raw materials r required to make a unit of component n in period t.

$RTC_{rvft}$ Transportation cost of raw material r from supplier v to plant f in period t.

$RHC_{rft}$ Inventory holding cost of raw material r at plant f in period t.

$NGC_{nft}$ Regular time fabricating cost of component n at plant f in period t.

$NOC_{nft}$ Overtime fabricating cost of component n at plant f in period t.

$NHC_{nft}$ Inventory holding cost of component n at plant f in period t.

$\mu_{pn}$ Quantity of component n required to assemble a unit of product p.

$GC_{pft}$ Regular time production cost of product p at plant f in period t.

$OC_{pft}$ Overtime production cost of product p at plant f in period t.

$WTC_{fwt}$ Product transportation cost from plant f to DC w in period t.

$PHC_{pwt}$ Inventory holding cost of product p at DC w in period t.

$PTC_{cwt}$ Product delivery cost from DC w to CZ c in period t.

$BC_{pct}$ Backorder cost of product p occurred at CZ c in period t.

$Plt_{vf}$ Procurement lead time from supplier v to plant f in period t.

$NPt_{nf}$ Required processing time to fabricate component n at plant f.

$GNU_{ft}$ Regular time fabrication capacity of plant f in period t.

$ONU_{ft}$ Overtime fabrication capacity of plant f in period t.

$PPt_{pf}$ Required production time to assemble product p at plant f.

$GPU_{ft}$ Regular time production capacity of plant f in period t.

$OPU_{ft}$ Overtime production capacity of plant f in period t.

$RL1_{r}$ Initial inventory level of raw material r at plant.

$RSU_{rvt}$ Maximum capacity of supplier v to supply raw material r in period t.

$RIU_{rft}$ Maximum inventory capacity of plant f to stock raw material r in period t.

$NIU_{nft}$ Maximum inventory capacity of plant f to stock component n in period t.

$PIU_{pwt}$ Maximum inventory capacity of DC w to carry product p in period t.

$\pi_{pc}$ Minimum allowable demand fulfillment rate of product p at CZ c.

**Decision Variables**

$RTQ_{rvft}$ Quantity of raw material r supplied by supplier v for plant f in period t.

$RIL_{rft}$ Inventory level of raw material r at plant f at the end of period t.

$NGQ_{nft}$ Quantity of component n produced in regular time at plant f in period t.

$NOQ_{nft}$ Quantity of component n produced in overtime at plant f in period t.

$NIL_{nft}$ Inventory level of component part n at plant f at the end of period t.

$GPQ_{pft}$ Quantity of final product p produced on regular time at plant f in period t.

$OPQ_{pft}$ Quantity of final product p produced on overtime at plant f in period t.

$WTQ_{pfwt}$ Quantity of product p shipped from plant f to DC w in period t.

$PIB_{pwt}$ Inventory balance of final product p at DC w at the end of period t.

$PTQ_{pcwt}$ Quantity of product p delivered to CZ c from DC w in period t.

$BQ_{pct}$ Quantity of backordered product p incurred at CZ c in period t.

### 3.3 Constraint

The constraints involved are also set out in equations (2) to (18).

$$RIL_{rft} = RIL_{rf,t-1} + \sum_v RTQ_{rvf,t-Plt_{vf}} - \sum_n \gamma_{nr}\left(NGQ_{nft} + NOQ_{nft}\right) \quad \forall r,f,t \quad (2)$$

$$NIL_{nft} = NIL_{nf,t-1} + NGQ_{nft} + NOQ_{nft} - \sum_p \mu_{pn}\left(GPQ_{pft} + OPQ_{pft}\right) \quad \forall n,f,t \quad (3)$$

$$PIB_{pwt} = PIB_{pw,t-1} + \sum_f WTQ_{pfwt} - \sum_c PTQ_{pcwt} \quad \forall p,w,t \quad (4)$$

$$\sum_f RTQ_{rvft} \le RSU_{rvt} \quad \forall r,v,t \quad (5)$$

$$\sum_n NPt_{nf} \cdot NGQ_{nft} \le GNU_{ft} \quad \forall f,t \quad (6)$$

$$\sum_n NPt_{nf} \cdot NOQ_{nft} \le ONU_{ft} \quad \forall f,t \quad (7)$$

$$\sum_p PPt_{pf}.GPQ_{pft} \le GPU_{ft} \quad \forall f,t \quad (8)$$

$$\sum_p PPt_{pf}.OPQ_{pft} \le OPU_{ft} \quad \forall f,t \quad (9)$$

$$RIL_{rft} \le RIU_{rft} \quad \forall r,f,t \quad (10)$$

$$NIL_{nft} \le NIU_{nft}. \quad \forall n,f,t \quad (11)$$

$$PIB_{pwt} \le PIU_{pwt}. \quad \forall p,w,t \quad (12)$$

$$\sum_f \left(NGQ_{nft} + NOQ_{nft} + NIL_{nf,t-1}\right) \ge \sum_{p,c}\left(D_{pct}\right)\mu_{pn} \quad \forall n,t \quad (13)$$

$$\sum_w WTQ_{pfwt} = GPQ_{pft} + OPQ_{pft}. \quad \forall p,f,t \quad (14)$$

$$\sum_c PTQ_{pcwt} = \sum_f WTQ_{pfwt}. \quad \forall p,w,t \quad (15)$$

$$\sum_w PTQ_{pcwt} + BQ_{pct} = BQ_{pc,t-1} + D_{pct}. \quad \forall p,c,t \quad (16)$$

$$BQ_{pct} \le \left(1-\pi_{pc}\right) \cdot D_{pct}. \quad \forall p,c,t \quad (17)$$

$$RTQ_{rvft}, RIL_{rft}, NGQ_{nft}, NOQ_{nft}, NIL_{nft}, GPQ_{pft}, OPQ_{pft}, WTQ_{pfwt}, PIB_{pwt}, PTQ_{pcwt}, BQ_{pct} \ge 0, \quad \forall t \quad (18)$$

Equations (2), (3), and (4) represent the inventory balance constraints of raw materials, component parts, and final products, respectively. The supply capacity constraint of raw materials is stated in (5) and (6), (7), (8), and (9) determine the production capacities of plants for components and final products.

Equations (10) and (11) show the inventory capacity constraints at a plant for raw materials and components. Product inventory capacity constraint at a distribution center is stated in (12). Equations (13) to (16) are demand satisfaction constraints. Equation (13) is to maintain the flexibility of the entire chain by fabricating components based on a short-term forecast of final product demands. Capturing the advantage of the BTO strategy, (14) is to eliminate the cost incurred for storing finished products at plants. Equation (15) is to maintain the level of responsiveness in the system through delivering final products to CZs in the same period when they are being received by DCs. Equation (16) determines the volume of backordered products in each period. Equation (17) maintains the desired customer service level through restricting the quantity of backorders in order not to exceed the allowable customer demand non-fulfillment level requirement. Finally, (18) ensures that all of the decision variables are non-negative.

## 4 COMPUTATIONAL RESULTS AND DISCUSSION

To illustrate the effectiveness of the proposed model, a case study related to a computer accessory manufacturing company operating in a BTO environment is considered. The company is working in a BTO environment taking the strategy of being agile to the changing market demand into consideration. To this end, flexibility and responsiveness are jointly considered in the entire chain in order to be able to quickly respond to volatile customer demand. The presented BTO supply chain network consists of three suppliers, two manufacturing plants, two distribution centers (DCs), and four customer zones (CZs). All suppliers are capable of providing various types of required raw materials for manufacturing plants. Each manufacturing plant fabricates seven types of component parts in its fabrication shop. Component parts are accumulated in stock at manufacturing plants to form three types of final assembled products according to order specifications. The finished products may be produced at any of the two manufacturing plants and shipped to any of the two distribution centers. Three different models of keyboards are considered as final products which are assembled from seven different component parts, which in turn are fabricated from seven types of raw materials. The planning horizon for this problem is taken to be 12 periods. Taking the advantages of the BTO strategy, product samples are displayed in customer zones in order to provide the capability of selecting the desired products, through product catalogues, for the customers. Customer zones are the market outlets from which final products are sold to customers and new orders are passed to assemblers. Assembly orders are placed in customer zones based on customer requisitions. Customized products are sent directly to DCs, after they are completed. Each DC collects the final products from the assembly plants and distributes them to the respective customer zones.

Computation is run using IBM ILOG CPLEX optimization studio 12.4. Tables 1 to10 provide an insight into the output data characteristics.

In Table 1*, the blank cells similar to other unreported relevant data are equal to 0, which means no optimal supply is suggested for that particular period. As depicted in the table, it is mostly suggested for the plants to obtain the raw materials from the third supplier due to lower procurement cost, except for raw material four and six, for which there is no cost advantage in purchasing from the third supplier (global supplier) whereas it can be supplied by the local supplier at a lower price. In order to provide the capability of being agile to the market demand, components are suggested to be stocked at the plants as depicted in Table 2. Besides, final product inventory at plants is not allowed, capturing the advantages of the BTO strategy, thus, it is suggested to stock a high level of components in plants to provide the capability of being agile to the volatile market demand. Generally, more component parts are advised to be stored at the first manufacturing plant due to lower inventory holding costs. The optimal production plans for regular time are shown in Tables 3. It should be mentioned that final products are suggested to be fairly assembled in both manufacturing plants, except for product three which is advised to be almost thoroughly produced at the second manufacturing plant due to the lower production cost involved.Table 4 represents the optimal delivery plan of final products to all customer zones. As elaborately shown, products are delivered to the customer zones in the same period of being transported due to the delivery lead time is not longer than one planning period. The optimal delivery plan for products one and two shows most of the product demands in customer zones one and two are suggested to be satisfied through distribution center one, although distribution center two mainly fulfills the demands of customer zones three and four which indicates lower transportation cost involved. However, for the product three almost all the product demands at all customer

| Raw material *r* | Supplier *v* | Plant *f* | Planning Period *t* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1 | 3 | 1 | | 55 | 267 | 115 | 177 | 19 | 3 | 196 | 190 | 196 | 216 | |
| | | 2 | 136 | 423 | 405 | 339 | 441 | 344 | 425 | 350 | 385 | 383 | 498 | |
| 2 | 2 | 2 | | | | 161 | | 94 | | | 33 | 54 | 57 | 149 |
| | 3 | 1 | | | 201 | 89 | 141 | 14 | 3 | 152 | 148 | 150 | 167 | |
| | | 2 | 41 | 337 | 170 | 258 | 230 | 262 | 312 | 219 | 223 | 221 | 204 | |
| 3 | 1 | 1 | | | | | | | | | | | | 3 |
| | 2 | 2 | | 4361 | 16220 | 16216 | 8474 | 12457 | 2 | | 10 | 13133 | 16217 | 16220 |
| | 3 | 1 | 7657 | 8688 | 17055 | 8996 | 11201 | 1511 | 171 | 14442 | 13423 | 15600 | 16318 | |
| | | 2 | 24783 | 23752 | 15385 | 23444 | 21239 | 30929 | 32266 | 17998 | 19017 | 16840 | 16122 | |
| 4 | 1 | 1 | | | 788 | | | | | | | 369 | 1 | 775 |
| | 2 | 1 | | 632 | 298 | 1997 | 1078 | 1350 | 178 | 21 | 1714 | 1230 | 1837 | 1157 |
| | | 2 | | 3122 | 4818 | 3118 | 3590 | 3766 | 2623 | 4827 | 1940 | 3886 | 3279 | 3959 |
| 5 | 1 | 1 | | | | 1161 | | | | | | | | 850 |
| | 3 | 1 | 43 | 771 | 676 | 1112 | 1039 | 136 | 24 | 1425 | 1404 | 1385 | 711 | |
| | | 2 | 617 | 2916 | 3011 | 2108 | 2649 | 2285 | 2574 | 2135 | 2279 | 2303 | 2976 | |
| 6 | 1 | 1 | | 10212 | 5544 | 18634 | 7776 | 12190 | 1266 | 222 | 13268 | 12878 | 13096 | 14534 |
| | | 2 | | 15764 | 23495 | 10405 | 19840 | 16849 | 21246 | 24274 | 15771 | 16161 | 15943 | 14505 |
| | 3 | 2 | | 3891 | 17511 | | 7913 | | | 3989 | 5261 | 5585 | 13273 | |
| 7 | 3 | 1 | 614 | 1386 | 4320 | 1758 | 2847 | 273 | 54 | 2952 | 2904 | 2826 | 3201 | |
| | | 2 | 5054 | 8059 | 7382 | 6194 | 7211 | 5500 | 7024 | 4764 | 5845 | 5829 | 6784 | |

Table 1: Optimal supply plan of raw material / $\mathrm{RTQ}_{rvft}$. *All the units used in the tables are pieces.

| Component *n* | Plant *f* | Planning Period *t*: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 839 | 624 | | 120 | | | | | | | | |
| | 2 | 438 | | | | | | | | | | | |
| 2 | 1 | 2253 | 1187 | 101 | 120 | | | | | | | | |
| | 2 | 1700 | | | | | | | | | | | |
| 3 | 1 | 67 | 67 | 67 | | | | | | | | | |
| | 2 | 758 | 411 | 970 | 92 | 84 | | | 984 | 54 | 446 | 375 | |
| 4 | 1 | 2012 | 1392 | 603 | 28 | | | | | | | | |
| 5 | 2 | | | 62 | 212 | | | 1429 | 574 | | 3 | 661 | |
| 6 | 1 | 434 | | | | | | | | | | | |
| | 2 | 3 | | | 120 | | | | | | | | |
| 7 | 1 | 6808 | 6188 | 5399 | 4013 | 3613 | 3212 | 3125 | 3122 | 2392 | 1761 | 865 | |
| | 2 | 8118 | 5998 | 4073 | 1511 | | | | | | | | |

Table 2: Optimal inventory plan of component / $\mathrm{NIL}_{\mathrm{nft}}$.

| Product *p* | Plant *f* | Planning Period *t*: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 290 | 275 | 297 | | 306 | 548 | 4 | 15 | 254 | 337 | 46 | 202 |
| | 2 | 194 | 69 | 656 | 2 | | 2 | 927 | 400 | 302 | 111 | 312 | 49 |
| 2 | 1 | 480 | 620 | 789 | 854 | 400 | 401 | 87 | 3 | 730 | 631 | 896 | 865 |
| | 2 | 128 | 2 | 3 | | | | 323 | 727 | 124 | 771 | 332 | 471 |
| 3 | 1 | | | | 66 | | | | | | | | |
| | 2 | 620 | 983 | 808 | 1234 | 1235 | 1028 | 350 | 335 | 930 | 483 | 740 | 788 |

Table 3: Optimal regular time assembly plan of products / $\mathrm{GPQ}_{\mathrm{pft}}$.

| Product *p* | CZ *c* | DC *w* | Planning Period *t*: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 100 | 96 | 297 | | 100 | 200 | 4 | | 74 | 147 | | 92 |
| | | 2 | | 154 | 53 | 250 | | | 246 | | 26 | 3 | 100 | 8 |
| | 2 | 1 | 190 | 350 | | 1 | 120 | 320 | | 15 | 180 | 190 | 46 | 110 |
| | | 2 | | | 540 | 489 | | | 380 | 185 | | | 84 | |
| | 3 | 2 | 90 | 190 | 30 | 80 | 40 | 300 | 140 | 100 | 130 | 50 | 60 | 20 |
| | 4 | 2 | 104 | 219 | 35 | 92 | 46 | 345 | 161 | 115 | 150 | 58 | 69 | 23 |
| 2 | 1 | 1 | 200 | 250 | 300 | 350 | 200 | 200 | | 3 | 400 | 251 | 496 | 350 |
| | | 2 | | | | | | | 200 | 347 | | 199 | 4 | |
| | 2 | 1 | 210 | 370 | 489 | 300 | 150 | 70 | 87 | | 330 | 380 | 400 | 515 |
| | | 2 | | | 1 | | | | 13 | 160 | | | | 5 |
| | 3 | 2 | 90 | 70 | 140 | 272 | 38 | 60 | 50 | 100 | 160 | 260 | 200 | 510 |
| | 4 | 2 | 108 | 84 | 168 | 330 | 12 | 72 | 60 | 120 | 192 | 312 | 240 | 632 |
| 3 | 1 | 2 | 150 | 200 | 250 | 213 | 137 | 50 | | 100 | 200 | 250 | 300 | 400 |
| | 2 | 1 | | | | 67 | | | | | | | | |
| | | 2 | 290 | 400 | 220 | 523 | 420 | 380 | 170 | 190 | 190 | 120 | 170 | 140 |
| | 3 | 2 | 80 | 170 | 150 | 235 | 335 | 300 | 80 | 20 | 240 | 50 | 120 | 110 |
| | 4 | 2 | 100 | 213 | 188 | 310 | 350 | 375 | 100 | 25 | 300 | 63 | 150 | 138 |

Table 4: Optimal delivery plan of product to CZ / $\mathrm{PTQ}_{\mathrm{pcwt}}$.

| Product *p* | CZ *c* | Planning Period *t*: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | | 28 | | | | | | | | |
| 3 | 2 | | | | 37 | | | | | | | | |
| | 3 | | | | 55 | | | | | | | | |

Table 5: Optimal backordering plan at CZ / $\mathrm{BQ}_{\mathrm{pct}}$.

zones are advised to be sent from distribution center two, at which these products are received. Finally, The optimal backordering plan of final products at customer zones is stated in Table 5. As shown, no backordering plan is suggested for the products one and two throughout the planning horizon. This phenomenon is a result of having not enough capacity to fulfill customer demands. However, it is suggested to backorder the third product in the fourth period. It should be noticed that the solution for the proposed mathematical model is not suggesting any assembled product to be stored at distribution centers during the planning horizon, since the transportation lead time between distribution centers and customer zones is within one planning period and a smooth flow of products is maintained in the entire system which removes the need for keeping inventory of assembled products at the distribution centers.

As compared to the current situation, the optimal plan provides more accurate as well as reliable result particularly in the presence of uncertain input parameters. For instance, capturing the advantage of BTO strategy by fabricating common component parts at the manufacturing plants based on a short term demand forecast caused the raw material to be consumed at the same period of being supplied and hence it is not suggested to stock a huge level of raw material as an inventory at plants along the planning periods in the optimal plan, which leads the supply chain to be responsive to the demand changes and exploiting high level of efficiency at the same time. In the optimal component inventory plan, on the other hand, there is no inventory for final product at the manufacturing plants and hence the level of the stock component in the plant is proposed to be high in order to provide the capability of being agile to the uncertain market demand. Other main differences between current practice and the proposed optimal plan is in the recommended production plan. In the optimal plan, final products are suggested to be assembled in the plants with lower fabrication cost, as opposed to the existing system in which the main focus is to evenly assemble products in both manufacturing plants on regular time.

The company captures the advantages of BTO environment through supplying exactly what customer needs which can have a direct influence on reducing cost of sales discount and product inventory holding cost as well as stock obsolescence cost. Customized products can then be sent directly to DCs, after their finishing is completed which leads to a reduced capacity utilization at the manufacturing plant. Moreover, the capability of selecting the desired products, which can be provided through product catalogues at the customer zones, might increase the level of customer satisfaction which in turn causes to enhance the index of customer service level in the whole supply chain. This can increase the customer service level by fulfilling the demand on time and improving the level of responsiveness which is indeed an important factor in agile manufacturing. The obtained value of the objective function Z is equal to 747,318 US Dollars.

## 5 CONCLUSION

In this study, the optimal mid-term planning of a multi-period, multi-product, multi-echelon, supply chain problem consisting of suppliers, manufacturing facilities, distribution centers, and customer zones has been considered. A novel approach for optimizing supply chain planning in a BTO environment has been presented. Particularly, a MILP model has been designed to minimize the overall operating cost while maintaining the customer demand satisfaction. The proposed model can be used to aid the operation of an integrated supplier, manufacturer, distributor, and customer zone network. An illustrative numerical example related to a computer accessory manufacturing operating in a BTO environment also has been considered and solved using CPLEX optimization software to demonstrate the effectiveness of the proposed model.

Several avenues of future research remain open to researchers. One is incorporating other objectives related to supply chain planning, such as lead time minimization and financial risk minimization. Using a combination of efficient analytical and simulation techniques, as a hybrid approach, is also an area for future studies.

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# Strategic Screening of Manufacturing Technologies

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**Abstract**
Manufacturing companies have to keep abreast of established and emerging manufacturing technologies to take advantage of opportunities arising from the application of innovative technologies and to become aware of potential threats. Identifying and keeping track of available technologies at all times is a complex and very time-consuming task. However, in a competitive environment the capability to react to changing conditions quickly is crucial. Therefore, this paper presents an approach called technology screening which combines technology identification and preselection according to the company-specific technology strategy and future manufacturing requirements.

**Keywords:**
Technology Intelligence; Strategic Technology Planning; Technology Life Cycle

## 1 INTRODUCTION

Globalisation of markets, increasing customer demands, shortened product life cycles and accelerating rates of technological change are key challenges for today's manufacturing companies [1] [2] [3]. In order to remain competitive, manufacturers must permanently ensure that their manufacturing technologies will fulfil future requirements, such as fast adaptation to changing products [4]. Thus, the acquisition of applicable manufacturing technologies to produce current and future products is primary important in order to gain competitive advantages [1]. In this context, the term "manufacturing technology" denotes all emerging and established manufacturing processes that are needed to produce a product [5] and are referred to as "technology" in the following.

Over a long-term time horizon, a dynamic spectrum of potentially available technologies exists resulting from the evolutionary development of a technology [6]. This technological evolution can overall be described as a technology life cycle [7] [8], which incorporates individual technology cycles [9] such as increasing maturity of a technology over time [6]. However, potentially available technologies are not always mature enough to be used efficiently for manufacturing tasks [10]. This is especially valid for emerging technologies [9], which might need a further development until they can be integrated in the existing manufacturing environment [10]. However, developing a technology means building up know-how, which can be very time-consuming and expensive. For that reason, replacing a technology in the current manufacturing environment is a momentous decision, because it affects future conditions of manufacturing significantly. In order to select the right technologies in terms of strategic planning, companies need to evaluate alternative technologies. To identify alternative technologies companies must pay attention to market trends and contemplate technologies outside the companies' direct environment [4].

Starting from a brief literature review of technology intelligence and strategic technology planning, this paper presents an approach for screening technologies.

## 2 COMBINING TECHNOLOGY INTELLIGENCE AND STRATEGIC TECHNOLOGY PLANNING

In this paper, technology screening is defined as the identification, initial evaluation and trend assignment of manufacturing technologies in order to provide a preselection of most appropriate technologies for detailed strategic technology planning. Thereby, technology screening is a kind of technology intelligence process that integrates methods and models, e. g. for product analysis or technology evaluation, from strategic technology planning. Both terms, technology intelligence and strategic technology planning are briefly described below.

*Technology Intelligence* acts on the fore front of strategic technology planning [11]. It comprises a process to collect, analyse and communicate relevant information about technologies and technological trends to exploit potential opportunities and to defend against potential threats [11] [12] [13].

In contrast, *strategic technology planning* focuses on establishing and ensuring competitiveness in the long term taking the companies' technological orientation into account [14] [15] [16].

### 2.1 Technology Intelligence

Companies striving for technology leadership in their industry should keep up with the pace of technological developments, but they often do not apply a systematic approach to capture the important elements of technology change from the general information around them [17] [18]. The process of gathering and evaluating information on technology developments has various notations including technology intelligence [12] [13] [19] [20] [21] [22] [23], technology monitoring [24] [25] [26], technology forecasting [27] [28] [29], technology foresight [30] [31] and technology scouting [26]. Technological change is a major factor in gaining competitive advantages in manufacturing industries [11]. The contemplation of technological developments as a result of shortened product life cycles for example is necessary [32]. Therefore, technology intelligence and forecasting methods in general are used by companies to contribute to identifying threats and opportunities resulting from a fast changing environment by both capturing and delivering the right information in a timely manner [11] [13].

The technology intelligence process can be generalised as follows: determining information needs, sourcing, evaluating and communicating of technological information [12] [16] [17]. This process can also be expanded by considering the application of the results obtained in the above mentioned process [17]. Furthermore, collecting information can be differentiated in scanning and monitoring. Scanning is defined as the identification of relevant technologies and their trends outside the companies' environment, whereas monitoring specifies the observation of the development of identified technologies and technology trends [12]. The technology

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intelligence process can also be divided into two major steps including the identification and assessment of technologies [33] [34].

To design the technology intelligence process sustainable, the involvement of knowledge-management is required to detail gathered information [11], to improve its quality for technology planning [35] and further to increase planning reliability [12] [35]. Therefore, a monitoring-radar is an appropriate tool [22] [35].

Because of its complexity, the generic technology intelligence process cannot yet be applied to emerging or established technologies systematically [18]. By now, it is particularly conducted for product technologies and is not adaptable to company-specific requirements. Because of its exploratory nature, the process steps of technology intelligence are often difficult to formalise, so that technology intelligence can be explicitly used within an organisation to support decision making with respect to preselecting appropriate technologies for detailed strategic technology planning [11].

### 2.2 Strategic Technology Planning

In order to build up and increase competitiveness in the long term manufacturing companies have to conduct technology planning [15]. The major goal of technology planning is to make decisions in matters of the companies' technological orientation. Depending on the manufacturing requirements, companies not only have to determine in which technologies to invest but also to fix the right time for their launch to establish and sustain competitive advantages [16]. Methodologies primarily in the area of strategic technology planning can enhance an effective and efficient planning [36] [37] [38] [39] [40]. Technologies are often evaluated in detail by using criteria such as maturity or profitability [36] [38] [39] [40]. Further, the technology evaluation is mostly combined with strategic planning that ends up in technology roadmaps [36] [37] [40]. These provide a structured means for both giving an overview of relevant technologies [40] and for exploring and communicating their relationship to products and markets over time [37]. These approaches can also be extended by generating and evaluating technology chains, defined as the combination of technologies in order to manufacture more complex products. One way of visualising such an evaluation is the technology chain calendar [39].

In contrast to intelligence processes, strategic technology planning provides methods and models to analyse products or evaluate technologies based on criteria such as technology maturity or profitability [6] [38] [39] in more detail. This is needed to preselect relevant technologies, especially with regard to product feasibility and future manufacturing tasks.

However, strategic technology planning assumes that technologies are known and hence does not focus on identifying emerging technologies or technology trends.

### 2.3 Problem Statement

Manufacturing companies need to select technologies capable not only to produce current but also future products profitably. To remain competitive it is crucial to decide for the most suitable technology under given conditions as e. g., the individual technology strategy or the product spectrum. Thus, manufacturing companies need to be constantly aware of the large and dynamic range of relevant technologies available. To restrict the search scope, a preselection of promising technologies is indispensable to be able to react quickly to changing conditions—and finally to stay ahead of competition. A sound preselection methodology needs to incorporate both, elements of technology intelligence as well as of strategic technology planning. The remainder of this article therefore deals with combining these fields of technology management according to the discussed requirements by developing a new methodology for strategic technology screening.

## 3 TECHNOLOGY SCREENING METHODOLOGY

A methodology for strategic screening of manufacturing technologies is being developed which enables the identification and preselection of suitable technologies for detailed technology planning. The methodology is illustrated in Figure 1 and includes four steps: analysis, technology identification, initial evaluation and trend assignment. The methodology is executed cyclically, if e. g. current products are changed, future products are planned or manufacturing costs have to be reduced.

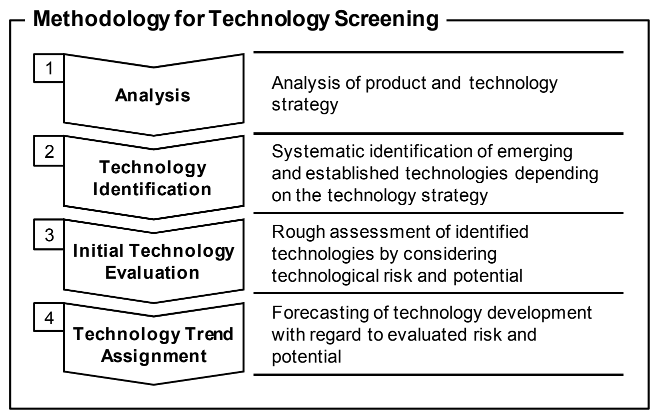


Figure 1: Methodology for Technology Screening.

### 3.1 Analysis

In the first step, both the product and the technology strategy have to be analysed to define a profile of potentially interesting technologies that have to be taken into consideration. The former is required to identify those technologies that are able to manufacture the analysed products [35] [39] [41]. Therefore, a requirements specification of the considered product must be created. This contains the following product requirements that are already available at early stages of the product development process: material from which the product should be manufactured, rough geometry dimensions, weight and shape as well as expected number of units, whereas the number of units has to be derived from estimated sales figures. This is of high importance concerning the economical value of a potentially suitable technology [35] [41].

The technology strategy a company follows, for example technological leader or follower [16] [42], has a strong influence on the preconditions of technology identification and evaluation [43]. For a precise identification of technologies, product features should be converted in technology functions, necessary to fulfil the manufacturing task. These technology functions restrict the search scope and thus prevent an information overflow [12]. Further, all relevant information about technologies, such as technical and economic data necessary for the initial technology evaluation, have to be collected e. g., by interviewing technology experts.

### 3.2 Technology Identification

Potentially suitable technologies have to be identified systematically. For this, companies need to collect information from different sources. From a company's perspective, these sources can be classified as internal and external and provide both implicit and explicit information [35]. This classification of information sources is illustrated in Table 1 including examples.

| | *implicit* | *explicit* |
|---|---|---|
| *intern* | • face-to-face contacts<br>• gatekeeper<br>• workshops | • internal documents<br>• internal data bases<br>• annual report |
| *extern* | • conferences<br>• trade fairs<br>• networks | • journals<br>• patents<br>• think tanks |

Table 1: Classification of Information Sources (based on [35]).

As stated above, the identification should be executed according to the technology strategy to narrow the search scope. Even the choice of information sources can depend strongly on the technology strategy as the following example illustrates: technology leaders usually have time advantages in research and development activities [16] [35]. To sustain these advantages, they also need to consider implicit, uncertain and immature information from both external and internal sources [16]. In contrast, followers are generally more risk-averse and thus tend to make use of explicit information, which implicates a late and non-exclusive information transfer [12] [16].

In order to support the identification of promising technologies, a process as depicted in Figure 2 should be defined. This process differentiates between general and company-specific process steps. Depending on the technology strategy a company follows, only selected company-specific process steps have to be carried out to identify those technologies that are relevant for the manufacturing company. To support a targeted identification of promising technologies according to the technology strategy, adequate information sources have to be used. Like the aforementioned technology functions (cf. section 3.1) the purposeful use of proper information sources restricts the search scope, so that an information overload can be avoided preventively. Figure 2 visualises the interdependence of different technology strategies and the choice of adequate information sources.

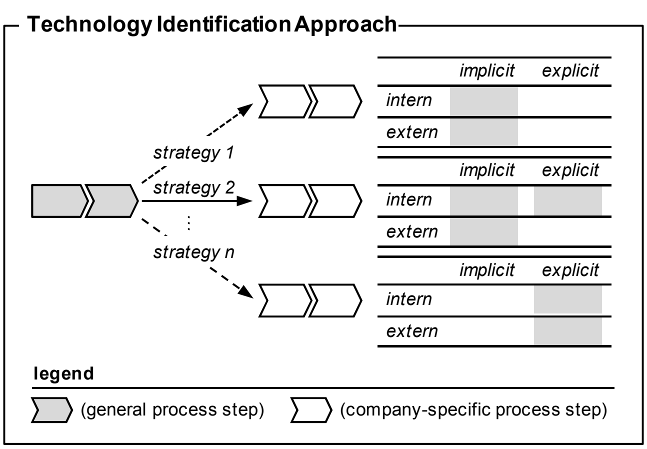


Figure 2: Technology Identification Approach

### 3.3 Initial Technology Evaluation

To reduce expenditures in the initial evaluation of technologies their ability to manufacture current and future products is revised. For this purpose, the requirements specification of the products resulting from a product analysis as described in section 3.1 has to be aligned with the technology's ability [35] [41].

From a strategic point of view, the technology maturity, potential and profitability should be considered [35] [38] [39]. These criteria are employed to determine the suitability of a technology [38]. In the following, a brief description of the mentioned criteria is given.

Decisions about replacing a technology in the current manufacturing environment are crucial, because they set the course for future conditions in manufacturing [38]. Hence, these decisions implicate some risk for a manufacturing company. To minimise these risks, only technologies that offer a certain level of maturity, should be applied [6]. In this context, maturity refers to the stage of development of a manufacturing process [38]. The assessment of maturity depends on the progress of seven defined Technology Readiness Levels (TRLs), which are used to classify the maturity of a technology. Therefore, a questionnaire consisting of qualitative and quantitative indicator-based questions representative for each TRL helps to assess the overall maturity level. To adopt the technology maturity model company-specific, each TRL has to be weighted because a full completion of previous maturity levels is not necessary to be able to reach the following ones and not all levels are of equal importance to a company. Basically, the overall technology maturity is calculated by multiplying the seven TRLs with their corresponding weightings, summing them up [6] [38].

Technologies can also offer potentials in matters of performance, which can be defined as technology potential. This includes technological improvements, e. g. to produce superior surface quality [39].

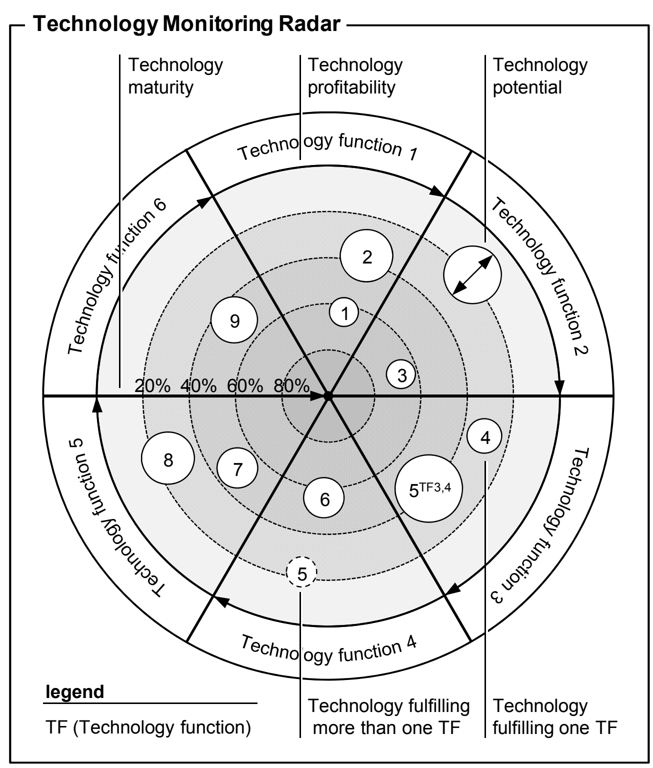


Figure 3: Technology Monitoring Radar (based on [35]).

The economic benefit of using a technology throughout its life cycle is a key factor to decide either for or against it [39]. Hence, profitability should be considered. A technology's profitability investigates future production costs, such as investments for production resources or estimated unit costs [38].

The results of the initial evaluation can be summed up and displayed in a Technology Monitoring Radar (TMR) as shown in Figure 3. The initially evaluated technologies are arranged as circles in the TMR with their position depending on the technology function(s) they are fulfilling as well as on their maturity, potential and profitability. On the radial axis, the maturity is plotted and the technology potential is represented by the diameter of the circle. On the outer rim of the radar, technology functions and profitability are assigned clockwise. In case a technology covers more than one technology function, its circle is arranged according to the primary function and the remaining functions are listed as superscripts.

The TMR can support the monitoring of identified technologies as described in section 2.1 because it documents the development of technologies over time [22] [26] [35]. Besides, the technology functions that are allocated to the outer rim of the TMR form the basis for the generation of alternative technology chains [35].

### 3.4 Technology Trend Assignment

Evaluating the identified technologies based on the aforementioned three criteria including technology maturity, technology potential and technology profitability at a given point in time is not sufficient. For instance, the suitability of a technology, which was rejected based on the initial evaluation, could improve faster over time than the suitability of the actually selected technology. Hence, the suitability of a technology has to be forecasted throughout the time horizon considered.

A large number of methods and models have evolved in attempts to anticipate the direction of technology change [27] [28] [33] [44] [45] [46]. These can be classified as explorative and normative [33] [45] [47] and are subdivided into qualitative and quantitative methods and models [46]. Explorative methods and models, such as those listed in [33] [45] like delphi studies or system dynamics are characterised by the anticipation of potential technological developments [33], whereas normative, for example requirements analysis or trend impact analysis [33] [45], are used to forecast desirable developments. The described classification is shown in Table 2 and lists further forecasting methods and models.

| | *qualitative* | *quantitative* |
|---|---|---|
| *explorative* | • delphi studies<br>• interviews<br>• scenario analysis | • trend extrapolation<br>• system dynamics<br>• exponential smoothing |
| *normative* | • requirements analysis<br>• relevance trees<br>• science fiction analysis | • trend impact analysis<br>• TRIZ<br>• roadmapping |

Table 2: Classification of Forecasting Methods and Models (based on [28] [33] [45]).

The above mentioned classification can also be extended by subjective assessment methods, which are not yet broadly used in the context of forecasting technology trends, e. g. formal surveys or market research-based assessments [46]. In order to benefit from the synergetic effects of the above mentioned methods and models, they should be combined adequately [33].

In this paper, forecasting refers to three technology life cycle models, which show the prognosis for maturity, potential and profitability based on the current evaluation. Figure 4 displays one of these models, which plots the growth of technology maturity against time. The model separates the technology life cycle into four different stages including innovation technology, key technology, standard technology and displaced technology [48]. Depending on the current stage a technology has specific characteristics [4]. While an innovation technology is still aspiring, a standard technology is characterised by a high productivity. Using the technology life cycle for forecasting the growth curve should be based on a mathematical function. Since each technology has a different lifecycle, parameters have to be integrated in order to predict the life cycle individually.

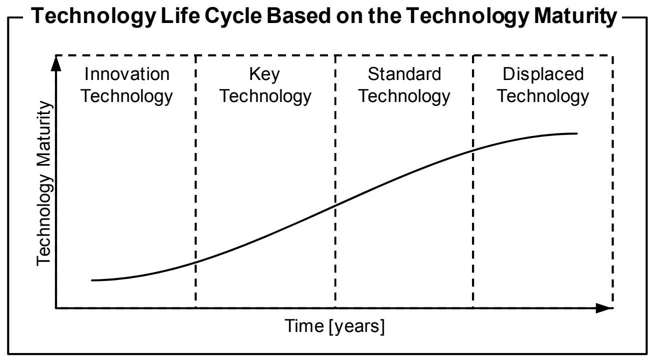


Figure 4: Technology Life Cycle Based on the Technology Maturity (based on [4] [8]).

Each of the basic technology life cycle models is weighted company-specific in order to integrate the companies' target system which also depends on the technology strategy. The result is an aggregated technology life cycle model that illustrates the future suitability of a technology during the considered planning horizon. In order to aggregate the aforementioned basic technology life cycle models the ordinate axis of each model has to be standardised using an interval scale from zero (0, low) to one (1, high).

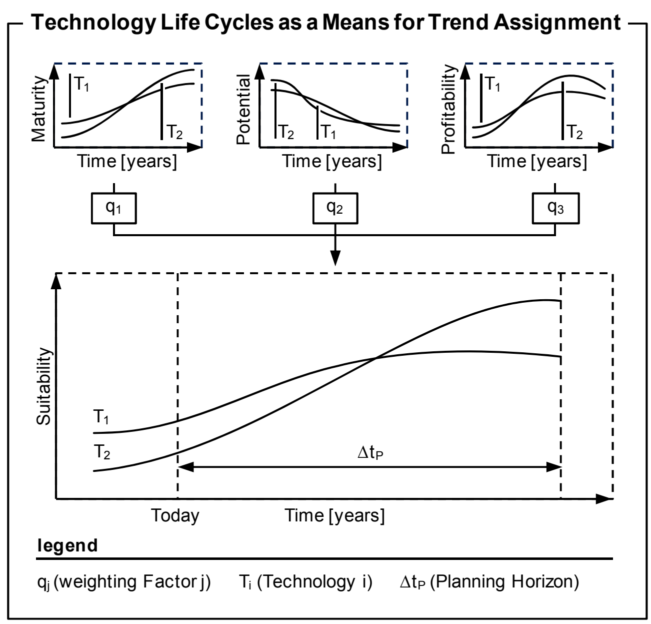


Figure 5: Technology Life Cycles as a Means for Trend Assignment.

Figure 5 depicts the described life cycle models comparing two alternative technologies $T_1$ and $T_2$. Therein, the planning horizon $\Delta t_p$ for forecasting the trends of the considered life cycles has to be determined depending on the companies' technology strategy. Technology leaders often have a larger planning horizon compared to followers because they might have to develop emerging technologies further in order to use them efficiently in current and future manufacturing tasks. Furthermore, the three basic technology life cycle models are weighted using weightings $q_j$ resulting in the suitability graph. These weightings are generated by applying the Analytic Hierarchy Process [49].

## 4 SUMMARY AND OUTLOOK

Manufacturing companies have to identify and preselect potentially useable technologies in order to stay competitive, for example by reducing manufacturing costs. Implementing a technology into the existing production environment is very time-consuming and expensive. Therefore, the decision in favour or against an alternative is crucial for strategic reasons. Producing companies need an applicable methodology to support the decision process of choosing the most appropriate technologies for detailed planning. To close this gap, this paper presents an approach for the strategic screening of technologies. First, relevant information for the identification, the initial evaluation and the trend assignment of technologies is analysed. Information concerning both the product and the technology strategy is used to identify emerging and established technologies. They are roughly assessed in order to preselect the most suitable technologies for the manufacturing task. The TMR is introduced as a sustainable method for visualisation of the evaluation results. Throughout the planning horizon, the suitability prognosis for each evaluated technology is assigned, showing its time-dependent behaviour.

Further research activities will address the development of a methodology for a systematic identification of manufacturing technologies depending on the corporate strategy. For assigning proper trends, cyclic influences based on a mathematical and configurable technology life cycle model should be considered. Based on the described suitability graph decision criterion for preselecting alternative technologies has to be derived. It should take risk as well as the dynamic behaviour of a technology's suitability into account. As many of the influences on technology planning are changing, such as maturity or technology potential, and the planning horizon is long ranged, also uncertainties should be integrated into the methodology.

## 5 ACKNOWLEDGMENTS

The German Research Foundation (DFG) funds this research and development project. We extend our sincere thanks to the DFG for the generous support of the work described in this paper, resulting from the subproject B3 "Dynamic Production Technology Planning" of the second funding phase in the framework of the Collaborative Research Centre 768 "Managing cycles in innovation processes – Integrated development of product service systems based on technical products". The goal of the Collaborative Research Centre 768 is to reduce the knowledge gap regarding cycles and cyclic influences within the innovation process.

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# Key Success Factors for Production Network Coordination

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**Abstract**

Coordination of distributed production between different enterprises is seen to be the major future challenge in production management. The success of enterprises no longer only depends on their own performance, but on the performance of the entire production network they are situated in. This paper aims to link appropriate coordination modes and instruments with different types of production networks of small and medium sized enterprises to achieve most production network performance.

**Keywords:**

Coordination Instruments; Operations Management; Distributed Production; Production Network Performance

## 1 MOTIVATION

To reach high performance, manufacturing enterprises must not only concentrate on raising their own performance, but on coordinating the processes of their production network (PN) to reach efficient production processes and required product quality. The inter-organisational coordination within networks of manufacturing enterprises is the key for successful PNs and still it is difficult to realise [1]. Though recognizing these necessities, the effects and extent of PN coordination are yet unclear and needed to be empirically studied. The objective of the research presented in this paper is to obtain an empirically profound data basis to be able to choose appropriate coordination instruments for different types of PNs. Furthermore possible key success factors for coordinating different types of PN are investigated.

## 2 UNDERLYING CONCEPTUALITIES

### 2.1 Relevant Fields of Research

The necessity of inter-organisational coordination is spotted by diversified fields of research. The field of business studies tries to fulfil this task by Supply Chain Management (SCM), concentrating on general business processes but not on distinctive PN processes [2]. The Operations Management claims studying operations across multiple organizations and the management of distributed production as future challenge for their discipline [3]. The young research field of Dynamic Capabilities highlights coordination capabilities as one of four meta-capabilities enterprises must have, to be sustainably successful [4]. Yet this field of research lacks in specifying the operationalisation of capabilities [5] and still limits the focus on internal coordination of enterprises and not of networks.

Further approaches are found in the field of production engineering. One underlying theory, the Competence Cell Based Approach, allows the explanation and planning of regional PNs [6]. For operating and managing such a network a consensus and typology of coordination has not yet distinctively been found [7]. A further approach is the transfer of production planning and control (PPC) principles from single enterprises to the entire PN, e.g. the "Aachener PPS Modell" [8]. Though this approach gives suggestions on process operations and timings, not all tasks and possibilities of coordination within a PN are covered. The last relevant field of research is the approach of Virtual Enterprises. This approach was no longer intensively pursued over the last years, though it brought out very practical realisation suggestions for PN coordination [9]. The drawback of this research paradigm is its unclear distinction between supply chain and PN and its indistinct research focus.

### 2.2 Definition of PNs

This presented approach of research differs from prior work in business studies. It concentrates on production engineering while taking production specific circumstances into account. Therefore a distinctive definition of PNs for our special purpose will be given:

A PN adds value to a product by distributed production. It either emerges from addressable strategic networks or from latent informal network structures of manufacturing enterprises. Such a temporary network exists as long as a certain product or range of products is produced. A PN is influenced by its environment and the product with its stages of production.

In contrast to a supply chain a PN does not involve the sourcing of crude materials or the distribution of products. A PN can be a part of a supply chain. This infers the possibility to apply parts of SCM besides parts of PPC for coordinating PNs.

### 2.3 Coordination and Coordination Instruments

Inter-organisational coordination is needed to link between the strategic pursuit of goals and the occasion of operative tasks [10]. Coordinating, as described by the Dynamic Capability approach, is the organisation of tasks, resources and activities [11]. Coordination takes place in a strategic and an operative manner and has its main focus on raising performance. Therefore several tools and methods can be used, called coordination instruments. Strategic coordination instruments are methods to achieve goals in the long term. Operative coordination instruments are tools to obtain requested effects in the short term [12].

## 3 RESEARCH DESIGN

### 3.1 Research Question

The research question for this study is formulated as following: "What kind of coordination leads to a maximum of performance in a PN with certain characteristics?"

### 3.2 Conceptual Model

To be able to answer the question, relations between coordination, performance and characteristics of PNs have to be studied.

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Additional relations with product characteristics and enterprise performance have to be considered too. The supposed relations are formulated as hypotheses and summarized within the conceptual model (see figure 1).

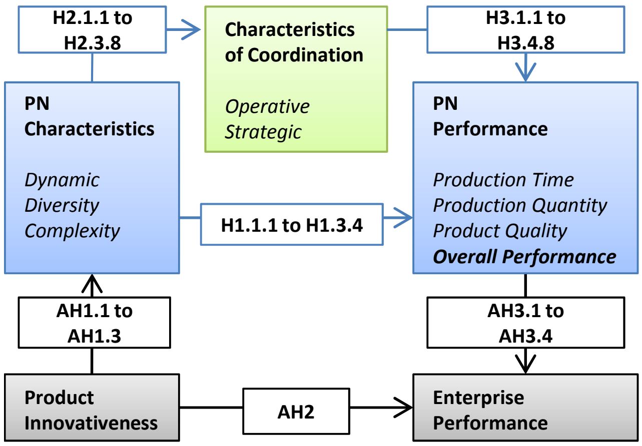


Figure 1: Conceptual model.

### 3.3 Main Hypotheses

H1.1.1 to H1.3.4: High dynamic/diversity/complexity of the PN negatively correlates with the production time / production quantity / product quality / overall performance of the PN.

H2.1.1 to H2.3.8: High dynamic/diversity/complexity intensifies the operative/strategic coordination.

H3.1.1 to H3.4.8: Intense operative/strategic coordination positively correlates with the production time / production quantity / product quality / overall performance.

### 3.4 Auxiliary Hypotheses

AH1.1 to AH1.3: High product innovativeness correlates with high dynamic/diversity/complexity of the PN.

AH2: High product innovativeness correlates with high enterprise performance.

AH3.1 to AH3.4: High PN performance indicators correlate with high enterprise performance.

### 3.5 Constructs for Empirical Measurement

The following five constructs were set to be able to test the hypotheses and to find out key success factors:

The first construct, *PN characteristics*, indicates the dynamic, diversity and complexity of the PN. It is based on the critical business environment characteristics of Mintzberg [13] (see figure 2) and is operationalized referring to Chi et al. [14].

The second construct, the *characteristic of coordination*, points out the intensity of operative and strategic coordination. It is divided into two sub-constructs: operative and strategic coordination referring to Sanders [12]. This SCM approach is transferred into a production engineering approach by adjusting SCM measurements; hence PNs are always part of a supply chain.

The third construct, the *PN performance*, actually fills a gap in recent empirical measurement. Existing literature proposes to apply the Overall Equipment Effectiveness (OEE) indicator, typically used to measure productions systems, to be adapted to measure the performance of supply chains and PNs [15]. Referring to the established OEE parts: time efficiency, quantitative effectiveness and quality rate, an approach for measuring the performance of the entire PN empirically was developed by basically questioning: "How efficient is the PN in utilizing available production time, how effective is the production in terms of production quantity, and how many products do fulfil the quality standards?" Hence the PN performance construct consist of the following three parts: production time, production quantity and product quality.

The fourth and the fifth constructs are *enterprise performance*, to measure the success of the studied enterprises, and *product innovativeness*, to measure the rate of new or standard products and considering statements on customer requirements and competitive contexts. Enterprise performance is measured referring to Chi et al. [14] by comparing market-share, profit margin and sales growths with the main competitor. Product innovativeness referring to Huang et al. [16] indicates the characteristics of the product by classifying it in a continuum of standard products to new products. All items of the constructs are measured by a 5-point Likert scale.

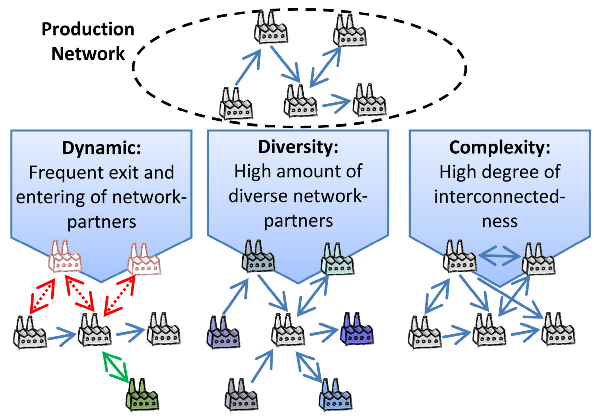


Figure 2: Dynamic, diversity and complexity of PNs.

### 3.6 Key Success Factors

To identify key success factors the moderating effects of coordination characteristics on the relation between PN characteristics and PN performance are studied. Therefore a regression model with 42 part models is set and analysed.

### 3.7 Applied Method

The quantitative method chosen for this research design was a telephone survey conducted in spring 2012 tending general managers of SME in Saxony (federal state in Germany). 600 enterprises of mechanical, textile and electronic manufacturing industries were phoned and if requested a digital questionnaire was sent to them by e-mail. This method achieved a response of N=52. The chance to get information from 52 managers about production coordination in Saxony is the research's limitation at the same time, because these results may only be generalized for Saxony at a first glance. Secondly a response of 52 (8.7%) is statistically a very low reply and the significance of the results must be considered. Nevertheless the application of a method originated in social science to production engineering has not been very common yet. Hence the results are still important, because they are an empirically ascertained basis among only a few.

With the software SPSS Statistics the correlation and regression analysis is realised. For correlation effects the significance level (two-tailed) is set at 0.05 for the first analytical run-down. To get a hint on more correlations, the significance level in the second run-down is raised to 0.1 and in a third analytical run-down even at a

0.2-level (two-tailed). For the classification of the strength of the correlation the Pearson Correlation Coefficient (PC) is also divided into three ranges: 0.4 to 0.6 for strong correlation, 0.3 to 0.4 for medium correlation and 0.2 to 0.3 for low correlation. The regression analysis tests the moderating effect of one variable (the moderator variable) on the relationship of two other variables. To quantify the moderation effect, the standardised coefficient of the interaction effect is calculated. At first every positive standardised coefficient provided an indication of a positive effect of the moderator variable on the relation between the two other variables. Secondly to get a hint on the success factors, the positive standardised coefficients are compared among each other.

## 4 FINDINGS

### 4.1 Results of Correlation Analyses

#### PN Characteristics and Performance

The results of the first correlation analyses reveal that high dynamic negatively correlates with high product quality. Furthermore it appears that diversity not negatively relates to performance, as actually assumed. A rising diversity within a PN even seems to have a positive effect on production quantity. This effect may have the reason that a PN with a high amount of different companies is better separated into core units, concentrating on their core competencies, than a network with a comparatively low amount of enterprises realising several core tasks at once. This finding supports the theory that networks of several small but different enterprises lead to more productivity and overall performance (although on a very low significance level in this study), than networks of large enterprises realising numerous competencies. Nevertheless confirming this theory needs deepened research on PNs. The results of the first correlation analysis is summarised by figure 3.

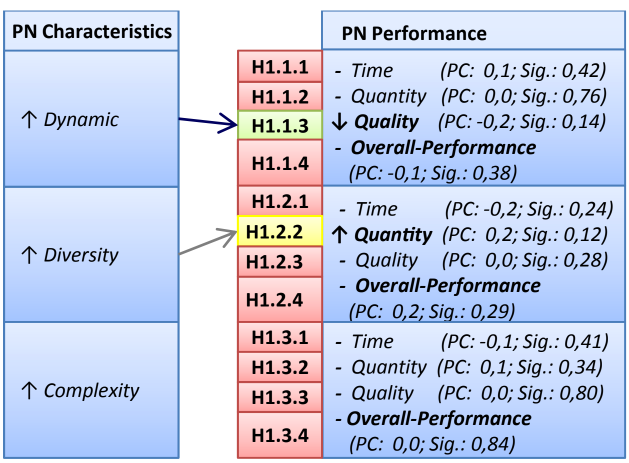


Figure 3: Correlations of PN Characteristics and PN Performance.

#### PN Characteristics and Coordination

All hypotheses for testing the positive correlations of PN characteristics and the intensity of operative and strategic coordination can be confirmed, except correlations between dynamic and diversity on database usage. Diversifications of the strength of the correlations can be made by the extent of the PC factors, which are shown in figure 4.

Dynamic PNs, more than diversified or complex PNs, have the highest positive correlation with operative and strategic coordination. All of the characteristics, dynamic, diversity and complexity, appear

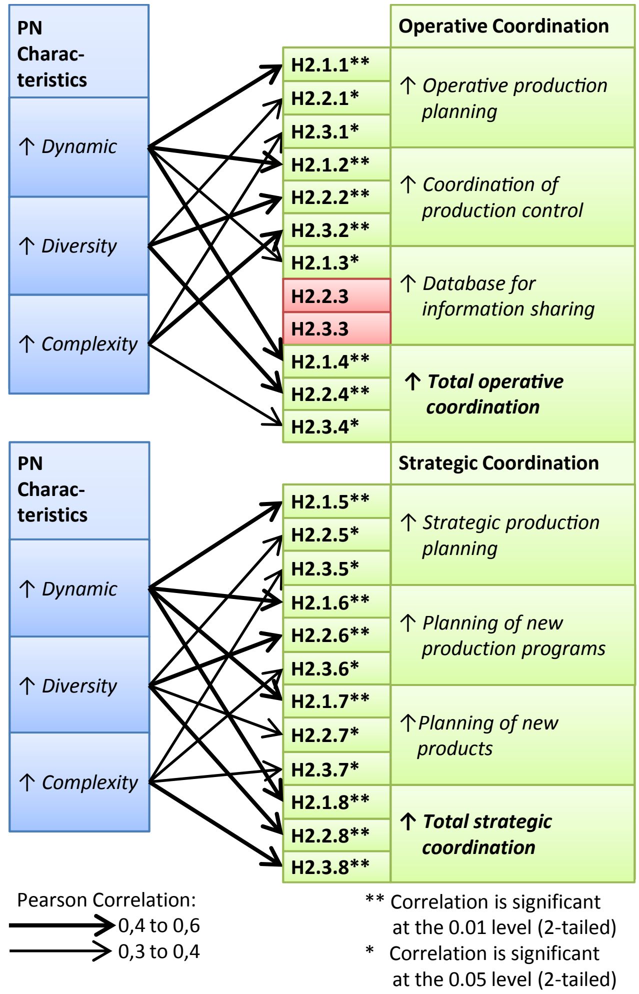


Figure 4: Manifestation of coordination through PN Characteristics.

to lead to a high intensity of the coordination of production control and total strategic coordination. These insights are comprehensible and by implication, less coordination is practically applied in networks of low dynamic, diversity and complexity.

#### Coordination and PN Performance

All hypotheses considering the positive effect of operative coordination on the overall-performance can be confirmed with a certain probability. Also, all types of operative coordination seem to have effects on improving production time, whereby databases for information sharing have the highest correlation factor on production time. Only one coordination instrument, the coordination of production control, seems to affect the production quantity positively and none of the tested coordination modes seem to be able to positively influence the product quality. The summary is drawn in figure 5.These findings reveal, that not the entire operative coordination may lead to performance increase. Some of the coordination activities conducted may only take place to cope with emerging problems. Nevertheless it is doubtful, that none coordination seems to have a positive relation with product quality. The reason of this occurrence may lie in the measurement of product quality, which will be more intensively explained in the chapter of auxiliary hypotheses.

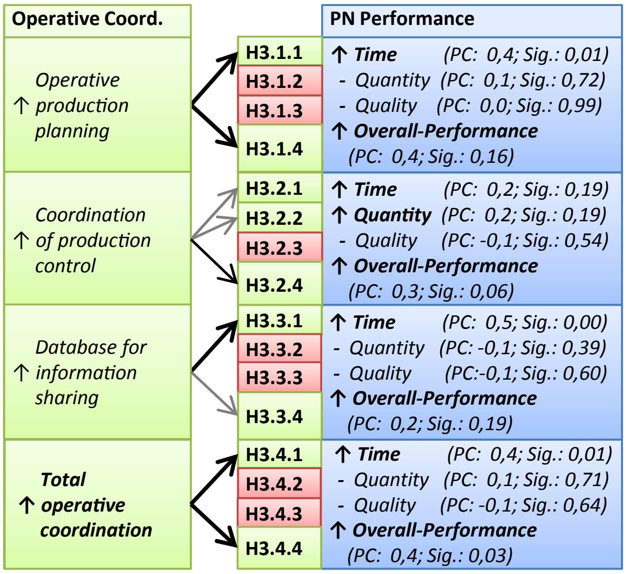


Figure 5: Relations of operative coordination and PN performance.

Also all hypotheses concerning correlations of strategic coordination on overall-performance and production time can be confirmed, except for planning new production programs. None of the strategic coordination instruments or the total strategic coordination tested appear to affect the production quantity or quality, see figure 6. The reason for this low amount of confirmed hypotheses may lie in the lack of timely coincidence between performance measurement and the effect of strategic coordination. For investigating detailed effects of strategic coordination on PNs a longitudinal study is more appropriate. Nevertheless this horizontal study gives indications on successful strategic coordination.

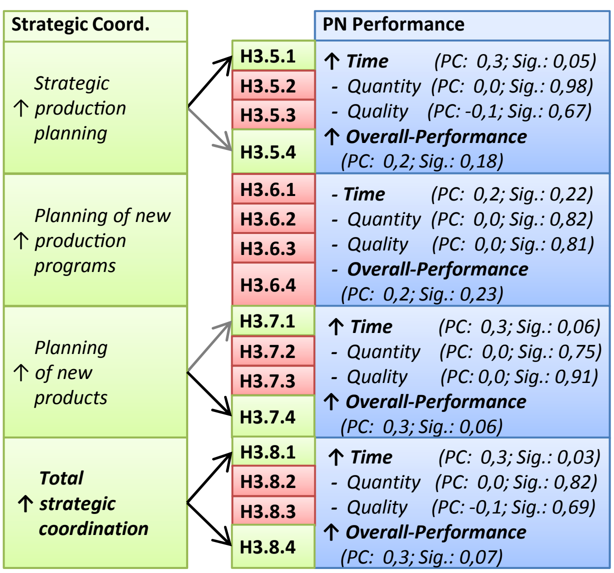


Figure 6: Relations of strategic coordination and PN performance.

**Auxiliary Hypotheses**

To reflect the investigated correlations with product innovativeness and enterprise performance the auxiliary hypotheses are analysed. The results show that the innovativeness of the product not correlates with the characteristics of the PN. This leads to the suggestion that the results of the main hypotheses are to some extent independent from certain types of products. Furthermore the findings indicate that product innovativeness has no correlation with enterprise performance, which supports the theory, that products do not solely influence the enterprises success, but the interaction of products and PN. Still innovative products are known to be necessary for sustainable success [17], though standard products are also very successful, because of a production that had been evolved and meliorated over a long time. Therefore the coordination of change processes more and more foregrounds for PNs. Unexpectedly production time and quantity do not correlate with enterprise performance. Product quality even negatively correlates to enterprise performance. To explain this it needs to be mentioned firstly, that a firm's economic performance not only depends on its manufacturing performance. Secondly the survey's operationalisation of quality may not be appropriate, because it was measured by asking for the potential to raise product quality within the PN and ambitious managers would never be completely satisfied, always answering there is potential to raise quality. Hence this operationalisation must be rethought and results concerning quality should be carefully construed.

### 4.2 Results of Regression Analyses

The summarised regression model with the variables: total operative and strategic coordination, dynamic, diversity and complexity on the dependent variable overall-performance is valued by $R^2 = 0.2$. In other words: it is possible to predict 20% of the PN performance by these 5 variables. This represents a useful result for a small sample and certainly PN performance is influenced by numerous other variables. To calculate the interactions between the single PN characteristics and all coordination instruments, and their effect on the performance variables, 42 part regression models are analysed. All models with a positive standardised coefficient of the interaction effect on the overall-performance are shown by figure 7. They reveal: to positively influence the overall performance within a dynamic PN, it could be possible to enhance the operative production planning, integrate a database for information sharing, apply strategic production planning and conduct planning of new production programs and products. Furthermore to enhance the performance within PNs of high diversity: apply all of the tested instruments, except planning of new production programs. To cope with complexity within a PN, a database for information sharing and the planning of new products are the only confirmed possibilities.

The regression models with positive interaction of PN characteristics and total operative and strategic coordination on production time, production quantity and product quality are also illustrated by figure 7. These results show that it might be possible to enhance production quantity and product quality within a dynamic or diversified PN through operative coordination. Also it is likely to raise product quality within a very complex PN through operative coordination. Through strategic coordination it is promising to positively influence production time and product quality within a very complex PN, or to reach positive effects on production quantity and product quality in diversified PNs. Furthermore it is possible to positively influence the product quality in dynamic PNs through strategic coordination. To improve production time within a dynamic or diversified PN, neither operative nor strategic coordination seems to function. Also for increasing product quantity within a very complex PN no instrument can be found. Hence more detailed research has to be conducted, to find out specific coordination instruments for these cases. Based on the extent of the standardised coefficient of the interaction effect between PN characteristics and coordination, and its influence on the PN performance, it is possible to identify the key success factors for different types of PNs.

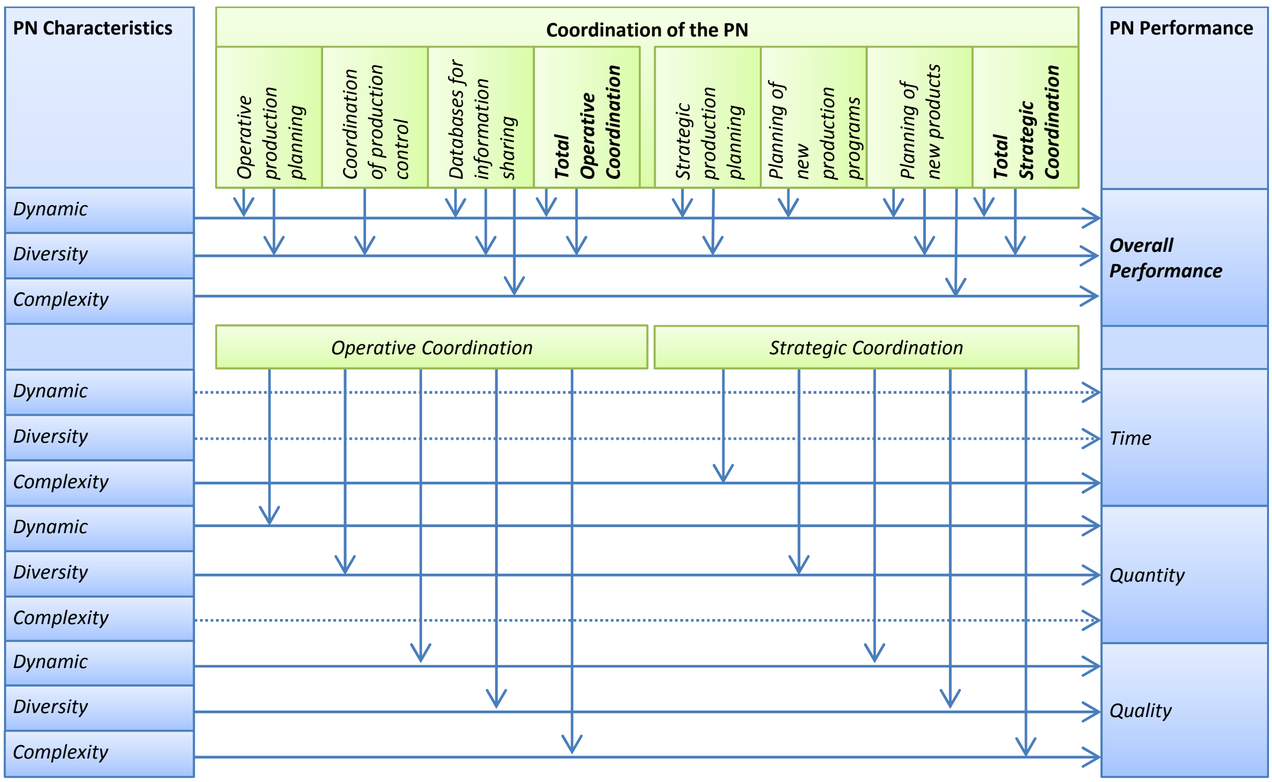


Figure 7: Positive Interaction effects on PN performance.

## 5 KEY SUCCESS FACTORS

### 5.1 Key Success Factors for Dynamic PNs

The correlation analysis shows that high dynamic has its most negative effect on the product quality. The regression analyses gives the hint to avoid this negative effect by strategic coordination, hence strategic coordination is one of the key success factors for dynamic PNs. To raise the total performance of the dynamic production net especially strategic and operative production planning are the key success factors. Operative coordination is a key success factor in raising the production quantity in such a network.

In reality these findings could mean that a focal enterprise takes the strategic lead to be able to involve new partners and to clearly and quickly assign their roles. To ensure product quality, an inter-organisational quality management should be applied with definite standards and requirements. In summary this characteristic of PN mostly refers to the use case of *The Ruled Network* found through scenario technique by Moch, Jentsch and Schmidt [18]. Further coordination instruments to be applied within the network are rules, plans and programs.

### 5.2 Key Success Factors for Diversified PNs

Diversity mostly decreases the utilisation of available production time. Unfortunately it cannot clearly be stated if operative coordination or strategic coordination is the solution to avoid this negative effect on production time. Though it can be stated, that operative coordination has a bigger positive effect on overall performance within a high diversified PN, than strategic coordination. Especially the application of databases for information sharing among the network partners is a key success factor. Besides this operative coordination instrument the strategic planning of new products also appears to be a further key success factor for PNs with high diversity.

For example to manage high variety and to gain an overview among the diversified processes and competences of the network-partners, internet based applications like software as a service (SaaS) for inter-organisational PPC can be applied. Yet it seems as if the efforts to control distributed production are only practical to solve emerging problems. To sustainably meliorate and evolve the PN, the partners have to build a common base of trust. As shown by the uses case of *The Group Network* [18] very person-oriented coordination instruments can be functional, such as internal consultations, commitment to one network culture or also the clear manifestation of hierarchy.

### 5.3 Key Success Factors for Complex PNs

No direct negative correlation of complexity and production time, quantity or product quality could be measured, which implies, that complex networks are already good working. Further the measured effects of coordination on PN performance are very small, though it shows that planning new products seems to be the most promising key factor for raising the overall performance of complex PNs. Strategic coordination as a whole seems to be more successful in raising production time utilisation and product quality, than operative coordination.

Complex networks show similar characteristics as the use cases *The Supported Network* and *The Goal-Getter Network* [18]. One strategic objective is pursued by the PN, such as bringing a new product to market and the structure of the network is very much interconnected, because every enterprise needs to adjust to a lot of partners within the network. In this case strategic external support, such as consultants, can help preventing the enterprises in losing in operative confusion.

## 6 SUMMARY

### 6.1 Limits of the Study and Improvements

A considerable limitation of this research is the reply of N=52 and partly the high significance level of 0.2. Furthermore there is no extra criterion set for regression analyses except the standardised coefficient of the interaction effect being above zero and the standardised coefficients compared among each other. Hence the conclusions and results are statistically still vague, although most of the results seem to be very comprehensible and some the measured effects even though are statistically very significant.

In addition to the response rate, the regional context of the survey has to be extended and the measurement of quality has to be rethought (see chapter 4.1). Also the measurement of coordination by a scale from “not involved” to “completely involved” has to be reconsidered, because almost none of the asked managers answered, that partners of the PN are completely involved. A suggestion is to measure the right extend of involvement in coordination issues, because a complete involvement seems to be unintended and practically impossible. Furthermore this study showed, that it is suitable to point out successful operative coordination, but it is not quiet appropriate to study strategic coordination. In addition to the operative performance measurement the long-term success of strategic change processes has to be clearly marked out and additional measurements have to be found.

### 6.2 Further Research

Furthermore the study can be deepened by focusing on the negative effects of coordination and their reasons. Also investigating unexpected results by longitudinal studies can be accomplished.

The research field of Dynamic Capability proposes coordination capabilities as one of the most important capabilities for enterprises. Yet it is a very internal view on coordination, which should be applied on inter-organisational PNs too. Likewise the strategic coordination instruments to be capable to react on a turbulent environment and to successfully fulfil change process have to be distanced from operative instruments applied to gain operational performance. Achieving this, an intelligible practical application of coordination instruments will be given.

### 6.3 Conclusion

Besides its compromises, this study revealed that within the field of production engineering it is possible to gain insights by quantitative empirical research. Further research based on this study with improved circumstances have to be undertaken to learn more about the relations within inter-organisational production systems and in result gain capability to cope with future challenges.

Still the suggested solutions in literature for the difficulties of distributed production are either too business process oriented or software supported. Besides these SCM approaches and the inevitably digital PPC utilisation, the development of capabilities and instruments for coordinating and engineering networked production are required. This study is a step forward achieving these goals.

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# Agility Enablers in Manufacturing Systems – Contributions of the Production Network Perspective

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**Abstract**

The production network, an organizational structure between markets and corporate hierarchies, holds a certain potential to cope with turbulence. In manufacturing, this potential becomes feasible in additional agility options due to the pooling and allying of network resources. This paper presents an overview on different types of mutual network resource usage. Therefore, redundant and complementary network resources as well as network slack are analyzed regarding their potential for agility gains to proactively relocate the corridor of flexibility. The finding of this paper is a set of requirements, which the agility enablers need to share to increase agility meanwhile minimizing opportunistic behavior.

**Keywords:**

Agility Enablers; Manufacturing; Production Networks

## 1 INTRODUCTION

The turbulent environment is more the new reality rather than an exception. Therefore, the challenges for manufacturing companies have intensified. Product variety and complexity, short product life cycles and volatile customer demands are challenges production companies have to face [1]. Mass markets are thereby replaced by diversified niche markets, which demand high production adaptability to fulfill customer needs [2]. To cope with turbulence, changeability in manufacturing becomes an essential competitive advantage as a result of potential changeability enablers arising from different levels within the enterprise [1].

For this purpose the Stuttgart Enterprise Model was established, a holistic approach for transformable manufacturing structures to adapt to environmental changes following the principles of cooperation, technical intelligence, self-organization, -optimization, -monitoring, and -configuration [3]. In this context, the manu-facturing system is defined as a hierarchic socio-technical system in which men in combination with machines, information and material perform a transformation process from input to output [1]. The efficiency of manufacturing structures arises from the combination of their capacity and the market demand. Therefore, manufacturing is highly challenged by turbulence. As capacity is affected by long-term investments and fixed costs, the efficiency of these investments results in sunk costs, if the environment changes while the manufacturing system remains static [1]. Under these aspects, manufacturing systems interact within a goal conflict of efficiency and changeability [4]. This setting is system-inherent as both efficiency and changeability are on the one hand necessary, while changeability on the other hand requires additional expenses, which reduce efficiency [1]. The potential of production networks to acquire additional changeability capabilities is considered promising to address this goal conflict. Therefore, the present paper focuses on changeability in terms of volume fluctuation as main change driver for manufacturing, which decreases the efficiency of value creation structures. Although other change dimensions may also influence efficiency aspects, for the sake of clarity volume fluctuation is used subsequently as the relevant change driver.

The remainder of this paper is organized as follows: Initially, the production network is defined as the research object in order to identify additional changeability potential within this organizational structure in section 2. Next, the method of structuring a changeability concept is introduced and applied on the research object in section 3. Section 4 discusses the identified agility concepts within production networks by pooling and allying resources. In section 5 the findings are concluded, while section 6 highlights the limitations of this paper and future work.

## 2 CONCEPTUAL UNDERPINNINGS

To enhance changeability, Lanza and Moser consider production networks to acquire an advanced scope of value added [5]. By the distribution of value creation within a network a proactive transformation process from possessed manufacturing structures to network capacity is enabled, which induces potential changeability gains. The consideration of production networks to enhance manufacturing performance is widely discussed in numerous theories and studies. However, it can be stated that almost 15 years after the relational view was established by Dyer and Singh, which became a critical milestone for explaining above-average returns in networks, concrete approaches to acquire economic benefits are still a field of additional research [6]. For though holding the relational view in high esteem Duschek and Sydow state that practicable indications for gains by accumulations or transformations through production networks still remain in the dark [7]. In this context, the present paper analyses the existence of changeability enablers in production networks with a clear focus on manufacturing structures. The aim is to identify additional potentials of changeability in terms of the Stuttgart Enterprise Model to provide "solution models, methods, tools and procedures to solve the major problems in day-to-day business, for middle and long-term planning activities & strategies associated with increasing the competitiveness aiming at transformable enterprise structure" [3]. With this research design the value creation within network structures is examined from the corporate perspective in line with Wiendahl and Lutz, who stated that the main idea behind production networks is the mutual use of resources and the joint planning of the

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value added process [8]. Hence the paper is exclusively focusing on the creation of Coleman-rents, which are rents arising from stable and trustworthy interactions within networks [9]. In contrast, Burt-rents emerging from opportunistic behavior or egoistic optimization are not considered, as these do not support long-term cooperations.

Despite countless approaches to establish a consistent classification, a “formal definition of production networks does not exist” [8]. Sydow defines networks from an organizational perspective as “specific set of linkages among a defined set of actors" in which companies interact within a strategic mode of organization between market and hierarchy [10]. By reason of the paper’s focus, we would like to highlight a definition, which concentrates on competitive advantage within production networks instead of a holistic definition of this organizational structure. Therefore, the production network definition “from the resource view as production units linked by material and information flows along the supply chain” seems to be constructive [2]. This is in line with the definition of Gulati, who perceives a network as a “voluntary arrangement among firms that exchange or share resources and that engage in the codevelopment or provision of products, services, or technologies” [11]. Hereby, both definitions point out the voluntary cooperative usage of resources that forms the basis for advanced options.

To identify additional changeability enablers on production network level, the paper examines the relational view, which deconstructs cooperations as discrete competitive advantage on the basis of interfirm resources [12]. For this reason, the combination, exchange or mutual investment leverages the performance of the network resources based on two mechanisms: the Ricardo rents from picking superior resources and the Schumpeter rents from deploying unique resources within the network [12]. Dyer and Singh identify four sources of competitive advantage, which allow above-average returns within a network: relation-specific assets, knowledge-sharing routines, complementary resources/capabilities and effective governance [6].

For this purpose, the management of production networks needs to create unique resources out of the existing network partners’ assets. These network resources can not only enhance the performance of the network, but leverage the changeability of the network as turbulences are addressed on the highest production level and therefore watered down before hitting the shop floor with its static and inflexible structures [5]. Therefore, this paper considers the production network as a platform to access higher degrees of freedom within the distribution of value creation. The research goal is to highlight the potentials of resource pooling and allying within the network to form additional changeability enablers to overcome turbulence [13].

The pooling concept is defined as the mutual usage of similar resources owned by multiple network partners enabling greater scale [14]. Allying refers to the combination of distinct resources to form synergies and acquire unique features [11]. This is in line with Nohria and Garcia-Pont, who highlighted, based on their empirical findings in the automobile sector, that networks should be perceived as complementary blocks, which contain firms of different capabilities and pooling blocks based on similarities in capabilities [15]. Both approaches hold the potential to leverage the performance of manufacturing structures and are subsequently analyzed under these aspects. The general hypothesis of this paper is:

> *Production networks favor the efficient distribution of value creation within the network by pooling and allying of resources, which enhances its changeability.*

## 3 METHOD AND RESULTS

To structure this paper, the framework of Wiendahl et al. (see Figure 1) is applied [2]. As changeability is a complex concept this well-established framework is used to sharpen the changeability construct on network level. Therefore, this framework is adapted to define the change object of manufacturing resources within its context of change drivers, change focus, change strategy and change extension. Due to the early stage of the investigation, a performance measurement system is not established yet, but is explicitly part of the further work.

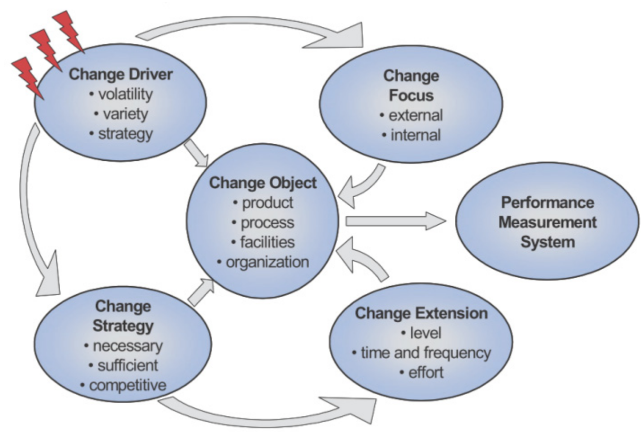


Figure 1: Framework to define Change Objects according to [2].

- The change objects in this paper are the manufacturing resources in production networks. Therefore, additional changeability enablers are identified on network level regarding the “manufacturing system to vary the production volumes of different products to accommodate changes in demand, while remaining profitable” [2]. The aspects of product mix flexibility are excluded because this would go beyond the scope of the research focus. Furthermore, sales crisis and technology changes are not cured merely through flexibility in terms of the product mix.
- The change drivers, manufacturing has to face, are based on high demand volatility, product variety and complexity as well as shorted product life cycles [1]. In line with the research question discussed in the introduction, the surveyed change driver is the demand volatility, which can be quantified by the volume fluctuation over time in accordance with Wiendahl et al. [2].
- The change focus is internal because the desired changeability in the manufacturing resource context is not aiming for additional customer benefits or other external stakeholders. Instead, an increase in performance through an optimization of internal manufacturing structures is intended. Therefore, an enhanced positioning of value creation in line with the market needs is required.
- The change strategy defines the observed production level. In this paper, the shop-floor is not explicitly considered because the operating level only impacts the defensive flexibility within a given structure in terms of a behavioral change without a configurational change, classified as the corridor of flexibility [16]. Instead, the organizational structure of the production network shall enable the manufacturing system to adopt proactively beyond this flexibility corridor [2]. For this reason, tactical and strategic levels are addressed to meet multiple futures through investments into additional options to overcome potential turbulence by deliberately relocating the flexibility corridor [13].
- The change extension classifies changeability within the structuring level of the factory. In compliance with Westkämper,

Wiendahl and Nyhuis, five factory levels can be identified on either resource or space view from the structuring level of the station to the network level (see Figure 2) [2]. Wiendahl et al. assign a certain class of changeability to these production levels to meet turbulence on specific stages. The present paper is focusing on the concept of agility within this changeability classifications as the "strategic ability of an entire company to […] build up necessary manufacturing capacity" [2]. Taking into account the network level, additional options are gained, which may not be available on shop floor level. In this context, Westkämper and Zahn recommend the consideration of dynamic, heterarchic production networks, which combine specific competences along the value creation process [1]. Especially when turbulence is of global and broad nature, network agility can meet the adaptation requirements on the highest production level. This enables a reduction of changeability constructs required on lower production level. These constructs are not considered in this paper, because they have already been analyzed extensively by Wiendahl et al [2].

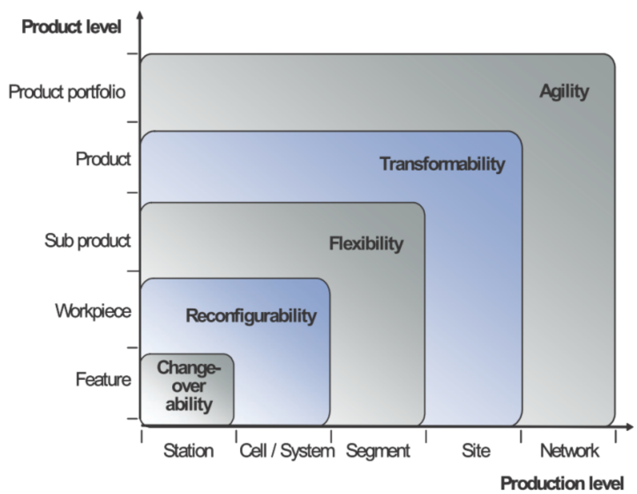


Figure 2: Classifications of Changeability according to [2].

Currently, different approaches to acquire changeability enablers exist. For example, Nyhuis et al. identify five enablers on factory level: universality, scalability, modularity, mobility and compatibility which lead to advanced options for adoption through multiple potential production routing [17]. The current paper focuses on agility on network level and therefore involves more strategic aspects like operator models, multiple future scenarios and decentralization. Hence, this paper focuses on structuring agility enablers on production network level. Therefore, agility is subsequently considered as a batch of additional options accessible through production networks.

## 4 DISCUSSION

From the potential of pooling and allying manufacturing resources within the production network, different agility enablers can be identified. These enhance the ability to modify manufacturing structures to achieve a higher strategic fit between production volume and market demand. In line with Duschek, these agility enablers have to share three characteristics to enhance agility in production networks on a long-term and goal-oriented basis: First, they should follow a strategic approach leading to a turbulence buffer to reduce the need of shop floor flexibility [9]. Second, they are applicable in terms of adapting the potentials of these enablers based on previous investments. Third, they aim for Coleman-rents based on win-win-situations in networks instead of opportunistic behavior [9].

In these terms, the consideration of operator models may be appropriate because these long-term cooperations may provide references for corporate manufacturing capacity within networks. Operator models release the utilization of infrastructure from the possession. According to Wildemann, who analyzed the success factors of operator models, two factors are critical to enable an efficient cooperation regarding the creation of additional changeability instead of just shifting risks between partners [18]. The first comes with a know-how advantage for the capacity holder. Detailed information about the usage allows a superior utilization of the resource based on "feedback to design". The second is the potential to hedge the market risks of the capacity possession through seasonally different capacity demands of the different network partners. We subsequently analyze to what extent the fulfillment of these factors is better accessible within production networks.

### 4.1 Network Pooling

Production networks, in particular heterarchic ones, are characterized by their redundant resources [19]. Therefore, the value creation of the entire network can be divided more dynamically between the network partners resulting in higher path-independency in line with Nyhuis et al. [17]. Capacity demand can be moved to network partners holding available capacity, so called production shifts [20]. Although only capacity-driven subcontracting is enabled by redundancy (not its technology-driven counterpart), the ratio of value creation and utilization on network level can be optimized and external partners become less essential [19]. This requires a high transparency of capacity availability within the network [8]. Ahlert et al. developed a holistic approach to optimize redundant network capacity management in terms of agility [14]. They state that on the one hand a production network provides the organizational format to establish a long-term capacity pool based on the network partners' expectations about the market development. In this network capacity pool, available future capacity utilization can be reserved. On the other hand, a short term "capacity on demand" pool enables the exchange between underemployed manufacturing systems. The prices for the utilization are varying according to the idea of revenue management indicating excessive or missing capacity within the network. This feedback in combination with the long-term expectation of the network partners and high capacity usage transparency form the necessary success factors of the operator model to make production networks an organizational structure to profit from redundant resources and attain Coleman-rents.

### 4.2 Network Allying

Production networks allow the distribution of the entire value creation with a higher degree of agility because its corporation partners can focus on core competences, while simultaneously depending on its network partners instead of uncertain market actors. Especially when customers request complex products, which require companies to act as full-service-provider, production networks form a vehicle to combine both – the concentration on strengths and a wide range of products and activities available in the network. The selection of network partners is critical to reach the "strategic fit" as a function of market needs and own resources [6]. On the one hand, this gives an enterprise the option to outsource non-core competence tasks to the network, while simultaneously reducing traditional market dependence and still being perceived as a full-service-provider by the customer [15]. This outside-in approach in manufacturing empowers an access to a heterogenic resource base on network level, which combines a unique selling proposition with a higher autonomy in the provided manufacturing capacity. On the other hand, the production network allows its partners to undertake tasks for other network partners, which are within their own competence range. With this inside-out approach, manufacturing opens up higher sales quantities and potential economies of scale in networks. Summing up, the allying of manufacturing capacity facilitates the elimination of non-core competence activities without neglecting complex product requirements. Furthermore, additional resources can be accessed and core competence activities can be increased by performing tasks for network partners.

### 4.3 Network Slack

Slack resources are defined as the designated excess of resources above functional demand, which form a corporate potential for changeability [21]. Production networks enable corporate slack to be lifted on network level, where it can be consolidated. This leads to economies of scope in terms of a broader scope of actions, where, e. g., investments into “low cost probes” can be combined and the results are shared [13]. In case of slack, redundancy along the hierarchic levels is dissipation. Instead, the consolidation at one central position facilitates high variances and leverages the information outcome. Above that, each network partner has the option to capitalize the entire network slack, if it is faced by change drivers not concerning the rest of the network [14]. Therefore, the centralization of slack resources contains certain potential to increase the agility enablers in production networks.

## 5 FINDINGS

The organizational structure of production networks provide significant potential to cope with turbulence in manufacturing. Therefore, redundant as well as complementary resource usage holds certain potential for additional agility. By pooling and allying manufacturing systems, three potential agility enablers arise out of information availability, natural hedge and synergy potential from combining core competences in networks: Firstly, redundant network capacity facilitates capacity-driven order shifts. Secondly, the combination of complementary manufacturing structures allows core competence concentration combined with complex product output. Thirdly, slack resources are leveraged through consolidation and allocation on strategic network level.

Turbulences can threaten the efficiency of manufacturing systems. Hence change drivers need to be faced with the available changeability on corporate and subjacent levels to maintain profitable.

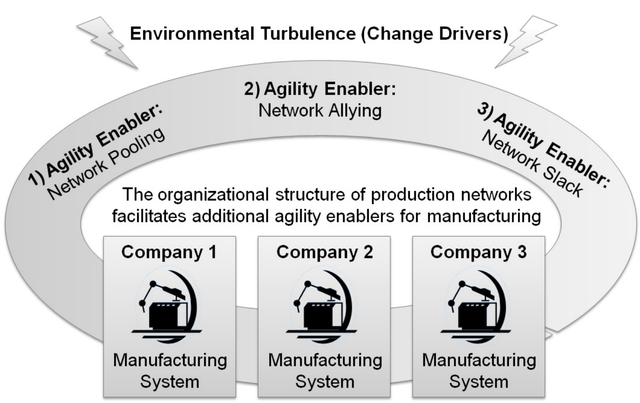


Figure 3: Agility Enablers in Production Networks.

Above that, production networks enable manufacturing companies to address change drivers like volume fluctuation on strategic level using additional agility enablers through combined resources. Therefore, changeability requirements on corporate level are diminished (see Figure 3).

To differ between pooling and allying concepts the key figure of value creation seems promising. If the value creation quota (percentages of value creation to sales) of one single production site in the network is similar to the value creation quota within the entire network this indicates a pooling concept (see Figure 4). In contrast, a spread between the value creation quota on production site level and production network level implies an allying concept. In this case the single complementary resources aggregate into higher value creation quota on network level, as products of one production site serve as input material for another production site. Therefore, the value creation quota on network level would correlate positively with the consideration of the entire quantity of network sites, while the correlation for pooling concepts should be weaker.

| Value Creation Quota as Indicator for the Agility Concepts | | |
|---|---|---|
| | Production Level | |
| | Site | Network |
| Pooling Concept | Low/Medium | Low/Medium |
| Allying Concept | Low | High |

Figure 4: Value Creation Quota as Indicator for the Agility Concepts.

It can be stated that, firstly, the three agility enablers described are reachable best within production network structures because hierarchical organizational forms require the maintenance of additional activities within the corporation, bear more market risks on its own and may hinder the access to heterogeneously distributed resources. In contrast, market structures do not provide adequate information exchange, knowledge combination and sufficient planning reliability for long-term capacity investments.

Secondly, the identified agility enablers address one of the present given manufacturing turbulences, namely the demand fluctuation over time. By pooling manufacturing structures the orders can be shifted within the network smoothing the capacity demand. Allying of manufacturing structures concentrates the company’s capacity portfolio on the core competences within the networks and eliminates other previously required activities by inside-out and outside-in approaches. Combined network slack finally favors new findings and supports manufacturing agility.

Thirdly and lastly, these three approaches lead to capabilities in the economies of scale and scope, but above that, they enable agility in terms of an adjustment of the flexibility corridor. Through a capacity on demand due to a capacity pool, more shifting options in the creation of value and higher modification potential on slack basis the corridor of shop floor flexibility can be superiorly positioned on purpose.

## 6 LIMITATIONS AND FURTHER WORK

This paper presents three agility enablers for manufacturing structures based on a theoretical production network perspective. Therefore, the examination lacks the consideration of impacts from networks for other corporate value activities like procurement, technology development or marketing. Global aspects of production networks like regional advantages were excluded. The most significant limitation of this paper however is the absence of an empirical validation. Currently, there is no established method at hand to measure the concept of agility within its strategic focus [22]. Furthermore production networks, especially intra-organizational, heterarchic ones, are classified as indirect empirical objects, which cannot be monitored straightforward; hence research of production networks requires additional preliminary work to access determinable data.

Further research is concentrating on the identification of significant indicators and typologies to quantify the impacts of agility enablers within production networks. Therefore, an industry-specific quantitative analysis is designed to determine the agility of production networks over multiple business years. Furthermore, the established dimensions of network configuration, e. g., hierarchical/heterarchical, intra-organizational/inter-organizational and vertical/horizontal need to be considered regarding their impact on the identified agility enablers.

## 7 ACKNOWLEDGMENTS

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# End-of-Life Indices to Manage the Demanufacturing Phase during the Product Design Process

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**Abstract**

The increase in product disposal rates and the speed of technology development are creating a new challenge in the waste management field. In this context, it is becoming even more important to evaluate the impacts of products at their End of Life (EoL), during the early design stage. The paper presents an approach to determine the most convenient EoL scenario for each product component from an environmental and economical point of view. The designer is aided in making choices through five EoL indices, one for each EoL scenario (Reuse, Remanufacturing, Recycle, Incineration and Landfill). The EoL indices have been used to evaluate the environmental and economical sustainability of the EoL scenarios for a cooker hood during a re-design process.

**Keywords:**

EoL indices; demanufacturing; closed-loop lifecycle

## 1 INTRODUCTION

Over the last few years, waste management and the reduction of raw material consumption have become important issues for society. In this global context, environmental consciousness is rapidly becoming a fundamental focus of product design in a wide variety of industries. This is due to the increase of product disposal rates, the speed of technology development and the changes in interactions between consumers and products.

Demanufacturing [1] can be defined as the reduction of a product into its individual components with the aim to reuse or remanufacture the parts and to recycle (if the first two possibilities are not applicable) the materials. It is very important to accurately manage the demanufacturing phase during the early design stage, when designers can change different characteristics of the products, such as component materials or component connection methods, with minimal impact on the manufacturing process or production costs. This is an excellent opportunity for designers familiar with the development of industrial products with an appropriate End of Life (EoL) scenario.

In this context, the paper presents an approach to evaluate the most convenient EoL scenario for each product component from an environmental and economical point of view. This method aids the designer in making choices through five EoL indices, one for each EoL scenario (Reuse, Remanufacturing, Recycle, Incineration and Landfill). These indices are based on a set of economical and environmental parameters (demanufacturing cost, economic value of recycled material, energy savings between production of recycled materials and virgin materials, etc.) that are characteristic of each EoL strategy and well-known by the demanufacturing stakeholders.

For the designer, the evaluation of these EoL indices produces quantitative feedback about the possibility of product components being reused, remanufactured or recycled at the EoL. Through the evaluation of such indices, the designer is now guided during the product redesign with the aim of improving its disassemblablity and favouring, as a consequence, closed-loop strategies. The advantages of such a methodology become more important with increasing product complexity because the product EoL and demanufacturing criticalities are easily highlighted.

## 2 STATE OF THE ART

The accurate estimation in the early design stage of the possible EoL scenarios is emerging as a fundamental eco-design strategy for companies that must assume responsibility about the product EoL due to, for example, regulatory requirements. [2]. In fact, in recent years, the EU (European Union) has issued directives about the end-of-life of vehicles, the restrictions on the use of hazardous substances and the disposal of electronic and electrical products and equipment, all of which force manufacturers to respect environmental issues related to the end of life [3] [4] [5] [6]. Furthermore, managing the EoL strategies reduces the cost of product disposal and can increase the revenue for companies which can recover components or materials [7].

Product EoL is a key phase of the product lifecycle because is the stage when the closed-loop of materials can be realized. It is well known that although only 5-7% of the entire product cost is related to early design, the decisions made during this stage affect 70-80% of the total product cost. That is, whether a product is relatively sustainable is largely determined during the early design stage [8]. Products need to be designed to reduce the amount of waste going to landfills, favouring closed-loop scenarios in which materials can be recovered and, as a consequence, the production of new virgin materials can be reduced [9].

The determination of the best EoL option for products and components is a problem that has to be faced by manufacturers. The development of a decision model to select between these options requires the consideration of various qualitative and quantitative factors, such as environmental impact, quality, legislative factors, cost, etc. [10]. In the literature there is an high number of studies concerning this important topic. For example, an interesting DFD (Design for Disassembly) index to evaluate efficient EoL treatment is described by Dewhurst [11]. This index can be used by designers to evaluate the beak-even point at which disassembly operations should be stopped; beyond this point the disassembly costs are greater than the revenue. Bufardi et al. [12] propose a multiple criteria decision aid (MCDA) method for supporting users in the selection of the best scenario for treating an EoL product on the basis of their preferences and the performances of the EoL scenarios with respect to the relevant criteria. Chan [13] extends this proposal using a Grey Relational Analysis to rank the

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EoL options under the uncertainty condition of incomplete information. Another method and its related tool are presented in [14]. The potential benefits of developing a footwear product recovery methodology and an associated software tool to aid the decision-making to determine the most suitable (in environmental, economic and social–technical terms) manner in which to treat post-consumer shoe waste are presented in [15]. Gehin et al. [16] propose a new approach to integrate EoL strategies in the early design phases to apply 3R (Reuse, Recycling and Remanufacturing) strategies considering the evolving architecture of the product and the translation of transversal information into design criteria. This work also highlights that the new challenge for industrial companies is to achieve a profitable business market based on product retirement, with the reintroduction of parts of the EoL products in a “second life”. From the dismantler point of view, the economic parameters that generally influence the different closed-loop scenarios can be summarised as the costs for the demanufacturing, cleaning, reverse logistic and Remanufacturing/ Refurbishing/Regeneration [17].

The environmental load can be analysed case by case using the Life Cycle Assessment (LCA) method, which allows the environmental impact of the whole product lifecycle to be measured. However, this methodology only considers environmental items and this represents a well-known limitation.

From the literature review emerges a lack of analyses of EoL scenarios and a lack of suggestions given to the designer for EoL alternatives of their products/components. No indices that take into account all the economic and environmental aspects described above have been previously presented. In this context, this paper aims to overcome these limitations by defining an index for each of the most common EoL scenarios for industrial products. All these indices are calculated using data and parameters that are characteristic of the required treatments (cleaning operations, recycle of materials, refurbishment, etc.) for each EoL strategy, which guarantees the accuracy and the significance of the analysis. The proposed approach yields a quantitative indication of the most convenient EoL treatment for each product component/sub-assembly. By considering this aspect during the early phases of the design process, designers are guided in the improvement of their product features in order to increase the amount of materials and components with a closed-loop lifecycle.

## 3 METHOD

The aim of EoL management is to realise a closed loop of materials through the implementation of one of the possible end-of-life strategies. Because products can vary significantly in their components or sub-systems, there are many potential scenarios, and some components could be more effectively recycled, reused or remanufactured than others.

Five new indices are proposed below to aid designers in choosing the correct end of life scenarios for each component, with the aim of improving closed-loop scenarios for products. These indices are able to define the best scenario for each component or subassembly, providing a quantitative value on the basis of a set of economic and environmental parameters. The indices help designers during the design phase with the selection of component materials, connection methods between the components and layout of the components to decrease the economic and environmental costs of the products when they are disposed. The indices will drive the service department (during the maintenance phase) and the dismantlers (during the EoL phase) to choose the most convenient solution for each specific component. Although currently there are EoL regulations only for few typology of products, such as electrical equipment and electrical vehicles, the proposed index methodology could represent a competitive advantage for companies, since that in the near future international governments will certainly issue more cogent regulations about EoL, to the aim of facing the waste problem. In the paragraph 3.1 the five EoL indices are presented and in the following one, the parameters introduced and used within the 5 formulas are shown.

### 3.1 EoL Indices

*Reuse Index*

The reuse index considers the possibility of a given component being reused in the same product (or in similar products) and involves only the typology of the component, not the material with which is made (Equation 1). This EoL scenario is possible only when the component’s lifetime is longer than the lifetime of the product.

$$I_{EOL-Ru} = \frac{C_p - C_c - C_{RL} - C_d}{C_r} \tag{1}$$

The index value can theoretically vary from $-\infty, to + \infty$ (this is true for all the other indices, except the landfill index ). Four cases are distinguished below:

$\text{Num.} > Denom. \quad \forall\, Cp, Cc, C_{RL}, Cd, C_r > 0 \quad \Rightarrow \quad I > 1$

$Num. < Denom. \quad \forall\, Cp, Cc, C_{RL}, Cd, C_r > 0 \quad \Rightarrow \quad I < 1$

$Num. = 0 \quad \forall\, Cp, Cc, C_{RL}, Cd > 0 \quad \Rightarrow \quad I = 0$

$|Num.| = |\text{Denom.}| \quad \forall\, Cp, Cc, C_{RL}, Cd, C_r > 0 \quad \Rightarrow \quad I = \pm 1$

In particular, there are three important ranges with related consequences:

$(+1, +\infty)$: reuse is suitable and is economically beneficial;

(0,+1]: reuse is suitable, but there is an economic benefit only if the production cost of the new component is higher than the regeneration cost of the component;

$(-\infty, 0]$: reuse is not suitable.

*Recycle Index*

The recycle index compares the difference between the production costs for virgin materials and the cost of the recycling process (Equation 2). In particular, it takes into account the energy savings resulting from the recycling process of a material. Another important parameter for the calculation of the recycling index is the quantity of material that can be recycled (recycling factor) in the current supply chain. This index establishes the real effective opportunity in terms of energy and cost reduction.

$$I_{EOL-Rc} = \frac{(m \cdot R_f \cdot C_{RC}) + (m \cdot E_s \cdot C_E) - C_c - C_{RL} - C_d}{C_m \cdot m} \tag{2}$$

$\text{Num.} > Denom. \quad \forall C_m, C_E, E_s, R_f., C_{RC}, C_c, C_{RL}, C_d > 0 \Rightarrow \quad I > 1$

$\text{Num.} < Denom. \quad \forall C_m, C_E, E_s, R_f., C_{RC}, C_c, C_{RL}, C_d > 0 \Rightarrow \quad I < 1$

$\text{Numerator} = 0 \quad \forall C_m, C_E, E_s, R_f., C_{RC}, C_c, C_{RL}, C_d > 0 \Rightarrow \quad I = 0$

$|\text{Num.}| = |\text{Denom.}| \quad \forall C_m, C_E, E_s, R_f., C_{RC}, C_c, C_{RL}, C_d > 0 \quad \Rightarrow \quad I \pm 1$

This index can be separated into the same 3 ranges:

$(+1; +\infty)$: recycling is environmentally and economically suitable;

$(0; +1]$: recycling is economically suitable only if the recycle cost is lower than $C_m$;

$(-\infty; 0]$: recycling is not suitable.

*Remanufacturing Index*

The remanufacturing index evaluates the possibility of a component being regenerated on the bases of different cost types and revenues involved in the "Remanufacturing loop" (Equation 3). This index contains many parameters, similar to the recycle index, so it is characterised by a more variability than the other indices.

$$I_{EOL-Rm} = \frac{C_p - (m \cdot E_s \cdot C_E) - C_{RL} - C_d - C_c - C_{ReMan}}{C_r} \quad (3)$$

$\text{Num.} > Denom. \forall, C_E, E_s, C_p, C_c, C_{RL}, C_d, C_{ReMan}, C_r > 0 \Rightarrow I > 1$

$\text{Num.} < Denom. \forall, C_E, E_s, C_p, C_c, C_{RL}, C_d, C_{ReMan}, C_r > 0 \Rightarrow I < 1$

$\text{Num.} = 0 \quad \forall, C_E, E_s, C_p, C_c, C_{RL}, C_d, C_{ReMan}, C_r > 0 \Rightarrow I = 0$

$|\text{Num.}| = |\text{Denom}| \ \forall, C_E, E_s, C_p, C_c, C_{RL}, C_d, C_{ReMan}, C_r > 0 \Rightarrow I = \pm 1$

This index also has 3 important ranges:

$(+1; +\infty)$: remanufacturing is environmentally and economically suitable;

$(0; +1]$: remanufacturing is economically suitable only if the regeneration cost is lower than $C_r$;

$(-\infty; 0]$: remanufacturing is not suitable.

*Incineration Index*

The incineration index establishes if particular combinations of materials can be directly incinerated for energy production (Equation 4). The incineration, in fact, is an opportunity for the EoL treatment of particular materials with a high heating value or for materials that cannot be easily recycled. In this case, the components can be separated by destructive demanufacturing techniques and the demanufacturing operations can be made without special attention. The time required for demanufacturing is therefore greatly reduced.

$$I_{EOL-Inc} = \frac{(m \cdot P_c \cdot C_E) - C_{dd}}{C_m \cdot m} \quad (4)$$

$\text{Num.} > Denom. \quad \forall C_m, C_E, P_c, C_{dd} > 0 \Rightarrow I > 1$

$\text{Num.} < Denom. \quad \forall C_m, C_E, P_c, C_{dd} > 0 \Rightarrow I < 1$

$\text{Num.} = 0 \quad \forall C_m, C_E, P_c, C_{dd} > 0 \Rightarrow I = 0$

$|\text{Num.}| = |\text{Denom.}| \quad \forall C_m, C_E, P_c, C_{dd} > 0 \Rightarrow I = \pm 1$

This index can also be considered inside the three major ranges:

$(+1; +\infty)$: incineration is environmentally and economically suitable;

$(0; +1]$: incineration is environmentally suitable, but it is economically suitable only if the profits given by incineration are higher than the cost of the new product;

$(-\infty; 0]$: incineration is not suitable.

*Landfill Index*

The placement of a product at the end of its life in a landfill does not generate any benefit from an environmental point of view and, therefore, must never be considered a sustainable EoL treatment. In some cases, however, landfill is an inevitable alternative (i.e. composite materials). Landfill treatment, by its nature, does not require careful demanufacturing and, therefore, the related costs are low. Only when all other possible EoL treatments are not profitable for the selected component should the landfill index be estimated (Equation 5).

$$I_{EOL-Lf} = \frac{(-C_l)}{C_p} \quad (5)$$

Only two cases are presented for this index, in fact its value can be at most equal to zero, because the numerator is never positive ($-C_l$):

$C_l \ll C_p \quad \forall C_l, C_p > 0 \Rightarrow I \to 0$

$C_l \gg C_p \quad \forall C_l, C_p > 0 \Rightarrow I \to -\infty$

$If\ I_{EOL-Lf} \to 0$, placement in a landfill is suitable.

$If\ I_{EOL-Lf} \to -\infty$, placement in a landfill is not suitable.

### 3.2 The Parameters

In this paragraph are reported all the parameters that constitute the previous 5 formulas:

$C_p$ is the value of the part at the EoL considering deterioration due to use [€]. It is evaluated on the basis of factory experience or on the basis of statistical data. The survey is done according to the deterioration grade due to its lifecycle;

$C_c$ is the cost of cleaning operations to regenerate the part [€]. It considers the cleaning area, the operator cost and the types of tools required;

$C_d$ is the cost to disassemble parts [€]. This is calculated considering the operator's cost per hour multiplied by the time required to complete each disassembly operation. The time necessary to complete each operation is calculated according to the type of connection and the related correction factors, which are introduced to take into account the level of difficulty in the disassembly that is influenced by, for example, the condition of the connection at the end of life, the mass and volume of the linked components, the use of specific tools for the operation and so on [18];

$C_r$ is the cost of items/parts to be replaced (material production and manufacturing cost for the same new part) [€]. It is provided by the component supplier;

$m$ is the mass of the disassembled part [kg];

$R_f$ is the recycling factor [dimensionless] that can be found in a common materials database;

$C_{Rc}$ is the economic value of the recycled material [€/kg]. It can be found in a common materials database that is linked to on-line databases with material data;

$E_s$ is the difference between the production energy necessary to obtain the virgin material and the recycling energy necessary for the material recycling treatment [MJ/kg]. It is calculated from information in common materials databases and the data elaborated by factories involved in recycling processes;

$C_E$ is the cost of energy [€/MJ]. It depends on the type of energy contract between the factory and the supplier

$C_m$ is the production cost of virgin material [€]. It is provided by the component supplier and depends on the type of material and type of production chain. It can also be extracted from specific European databases;

$C_{RL}$ is the cost of reverse logistics, including the transportation system from retailers to the dismantling centres and from the dismantling centres to different suppliers [€]. This value can be estimated by taking into account the volume of the components [$m^3$] and an estimated cost per unit of volume [€/$m^3$], and it depends on the transportation method (train, truck, ship etc.);

$C_{ReMan}$ is the cost of refurbishment for the specific components considering the inspection phase, the regeneration process or the remanufacturing operations necessary to obtain the new part starting from the selected component [€]. This value is provided by the refurbishing factory;

$C_l$ is the cost for placing the part in the landfill [€]. This cost considers EoL treatments such as pollutant separation, product compaction and transportation. This is estimated by the landfill manager;

$P_c$ is the material heating value [MJ/kg]. It is provided by the technical databases containing the lower heating value;

$C_{dd}$ is the demanufacturing cost of parts in relation to the destructive operations of demanufacturing [€]. This parameter considers the operator cost and the tools and/or machines used during demanufacturing and is provided by the demanufacturing factory;

### 3.3 Interpretation of EoL Indices

The designer can make clear decisions by comparing the values of these indices for each component. On the environmental side, there is a priority list in which reuse is the best option, followed in order by remanufacturing, recycling, incineration and landfill. However reuse cannot be applied when there is a changing in the external shape of the new components or product that often is required by market strategies (such as the cover of an household appliance), while reuse could be a good strategy when the component is inside the product and it is not showing (such as the electric motor of an household appliance).Despite the fact that reuse should be the best EoL scenario (when it can be applied), the indices contain cost parameters so that the choice is influenced by the economic benefit of each scenario. In the previous paragraph, a series of ranges of values have been given for each index, so all the indices must be interpreted for all the respective ranges. It is worthwhile to note that some scenarios are not always possible; for instance, composite materials cannot be recycled as they are made of thermosetting polymers. Commonly, the indices are spread across the three ranges, in which case the choice is clear (the most positive index is the correct choice). Instead, if all the indices are in the same range, the selection of the best choice is more complex and it requires certain considerations and the comparison of a couple of indices at once. In the next section, this type of approach has been used to interpret the values of the EoL indices.

*The first range considered is (+1; +∞)*

In this range, there are only the first four indices to consider; the landfill index can never be positive, at most it can be equal to zero because there can be no economical gain through the use of the landfill, even if the cost of the landfill is low. Due to the current manufacturing and demanufacturing technologies, it is unlikely for all of the indices to be positive.

*Incineration and recycle indices:* incineration is more economically suitable than recycling if the material's component has an high heating value, as the energy that can be extracted is high.

*Incineration and reuse index:* in this case, we must consider that incineration is more economically suitable if the income generated by the material combustion that supplies the energy is higher than the cost of the new component.

*Incineration and remanufacturing indices:* in this case, incineration is more economically suitable if the profits given by the production of energy are higher than the cost of the new component. In reality, incineration is more economically suitable than remanufacturing only if the net profit of the energy generated is higher than the cost of the new component minus the cost required for the component remanufacturing.

*Reuse and recycle indices:* recycling is preferable over reuse if the income generated by the recycling of the material is higher than the cost of the new component. The hypothesis that a recycled material can have an higher value than a virgin material is improbable, so reuse in this case is preferable over recycling.

*Recycle and remanufacturing indices:* recycling is preferable over remanufacturing if the income generated by the recycling of the material is higher than the cost of the new component minus the remanufacturing cost.

*Reuse and remanufacturing indices:* both reuse and remanufacturing are optimal choices because they exploit a component that was previously used. However, remanufacturing adds value to the component during the design and production phases. Hence, while remanufacturing may produce a lower economic benefit than reuse, it gives the component the same characteristics and performances of a new component. The designer has to particularly take into account the technological and functional aspects of the component in this comparison.

*The second range considered is* $(0;+1]$

As discussed previously, for this range, the economic benefits occur only with specific conditions that vary for each index. If all the indices are positive, the designer must select the scenario with the most positive value. For the comparison of the reuse and remanufacturing indices, the designer must consider not only the index value but also the benefit related to the economic savings associated with the absence of purchasing a new component.

*The third range considered is* $(-\infty;0]$

For this range, the scenario with the index closest to zero should be chosen. For scenarios with very negative values, the designer must consider revising the project, evaluating possible changes in those components with the largest impact to improve at least one of the reusing, recycling and remanufacturing scenarios so that an index has a positive value. Despite the fact that negative values are not desirable, they could occur in cases with products that are not eco-friendly, so it is important to describe them.

*Recycle and incineration indices*: both recycling and remanufacturing are not economically sustainable, but they are, however, useful for mitigating the increase of landfills. The choice should be made based on the minimisation of the waste size produced.

*Reuse and incineration indices:* once again, in this case, both choices are not economically sustainable. However, if the reuse index has a more negative value than the incineration index, incineration is not preferable because the cost of the new component has to be considered and added to the cost of incineration.

*Reuse and recycle indices:* for this comparison, the aforementioned considerations (the recycle cost replaces the incineration cost) remain valid.

*Reuse and remanufacturing indices:* in this case, the choice should be made based on the performances required. If the goal is to have additional value in the component, then remanufacturing is preferred. If a specified performance is not required, reuse is preferred.

*Remanufacturing and incineration indices:* in the case of remanufacturing, the waste size produced is zero; moreover, there is no additional cost to purchase the new component.

*Recycle and remanufacturing indices:* see the previous comparison.

## 4 CASE STUDY

The EoL indices reliability have been calculated in the field of household appliances and, in particular, the presented case study is on a wall cooker hood with a maximum aspiration capacity of 660 $m^3$/h. The cooker hood is widely used due to its importance inside the kitchen; hence, it is imperative to orient the design toward a closed-loop scenario (i.e., reuse or remanufacturing), also considering its numerous high-value components (from an environmental and economical point of view).

The calculation and analysis of the proposed indices have been carried out in collaboration with a company that desires to improve the eco-sustainability of their product through the development of products with closed-loop scenarios. Following this goal, the indices have been evaluated for a product currently sold by the company (configuration referred to as Old Configuration, or O.C.). The analysis of the indices allowed the designer to create a new solution (New Configuration, N.C.). The indices were evaluated again as soon as the cooker hood was re-engineered.

| EoL Strategies | Old Configuration | New Configuration |
|---|---|---|
| Recycle | 6,2% | 38,5% |
| Reuse | 1,1% | 16,8% |
| Remanufacturing | 3,2% | 7,2% |
| Incineration | 0,6% | 0,6% |
| Landfill | 84,3% | 32,3% |
| Different treatment | 4,6% | 4,6% |

Table 1: Percentage of cooker hood masses treated for each EoL scenario for the old and new product configurations.

Using the EoL indices (one for each EoL scenario), the company was able to establish the percentage of product mass treated with a specific scenario for the old and new product configurations (Table 1). The achieved environmental benefits (reduction of waste) were possible due to the following product improvements:

- reduction in the number of materials;
- reduction in hazardous material;
- use of easily disassembled joints;
- use of compatible materials for those components to be recycled without any disassembly;
- reduction in the number of components;
- use of environmentally friendly materials.

In this study, two specific modules of the cooker hood have been considered: the blower system and the electrical system support. The modules have been considered due to their environmental and economical relevance inside the product and due to the legislation that governs specific components (for example WEEE [5] for the electrical system). The electric motor, for instance, is made of materials with high economical value, such as copper, and hazardous components, such as the capacitor.

### 4.1 Blower System

The blower module, responsible for air movement, consists of a conveyor system, an electric motor and a rotor. This is the central module of the cooker hood and it is made of different materials (mild steel and thermosetting plastic). In addition to the possible recycling of the blower system, the importance of reusing or remanufacturing electric motors is another important feature of this analysis. The greatest problems of the old configuration, which does not feature an economical, closed-loop scenario, are the difficulties in disassembling the joints and by the variety of materials used. The new solution is characterised by the use of snap-fits to connect the two shells of the blower instead of screws (Figure 1) and by the use of a unique type of plastic (Polypropylene). As reported in Table 2, for the new configuration, the recycling scenario becomes the best EoL treatment. The other indices with negative values indicate that the particular EoL scenario is not convenient because demanufacturing costs are greater than the economic revenue of the components or materials.

### 4.2 Electrical System Support

Improving the disassemblability of the Electrical System Support is related to the management of the PCB (Printed Circuit Board), Capacitor and Transformer that are linked to it. The original design is characterised by a galvanized steel support to which all the previously listed items are attached using nut and bolt systems. This module is critical both during the maintenance and EoL phases because it must be disposed of following specific rules (see WEEE [5]); thus, it is important ensure an easily disassembled method. The new design consists of an Electrical Box containing the entire Electrical System, linked to the hood by cylindrical snap-fits to guarantee a rapid separation of the entire hood (Figure 1). The Electrical Cover and the Electrical Box are connected with rectangular snap-fits. Another important feature of the new design for the Electrical System is the use of Polypropylene plastic for the construction of the box.

### 4.3 Discussion of Results

Through the analysis of the EoL indices of the old configuration, the designers have been able to determine the aspects of the modules with the highest impact, which has led to the redesigning of the modules components to improve the demanufacturing capacity.

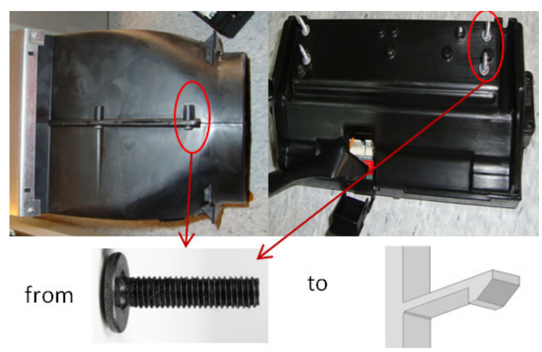


Figure 1: Substitution of fasteners with snap-fits to facilitate blower system disassemblability.

| Sub-assembly | BLOWER S. | | ELECTRICAL S. | |
|---|---|---|---|---|
| Configuration | O.C. | N.C. | O.C. | N.C. |
| Material | different materials | PP f.r. | different materials | PP f.r. |
| $I_{EoL-Ru}$ | / | / | / | / |
| $I_{EoL-Rm}$ | / | / | / | / |
| $I_{EoL-Rc}$ | -79,30 | 0,70 | -44,70 | 9,40 |
| $I_{EoL-Inc}$ | -34,20 | -16,90 | / | -8,90 |
| $I_{EoL-Lf}$ | -49,20 | -26,80 | -12,70 | -10,30 |

Table 2: Comparison of the EoL indices calculated for the two modules, relative to the old and new configurations.

Table 2 reports the five indices calculated for the modules presented above. In this case, the indices are not all in the same range; thus, the decision for each module is simple for the designer. In particular, for the blower system in the new design, the best scenario is recycling, with environmental and economic benefits. The same is true for the electrical system, though the reuse index is positive because the gap between the two indices is high. As is shown in Table 2, the reuse and remanufacturing scenarios for the two modules have not been considered because it is not possible to reuse or re-adapt them for new products. The improved benefits achieved with the redesign process are related in particular to the reduction of actions required to disassemble the module through the substitution of threaded connections with snap-fits. Future advancements of technologies related to the automation of the demanufacturing processes will further decrease this cost.

## 5 CONCLUSION

The waste management field is becoming an important and challenging area, especially for companies that are looking for products that are eco-sustainable for their entire life cycle, including the EoL. This paper is a step beyond the state of the art because it proposes numerical indices to evaluate the most environmental and economical EoL scenarios, which can be used by designers without any type of specific knowledge related to the dismantling processes. Using these indices, it is possible to quantitatively estimate how a product is compliant with a specific EoL strategy. As explained in the State of the Art section, the cost impact of performing this analysis is minimal in comparison to the cost of the entire product. Moreover, when new regulations will be issued this kind of analysis will necessarily have to be performed by companies before launching new products in the market. The case study is related to a cooker hood belonging to the WEEE, one of the world's most important waste categories. It demonstrates the usefulness of the index methodology in helping designers in the improvement of the product EoL performances.

Future works will involve the study of the EoL processes for products and components belonging to the WEEE category. The aforementioned processes are related to the cleaning activities required to restore the product properties, to the reverse logistics, i.e., the transportation phases to manage the waste (this item often depends on local organisations) and to the refurbishment activities that are specific for each product. Additionally, further work consists of the development of a software tool and a related database that can be used for the implementation of the proposed approach. This is a necessary step for the large and effective implementation of the method within companies, which will make it available to designers. Finally, another next step is to realise a normalisation of the five indices in order to make comparable in an easier way the values calculated for each index.

## 6 ACKNOWLEDGMENTS

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# Data Interface Concept for the Connection of Applications to Web-Based Systems

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**Abstract**

Data exchange between applications and servers is always a risky theme from the IT department point of view, because confidential data has to be kept secure. Usual direct connections make it necessary to get approved by the IT department before they can be used inside of the company what makes it expensive and takes a lot of time. The concept shows the possibilities of an alternative approach by connecting applications via the browser control element to a server and the corresponding opportunities as well as the advantages in saving the main program logic server side.

**Keywords:**

Data Interface; web-based; Data Security

## 1 INTRODUCTION

High data quality and continuous processes are key factors for most enterprises. Many of those companies use different software solutions with several interface problems, especially when the data flow crosses the enterprise boarders and has to be special secured, like e.g. by working with suppliers. The aspects of front-loading to increase the efficiency and product quality need accelerated ways to handle the necessary and sensitive data. Standard software is often able to create direct online connections, e.g. to a server, but enterprises are suspicious regarding the security. Furthermore the different departments are often interested in getting information as early as possible to react and plan early as well. As an example, one could think of the production planning which must organise the required resources before the start of production. Best case would be if the given information is always binding, but in most cases the information changes over the time and gets binding in a late project state. Continuous data flows without unnecessary interfaces over department and division boarders seem to be a desirable solution.

The following concept describes an alternative possibility how applications can exchange data in an already secured way, by using web-based systems as an interface. Section 2 starts with explaining the main idea and describes afterwards the data exchange process, section 3 will point out further advantages before it ends with the conclusion.

## 2 DATA INTERFACE CONCEPT

### 2.1 Main Idea

Usually the intranet connections of companies are already secured, often by their own IT departments. By using the browser control element, which is accessible from most Windows applications and every application supporting “visual basic for applications” (vba), it is possible to transfer the data directly via these connections. This has the very positive effect, that every existing security implementations can be used, as e.g. basic SSL encryption (secure socket layer) or the public key infrastructure (PKI) security system to encrypt the data personal for the data transfer and to clearly identify every user at the server. This accelerates also the approval process by the IT department because the data security is not anymore a big issue.

So the difference to usual connections is to connect not to a source directly, what is not necessarily transparent to the IT department and what might then does not fulfil their requested security requirements (s. Figure 1). Otherwise the IT department would have to analyse all source codes involved into the transmission process, while this concept reduces this work load by checking if the integrated browser (s. Figure 1) is only connecting to a defined and secured server.

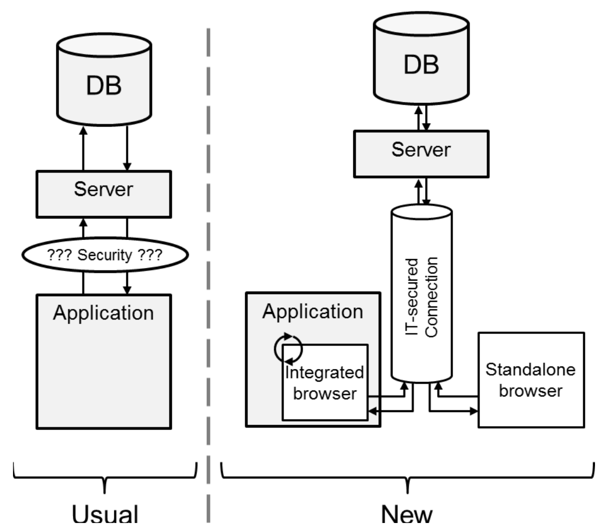


Figure 1: Comparison of usual and new concept.

By using the browser control there are different implementation possibilities. One with a hidden control, so that the data exchange takes place in the background or one where the control is also used as a graphical user interface (GUI) to deliver information and control abilities (menus, buttons, etc.) like an assistance. In the second case it might be also useful to give additional direct access with a standalone browser, so without a linked application. For some departments it is often not necessary to get e.g. a 3D view with CAD functionalities. Maybe as an example the production planning only wants to have a look at the actual bill of materials (BOM) of a current development project. That can be done with a standard browser and involves this department in a very early state, what gives the opportunity to take part of the development by providing constructive feedback.

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With the described new solution (s. Figure 1 on the right) it is possible to develop applications which can work at the client computer in a nearly closed environment and use the already secured and established connections to exchange data with a server (s. 0) what allows also cross-application data exchange. It is furthermore possible to work with a browser (included or standalone) instead of an independent application what has the side effect, that the application implementation (i.e. the source code) of the software is hidden on a server, so that the key knowhow is not accessible from the client. The linked applications in that case only need to provide necessary functionalities of their application so that they can work with or support the integrated browser control.

### 2.2 Data Exchange

In the following description the standard browser control of windows is used, which is in most parts comparable to the Internet Explorer.

This control has different events, which can be triggered. Useful is the event ‘TitleChange’ which is always triggered when the title of the loaded internet/intranet page changes. If the title is not needed for other purposes, this event can be used to control the data exchange. The page can trigger the event by itself with a JavaScript function and the vba source code can catch this event and react.

If the loaded page includes some defined hidden form fields for the data exchange, the JavaScript code can fill in these fields and trigger afterwards the event by changing the title. The vba code reacts on the event and access those form fields to interpret the given data.

For different and bigger amounts of data or orders to execute it is helpful to use standards like XML because they can be easily parsed afterwards [1]. The XML-data could include orders to start (like a macro) and additional needed parameters what gives the opportunity to build assistances (s. Figure 2).

```
<xml>
    <order name=“insertElement“>
        <param name=“type“ value=“Screw“ />
        <param name=”name” value=”M6x20 10.8” />
        <param name=”partname” value=”N12345678” />
    </order>
</xml>
```

Figure 2: Exemplary XML-order with parameters.

When the called vba function has finished, the results can be stored in the same or different form fields and be sent with usual HTML/JavaScript-functions triggered as well by the vba code.

If a complete reload of the page after sending the data is not necessary, AJAX (Asynchronous JavaScript and XML, allows asynchrony data exchange of a web-page and a server) could be used, what accelerates the exchange process with the server by reducing the amount of additional transfer data [2].

## 3 FURTHER ADVANTAGES

### 3.1 Tailored Views and External Access

A rights and role management on the server can allow and deny access requests on different levels. This makes it possible on the one hand to control the data access centrally for each employee and on the other hand it enables the company also to grant tailored access for external suppliers.

Furthermore server generated web-pages can deliver tailored views for the different user groups of e.g. different departments. They can be server side generated in an ergonomic way to support the usability and with it the acceptance of the system (s. [3]).

### 3.2 Central and Safe Program Logic

The presented system keeps most information and knowledge on the server, including the main program logic with the source code. There it is not accessible from a client computer what raises the IT security barriers.

The implementation of standards for the data exchange as described above facilitates the clear splitting of the program logic in a server and a client part. On the client it is only necessary to keep relevant functionality depending of the application while the server supports the clients with the program logic, data management, rights and role management, etc.

Also the maintenance and optimisation of the source code is easier if it is centrally organised, so that only the small macro like pieces on the distributed clients have to be up to date. But if they are developed in a farsighted way, updates should not be very often necessary. At least not on the client side, because the (improved) GUI is generated at the server.

### 3.3 Supporting Modern Devices

With an implementation as shown before, it is also possible to support modern devices like tablets and smartphones. Including the ability to generate device tailored views to support different screen sizes it should be easy by using templates (s. CSS in [1]) and facilitates the use of portable devices. Conclusion

The presented concept enables companies to use established secured connections to transfer (confidential) data from applications via the standard browser control to servers and back what allows also cross-application data exchange. Because already established and secured connections are used, the concept implementation is proportionate easy and will accelerate the approval process of the IT department. It has been pointed out that the concept includes the possibilities to give also controlled access to the web-services with a standard browser where linked applications are not necessary and to give suppliers controlled and restricted access.

Furthermore it has been explained that the integrated browser in the linked applications can work as an assistance on the client side to empower (partly) automated support when it uses macro-similar approaches.

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# Approach for Reducing Data Inconsistencies in Production Control

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**Abstract**

Companies of the manufacturing industry gather a high number of different high-resolution data concerning production and manufacturing processes. Advanced Planning and Scheduling Systems use these data sets collected on the shop-floor in order to adjust their scheduling for near- and middle-term production orders. Usually, the quality of these production feedback data is reduced by inconsistencies and errors which impairs the results of the planning process. The consequence is a low adherence to planned delivery dates. In this paper typical data inconsistencies are analysed for their rate of occurrence and an approach for reducing data inconsistencies by applying association rule induction is proposed.

**Keywords:**

High-resolution production data; Data inconsistencies; Association rule induction

## 1 INTRODUCTION

Today, manufacturing companies from high-wage countries like Germany are facing multiple challenges: Driven by a rising competition from companies residing in emerging markets and by increasing customers' demands, manufacturing companies need to be able to provide highly individualized products at short delivery times. A recent study by the Laboratory for Machine Tools and Production Engineering (WZL) shows that, in the context of this accelerating market dynamic, manufacturing companies which focus on a high adherence to promised delivery dates as their main logistic target, can consistently exceed their competitors' performances [1].

In recent decades, production planning and control (PPC) has become a more and more complex task which needs to compensate for ever-changing circumstances like last-minute wishes from customers concerning product features and delivery dates [2]. Consequently, manufacturing companies rely on a number of specialized IT-systems such as Advanced Planning and Scheduling Systems (APS-Systems) to support their PPC processes [3]. In order to feed these IT-systems with relevant information, companies of the manufacturing industry gather a high number of different high-resolution data concerning production and manufacturing processes [4]. APS-Systems use these data sets collected on the shop-floor in order to adjust their scheduling for near- and middle-term production orders.

Usually the quality of this collected data is reduced by a number of inconsistencies [5]. Using this compromised data as the basis for future planning, will inevitably have negative effects on the results of the planning process. The consequence is an unrealistically planned production schedule which leads to higher lead times, higher work-in-progress and ultimately to a bad adherence to promised delivery dates. Therefore, production feedback data sets with high integrity can be considered an important prerequisite for daily production planning operations. By effectively increasing the accuracy of planned production programs, these companies will achieve a better adherence to promised delivery dates which equals a considerable competitive advantage.

Within the publicly funded research and development project "Cluster of Excellence - Integrative Production Technology for High Wage Countries" we aim to develop an online platform for self-optimising production control based on planning simulation runs. As a prerequisite, typical data inconsistencies are analysed in this paper for their rate of occurrence and ranked by their severeness concerning these simulation runs. A methodology is proposed in order to increase data integrity in production control by reducing inevitable inconsistencies without introducing a high bias. This paper focuses on estimating the utilized work station by applying association rule induction on real production feedback data sets.

## 2 STATE OF THE ART

Manufacturing companies produce and gather extensive amounts of high-resolution data for production planning and control. Planning data involves information about each process step of all production orders such as quantities, earliest and latest start- and end-dates as well as necessary resources or work machines with corresponding set-up and processing times. The gathered production feedback data contain the actual outcome of these information for all intermediate- and end-products [6].

Many manufacturing companies use so-called Production Data Acquisition Systems (PDA-Systems) to gather production feedback data on the shop-floor. In these cases the data is uploaded directly by the utilized work machines via the companies IT infrastructure. However, most companies still have individual process steps which are not reported back automatically because installing the necessary hardware would not be economically reasonable. Where this is the case, machine operators have to manually report finished process steps on terminals which are installed specifically for this purpose.

Consequently, the data inconsistencies described in the following chapter emerge from a variety of reasons which include inaccurate or missing manual feedback from the shop-floor, a wrong aggregation of data in databases, impractical automated gathering of data with machine-tool-integrated sensors or even uncoordinated, manual interferences in the material flow.

Missing or inconsistent data in databases create various problems: The most obvious flaw is the reduction of the sample size which decreases the precision and validity of any analyses one might be

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interested in. In the context of practical applications, inconsistent and missing data constitutes a problem due to the fact that complete data sets are most often a prerequisite for computational operations. Consequently, the mechanisms of missing and inconsistent data and ways of dealing with them have been extensively discussed by researchers [7].

The most obvious approach is to delete any data sets with missing or inconsistent data. Discarding the affected data sets is easy to implement and may be a save way to proceed if only relatively few data are affected and all cases occur at random. However, if these assumptions prove to be incorrect there is a high risk of introducing a serious bias into the data by simply deleting affected data sets. Therefore, replacing missing data or substituting inconsistent data is a more appropriate approach. This process of replacing and substituting data is called imputation [8]. Data Mining (DM) techniques qualify for this purpose since they allow to make assumptions about true values of variables by making observations from historical data [5].

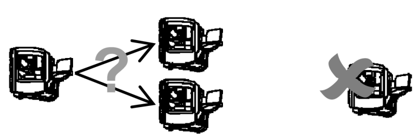
DM is commonly applied in fields such as banking, insurance, marketing and the like. While there is a vast number of existing research on the application of DM in a production and manufacturing context, it has not yet reached the same level of naturalness as in other fields. Wang considers the diversity and complexity of differing production processes being the reason for making it difficult to devise generic DM methodologies for production-related tasks [9]. However, extensive reviews of the existing literature on DM applications in production and manufacturing have been carried out by [9], [10] and [11]. Most research concentrates on production processes and operations, product quality improvement, engineering design and materials planning.

Kwak and Kim have developed a DM approach for optimizing semiconductor-manufacturing processes while explicitly considering missing values in the data [5]. Wang and Wang have proposed a framework for dealing with missing data in survey databases but have not applied their method on production feedback data [12]. Hence, there has not been carried out much research on DM techniques' capability to improve data quality by imputing missing or inconsistent data in production control.

## 3 DATA INCONSISTENCIES IN PRODUCTION CONTROL

### 3.1 Typical Data Inconsistencies in Production Control

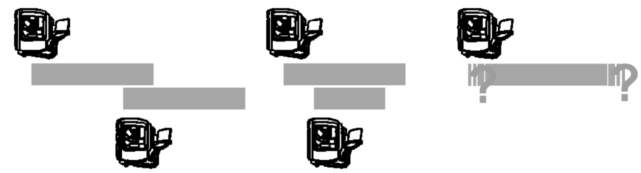
Seven data inconsistencies typically occur in production feedback data gathered on the shop-floor. These data inconsistencies can be aggregated to three groups which are depicted in Figure 1 to Figure 3.



(a) (b)

Figure 1: Depiction of data inconsistencies concerning work stations.

Figure 1 shows the first group of data inconsistencies. It is composed of case (a) and (b) which comprises inconsistent or faulty information about utilized work stations for a given process step. In the first case, the analysed data sets contain inconsistent information about the planned work station of the directly following process step and the actually reported work station for this process step. The second case comprises process steps which were reported without any declaration of the utilized work station. This ambiguous information about deployed work stations leads to incorrect assumptions concerning the utilization of capacities and the material flow of production orders on the shop-floor.



(c) (d) (e)

Figure 2: Depiction of data inconsistencies concerning start- and end-dates.

Figure 2 shows data inconsistencies of the second group which clusters data inconsistencies concerning inconsistent or missing information about start- or end-dates of process steps. In case (c), a process step was reported as 'finished' after the directly following process step has already been reported as 'started'. The affected data are evidently inconsistent, since handling of a production order on a specific work station cannot begin before processing was completed on the previous work station. The second case (d) subsumes process steps where the following process step has been reported as 'finished' even before the preceding process step has been completed. Case (e) includes all process steps which were reported with either a completely missing start- or end-date. The data inconsistencies comprised in this second group prevent the correct calculation of actual throughput times and consequently restrict the accurate determination of the adherence to promised delivery dates.

| Production order | Process step | Work station |
|---|---|---|
| xyz | 10 | A2 |
| xyz | 20 | C3 |
| xyz | 20 | D1 |
| xyz | 30 | E2 |
| | (f) | (g) |

Figure 3: Depiction of data inconsistencies concerning redundant reporting of process steps.

Figure 3 shows the third group of data inconsistencies in production control. Case (f) subsumes all process steps that were reported repeatedly in the production feedback data although each process step exists only once in the planned work schedule. Finally, case (g) comprises the subset of process steps of case (f) in which the reported work stations differed although the process step was declared to be the same. These inconsistencies in the production feedback data prevent correct calculation of throughput times and utilization of work stations.

### 3.2 Findings in Production Feedback Data

For this paper, data sets of four German mid-sized manufacturing companies of the machinery and plant engineering have been analysed regarding these seven typical data inconsistencies in production control. All companies produce and manufacture highly customised products and therefore apply job-shop manufacturing for

| | Data Inconsistency | Company 1 | Company 2 | Company 3 | Company 4 |
|---|---|---|---|---|---|
| (a) | Mismatch between planned work stations in consecutive process steps | 6.1% | N/A | N/A | 0.1% |
| (b) | No feedback about work stations | 3.2% | 0.4% | 0.4% | 0.0% |
| (c) | Previous process step reported as finished after following process step was already reported as started | 2.1% | 8.1% | 6.0% | N/A |
| (d) | Following process step reported as finished earlier than previous process step | 1.0% | 1.0% | 5.4% | 1.1% |
| (e) | Process step with missing start- or end-date | 1.4% | 12.3% | 0.0% | 0.0% |
| (f) | Process steps reported repeatedly | 0.0% | 0.1% | 0.1% | 0.0% |
| (g) | Different work stations if process step was reported repeatedly | 0.0% | 0.1% | 0.1% | 0.0% |

Table 1: Data inconsistencies with rate of occurrence in four different data sets.

small-scale series within their respective plants. Company 1 is a manufacturer of clutches and brakes for special applications, especially seafaring. The second company is a manufacturer of milling machines and flexible manufacturing systems. Company 3 is a manufacturer of drivetrain technology and the fourth company produces high precision machining spindles.

For each company, the analysed data sets represent a timespan between 12 and 18 months with information about 14.000 to 24.000 production orders which were processed over the respective period of time. Correspondingly, the number of reported process steps in the data sets ranges between 86.000 and 155.000. For each process step the production feedback data include information about the production order with the number of the respective process step, the utilized work station with designation of the planned following work station as well as the start- and end-date of each process step. In the majority of the four data sets, time-stamps for the beginning and end of the process steps were not included and consequently were not part of the evaluation.

Table 1 gives an overview on the described typical data inconsistencies with their respective rate of occurrence in the four analysed data sets. Except for company 4, all companies deal with a cumulated inconsistency rate of at least 10%. The second company's data set exceeds even this threshold easily. The analysis of the four data sets provides some insights concerning the importance of ensuring a higher data integrity in production control: The first group of data inconsistencies is especially relevant for company 1 while the second group primarily concerns the data sets of company 2 and 3. In comparison to the first two groups, data inconsistencies comprised in the third group do not occur frequently. Additionally, the production feedback data of company 4 is relatively free of data inconsistencies. In some data sets, missing table columns prevent the calculation of the rate of occurrence of case (a) and (c) which is why they are denoted with N/A.

The analysed data inconsistencies in production control prevent an accurate calculation of completion dates of already started and future production orders. Consequently, their elimination in production feedback data is a crucial step in ensuring a better planning basis and ultimately a better adherence to promised delivery dates. While companies can work on improving data quality by further automating the gathering of production feedback data via build-in sensors, the complete elimination of the gathering of inconsistent data is unlikely. This problem might even further exacerbate when the trend to employing multiple sensors to capture a single event continues. Hence, a methodology is needed to improve data integrity by reducing inevitable data inconsistencies in production control. While companies should work on reducing inconsistencies in their data sets by addressing the before-mentioned reasons, the complexity of production processes will prevent the collection of data with complete integrity.

### 3.3 Differing Severeness of Data Inconsistencies

The various groups of data inconsistencies as shown in Table 1 differ in the severeness of their impact on the simulation runs which build the foundation for future production planning in APS-Systems.

The data inconsistencies in the third group which are depicted in Figure 3 can be considered the least critical in terms of severeness for the simulation runs. Their occurrence is most likely attributable to necessary rework which has to be done only in a few cases as the analysed sample of the four data sets shows. Additionally, there is no need to specifically account for rework in simulation runs since this problem lies within the scope of product and production process design. Nevertheless, if rework becomes necessary on a regular basis it can be accounted for in the simulation runs by implementing statistically derived failure probabilities for affected work stations.

The second group of data inconsistencies, as shown in Figure 2, subsumes inconsistent or completely missing start- and end-dates of the individual process steps. These data inconsistencies are critical in terms of their rate of occurrence. However, when it comes to their impairing impact on the correct execution of the simulation runs, they are commonly uncritical since missing start- and end-dates can be remedied rather easily by switching to a resource-centred view of production processes [13]. If the work stations of the respective process steps are known, an estimation of the possible start- and end-dates can be done by taking the average waiting time, transport time and process time into account. The results can be crosschecked with the existing data of preceding or following process steps.

Therefore, this paper focuses on ensuring data integrity in data sets affected by the first group of data inconsistencies as shown in Figure 1. If the information about the utilized work station of a process step is inconsistent or missing, the material flow through the shop-floor and the utilization of the work stations is uncertain. In terms of severeness for correct simulation runs, this group of data inconsistencies is the most critical since the current utilizations of work stations are important input data for the planning process. Additionally, the utilized work station is not easily estimated since material flows in job-shop manufacturing tend to be very complex with a high number of possible preceding and following work stations for each process step [13].

## 4 ENSURING DATA INTEGRITY IN PRODUCTION CONTROL

### 4.1 Application of Association Rule Induction

Association rule induction is a methodology extensively applied within the so-called market basket analysis. Marketing specialists use association rule induction in order to find systematic regularities in shopping activities of supermarket and online-shop customers. This methodology provides a well established way to make assumptions about additionally purchased products by analysing a subset of products already chosen by the customer. In the field of market research, this extracted knowledge is used to design advertising campaigns or placing specific products next to each other in supermarket shelves [14].

For production control purposes, we propose that association rule induction can be used to estimate the most likely work station of any process step in case of missing or inconsistent information about the deployed work station. Hence, applying this algorithm on a production feedback data set will clear the data of all inconsistencies concerning work stations and consequently improve data quality. The main challenge when using association rule induction is to find the best-fitting rule due to the immense number of theoretically valid rules [14]. The number of possible combinations of work stations grows exponentially with every added work station in a data set. The four analysed data sets include between 82 different work stations for company 4 and 539 work stations for company 3 while the other two companies employed a number of work stations in the lower hundreds. Since testing each rule of the trillions theoretically valid association rules would be a very time consuming endeavour, specific algorithms have been developed to facilitate finding the best-fitting rule.

One of the most commonly applied and best-performing algorithms for association rule induction is the so-called apriori algorithm [15]. It was first described by Agarwal [16]. The apriori algorithm uses two indicators in order to determine the best-fitting rule: the *support* and the *confidence* of an association rule. The *support* of any given rule is the percentage of cases in which this rule can be applied while the *confidence* measures the conditional probability of choosing the correct rule given the antecedent information [17]. Before applying the apriori algorithm a *minimum support* and a *minimum confidence* need to be defined. Thereafter the apriori algorithm works in two basic steps: First, all rules which reach the given level of *minimum support* are determined and represent the subset called frequent rules. In the following second step, association rules are generated from this subset and tested for their *confidence*.

Translated to an application of the apriori algorithm in a production control context, the *support* measures the percentage of production orders in which any sequence of work stations has been observed. Analogical, the *confidence* states the conditional probability of a following work station given an antecedent sequence. Equation (1) shows the corresponding mathematical expression with W being a known work station and X representing a missing or inconsistent information about a following work station:

$$\text{confidence}\ (W1+W2 \rightarrow W1+W2+X) = \frac{\text{support}\ (W1+W2+X)}{\text{support}\ (W1+W2)} \qquad (1)$$

As shown in equation (1), in the first application of this algorithm, we decided to limit the length of the antecedent sequence to two work stations in order to keep the number of possible rules small. Since no expertise regarding a reasonable level of the *minimum support* exists in this field of application, this approach prevents risking the validity of the results due to setting this border to low.

From all association rules which meet the *minimum support*, the rule with the highest *confidence* is automatically chosen in order to impute the missing or inconsistent information concerning an employed work station. This procedure is easy to implement but one must be aware that a bias is automatically introduced into the data in the order of equation (2):

$$\text{introduced bias} = 100\ \% - \text{confidence} \qquad (2)$$

However, by just deleting data sets with missing or inconsistent information the data are affected by an even higher bias which justifies the application of such an imputation algorithm.

### 4.2 Validation of the Developed Algorithm

In order to validate the modified apriori algorithm, the proposed methodology has been applied to the four described data sets of the German manufacturing companies.

In order to get an idea of a reasonable value for setting the *minimum support* and *minimum confidence*, the arithmetic mean of *support* and *confidence* was computed for all data sets. Table 2 summarises these results.

| | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| support (*W1*+*W2*) | 0.2% | 0.1% | 0.1% | 1.0% |
| support (*W1*+*W2*+*X*) | 0.1% | 0.1% | 0.1% | 0.3% |
| confidence (*W1*+*W2*→*W1*+*W2*+*X*) | 33.3% | 32.5% | 54.3% | 24.3% |

Table 2: Mean of *support* and *confidence* in the four data sets.

As expected, the average *support* is rather low with values ranging between 0.1% and 1.0%. This finding hints at a high variety of process sequences since individual sequences can only be found in a low number of production orders. The average *confidence* ranges between 24% and 54% which allows the assumption that in case an association rule reaches the *support* threshold, the derived work station is correct in over a quarter of all cases. However, in average the introduced bias ranges between 46% and 76%. Since these values only represent an average, the actual results can be considerably better or worse.

To illustrate the application of the apriori algorithm, a production order with a missing work station for a single process is chosen at random from the data set of company 2. For this example, the *minimum support* shall be fixed at the level of the corresponding arithmetic mean which equals 0.1% in case of company 2. This approach created a subset of 593 frequent sequences. The antecedent sequence of the missing work station in the chosen production order is a bending press followed by a welding process step. In the whole data set, 12 possible following work stations can be identified for this sequence which represent the candidates for the missing information. However, 5 of these 12 theoretically possible sequences do not have a *support* value of 0.1% or higher and are therefore discarded. The *confidence* of the 7 remaining sequences ranges between 0.3% and 81.8%. Consequently, the algorithm chooses the sequence with the highest *confidence* value which equals the imputation of a manual tinsmith process step. Theoretically, a bias of roughly 20% is simultaneously introduced into the data. However, since the imputed process step represents a reasonable activity given the antecedent sequence, the added information for the missing work station can be considered a valid result.

Applying this modified apriori algorithm to the entire data set will ultimately create an estimation for all missing information regarding work stations.

## 5 CONCLUSION AND FURTHER RESEARCH

In this paper, typical data inconsistencies in production feedback data have been analysed for their rate of occurrence and severeness in regard of the planning simulations. The superior goal is to improve data integrity in production control in order to realise better planning results and a higher adherence to promised delivery dates by developing an online platform for self-optimising production control. An approach for reducing a frequently observed data inconsistency by applying a DM algorithm is presented. For this purpose, the apriori algorithm which is a popular algorithm for association rule induction in the domain of market basket analysis has been modified to fit the requirements in a production control context. A first estimation of reasonable values for *minimum support* and *minimum confidence* has been undertaken by analysing four data sets of German manufacturing companies.

Further research is necessary in several directions: First of all, production feedback data need to be analysed further in order to determine additional data inconsistencies. For example, reported quantities of any given process step can fluctuate within a production order. Additionally, missing information about set-up or processing times of process steps impair the observed data quality. Eventually, a way of dealing with every single data inconsistency is needed. In addition, the proposed algorithm needs to be further improved by taking into account those sequences that follow a missing or inconsistent value or by extend the antecedent sequences. Furthermore, approaches differing from the support-confidence framework already exist which avoid difficulties such as the combinatorial explosion of imaginable association rules [15].

Ensuring data integrity in production control will become an even more important topic in the near future when data is gathered simultaneously by multiple sensors in cyber-physical systems. As more data is gathered, the possibility of creating data inconsistencies rises as well. An extension of DM techniques in a production control context will be necessary in order to deal with these conditions.

These efforts are directed at one goal within the Cluster of Excellence (CoE) “Integrative Production Technology for High-Wage Countries” at RWTH Aachen University which is to improve production control efforts through a increased understanding of possible actions which are adequate to the current situation by applying DM techniques on production feedback data.

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# Concept and Data Model for Assembly Work Content Determination

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**Abstract**

Strategic decisions in early production planning phases have a high impact on various production aspects. Decision making is often based on vague expert knowledge due to lack of a reliable knowledge base. Implications of this problem are especially observable in the field of assembly planning, which integrates results from various planning disciplines. The proposed paper introduces a new concept and the corresponding data model for application of Data Mining methods in the field of production assembly planning and product design. The concept presents assistance potentials and prototypical implementation for development of new products variants along the product emergence process (PEP).

**Keywords:**
Digital Manufacturing; Data Model; Data Mining

## 1 MOTIVATION

Market situation for manufacturing industry is distinguished by a volatile market behavior combined with constantly changing consumer demands and expectations. These factors have significant impact on producing companies, which result in higher product complexity, increased variety of products and shortened product lifecycles. The companies invest great efforts to address this situation and reduce the production costs and time-to-market with a quicker technological development [1] and furthermore, to create an adaptable and flexible production system. In order to overcome these challenges, developing decision and planning support for early planning stages are crucial [2]. Though the products also influence the corresponding production processes and increase their complexity accordingly. Therefore, optimized and standardized manufacturing planning processes are essential requirements to be competitive [3]. Additionally, integration of product development and assembly process planning are also especially important [4, 5]. Two of the key factors assisting companies to achieve these goals are consistent and integrated databases and data in Digital Manufacturing (DM) systems as well as efficient methods for analyzing and evaluating the existing data. Better data integration allows decreased data redundancy, improved exchange and flow of information between different systems along with reduced integration complexity of new DM tools in the existing systems [6]. Efficient evaluation methods, in combination with data integration, also induce shortened of product development period and more reliable development time and cost estimation [7]. However, a lack of technological and methodical support prevents companies from utilizing full potentials of these concepts [8, 9].

A proper data model and evaluation concept can help to transpose these steps to intelligently utilize digital databases and information of current and previous products and product generations, to achieve better parallelization of the planning process. It is also possible to use these databases to determine assembly time and work content in the early phases of PEP [7]. The consequences will be accelerated decision making and better market adoption. Furthermore, the connection between different data and knowledge bases – for instance digital and expert knowledge – from various portions of PEP is an important tool to amplify these effects. Significant factors are efficient knowledge utilization and knowledge exchange on an interdisciplinary level.

This article, as partial results from the research and development project “Prospective Determination of Assembly Work Content in Digital Manufacturing (Pro Mondi)”, offers a concept using methods of data modeling and Data Mining to generate information with focus on the product assembly planning for new products in early production planning phases.

## 2 OBJECTIVES

In order to address the introduced challenges of DM regarding the integration of various planning tasks within the PEP, new concepts are necessary. Though, as a part of integrated product and process development there are different definitions for various phases and aspects of planning activities along the PEP [10, 11, 12]. Regardless of the specific definition of these phases and aspects, however, based on the analysis it is certain that great amount of their containing information and knowledge are either utilized insufficiently and ineffectively or remain unused [7]. In this regard, the presented concept focuses on product design and production assembly planning. Subsequently, for the product designer and production planner, there are varieties of applications, which can assist the design or the planning process through information gathered by Data Mining. The considered applications are briefly described as follows:

**Suggesting Assembly Connections:** An assisting option for the designer is a suggestion list of similar previously constructed component connection variations. These lists give a quick overview of possible and already implemented connection types in the assembly.

**Estimation of Assembly Process and Information:** Main focus here is the production planner with emphasis on the creation of an assembly process for a new product. A compilation of a first approximated assembly process for a new product can be

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developed based on existing product and process data. Then the production planner can specify further details and thus determine a first estimation regarding assembly time. Based on the assembly time and associated calculation scheme, the planner can perform a first cost estimation in a very early production phase. Concurrently the designer benefits also from these estimations. Within the definition of design for manufacturing (DFM) the computer-aided design (CAD) system information can be extended in terms of assembly time as well as assembly cost and is upgraded by an accumulation of time management data associated with the product data. These allow the designer to assess the constructed assembly connections in a model, the time management data regarding expected assembly time and thus upcoming assembly costs can also get integrated in the design information. Then the designer can perform a quick comparison of various alternatives regarding the assembly expenses and optimize the design at a very early stage.

## 3 PREPARATION AND REQUIREMENTS

The information in production planning and design can mutually enrich each other. Additionally intelligent interconnecting information from both disciplines creates added value. The newly obtained information supports the workflow throughout the PEP. Therefore, as part of this concept some requirements need to be met. Thus the pre-conditions attached to both systems as well as their respective processes have to be fulfilled. The focus lies on significant attributes in different DM systems, necessary adjustments and aggregation of information from different sources.

### 3.1 Attributes and Data Sources

Each DM system uses certain amount of variable to store different information. For data classification and clustering using Data Mining methods, however, criteria for comparison of data sets have to be identified. To determine these criteria and corresponding attributes, within the scope of Pro Mondi project, a survey of users as well as an analysis of various tools of the DM was performed. The objective of this analysis was to identify attributes relevant for assembly processes that could be assigned to products and parts in CAD, product data management (PDM) and production planning systems. In CAD systems attributes assigned to parts contain mainly geometric information including volume and weight. The PDM systems contain organizational information, such as creator, version and revision as well as the mentioned parts information from CAD. In addition to the conventional systems for design and stacking product parts and assemblies, systems for process planning and time measurement were also taken into account. They sustain a comprehensive portfolio of information, including assembly sequence, work content and time. The information from various systems can be used to distinguish different product parts and assemblies. The results of this analyzing are capsulated as an object oriented data model, further described in section 4.1.

### 3.2 Additional Attributes and Extensions

The necessary enrichment of product and process data for the presented concept on the fly requires additional efforts in the design. This additional expenditure also relates to the assembly connections and includes the acquisition of new information from the designer's know how. The designer usually constructs assembly connections either implicitly through formed locked joints by the shaping of parts or explicitly by connecting elements such as in screwed fasteners. The designer of the assembly connection considers all these information in the design, but cannot store them in the CAD model. Due to restriction of CAD tools the necessary attributes are mostly not defined.

To overcome this problem as part of the concept presented in this paper, the designer is provided with an additional tool in the CAD system. It can be used to create assembly connections and gives additional information and explicit design possibilities. These assembly connections are named below as ‘assembly feature’. Thus, data will be collected in the source system, the CAD system in particular. Since the defined objects are not part of PDM systems an extension is necessary in order to implement connections as objects and to store them after the transfer in the PDM system persistently. In the further processing, the product information is linked to the planning processes. Unless the storage of product data are in the same system as for production planning, the information flow from the PDM system to the planning system as well as the Data Mining tool, for further analysis, has to be ensured.

### 3.3 Aggregation of the Existing Data

In current planning systems direct linkage of processes to products is often possible. Thus an allocation of product to be assembled and the associated assembly processes is realized. In the assembly, however, parts are joined with other parts or products. These assembly connections have no digital equivalent object. However, by means of an object such as the assembly features it is possible to store useful additional connection information, which relates directly to the respective assembly connection. As part of this concept, the combination of the products and processes does not take place directly but through the assembly feature. The linking of product and process does not necessarily need to occur at the part level.

## 4 CONCEPT

The concept presented in this paper describes an assisting workflow from the designer to the production planner (see Figure 1). As part of a new or modified design the designer creates new product data. A software assistant supports the designer during the creation of assembly connections and enriches the CAD model with an assembly feature for each connection (Enhanced CAD Design Process + in Figure 1). This assembly feature includes additional connection information including the torque screwed fasteners or the type and the form of a welded joint e.g. and information about other connection types. Via the assembly feature from the CAD model the designer has an overview of the constructed assembly connections and can also manage them. With the initial release of the product, the designer provides the production planner with the enhanced CAD data (3D Model + in Figure 1). Further in the development of an assembly process the production planner will be assisted through a semi or fully automated process for the estimation of assembly work content and costs depending on the product specification and the available data pool of existing products.

For this purpose, the product data is first prepared and analyzed with Data Mining methods (section 4.2). The analysis focuses on the assembly feature and their properties (Data Mining data base in Figure 1). The parts associated with the assembly feature and their geometric properties, are also included in the analysis as additional information set. Furthermore, an extended database is also provided on basis of the available database of related data sets. This database consists of product and process data of existing products, which are linked via assembly feature (section 4.1).

The characteristics of the assembly feature of the new product are compared with the properties of the assembly feature of the existing product in the extended database. Then the most similar assembly feature is determined from the existing products. This analysis can be restricted by a class of the connection types (screwed, welded, riveted) or deliberately left open to widen the solution space and to provide the designer with other assembly connections. A limitation on the particular type of connection yields as a result of the closest realized assembly connection of the same kind. Depending on the properties of the parts, other mounting connections can also be found and given to the designer in a proposal list. In this case information flows back directly from the analysis to the designer.

The presented application for the determination of assembly processes and the work content uses the assembly feature identified in the analysis of the PDM database to determine the respective associated and related sub processes. Each assembly feature represents an assembly connection. By multiple connections within the assemblies multiple sub-processes for the assembly can be determined. These sub-processes are, however, at first in an unordered list. These unordered sub-processes and assembly work content represents a first approximation of overall process, regardless of the assembly sequence. Through a proceeding per sub assembly the determined sub-processes can be automatically structured for each assembly. With the interaction of the production planner a reasonable sequence of the individual assembly work contents can then be implemented.

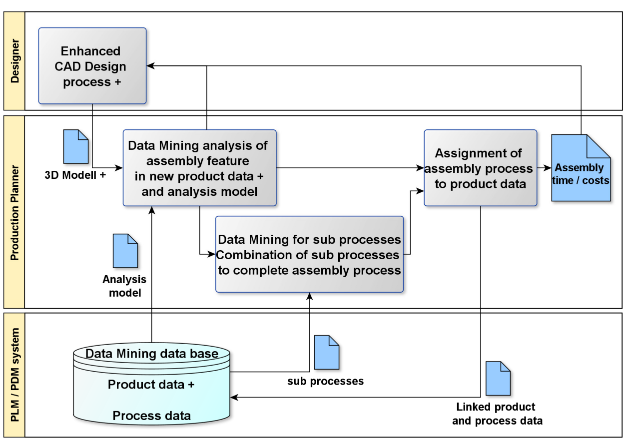


Figure 1: Data Mining with enhanced product data +.

In the final step the resulting process data is duplicated for each assembly feature of the new product. It ensures that the used process data in the PDM dataset remains unchanged. The duplicated process data are assigned to the assembly feature of the new product data (Assignment of assembly process to product data in Figure 1). In a semi-automated process the assembly planner can customize these identified assembly process. Then the automatically assigned and duplicated process data are added to the PDM data inventory for the next analysis. The result is the determination of a first assembly process using Data Mining techniques based on the existing data set in the early stages of the product development. This assembly process can include assembly work content and thus the assembly time and the installation costs with a given enterprise-specific factor (see assembly time/cost in Figure 1). A first estimation of cost and time of the assembly as information can be returned directly to the production planning and design teams depending on the application. The quality of the results can be further increased by supplements of the production planner and designer.

### 4.1 Data Model

Based on determined component characteristics (section 3.1) a range of attributes is derived to classify the assembly of the parts. Figure 2 shows an overview of the generated data model.

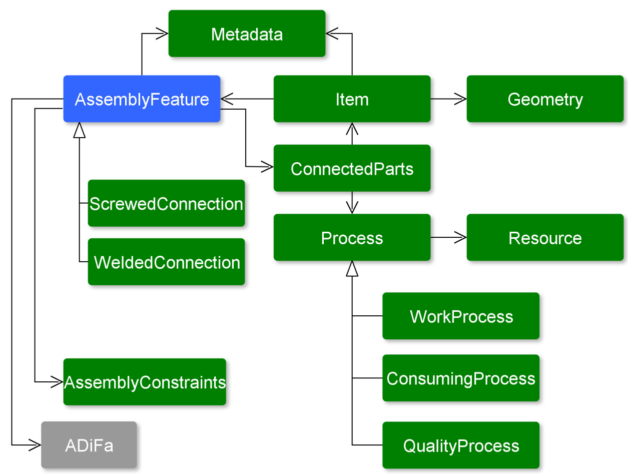


Figure 2: Data model overview.

The AssemblyFeature is the central element in this data scheme and represents the assembly of the product parts. References for time analysis, assembly requirements, designed parts or products as well as a wide range of meta data including the assembly department and other information are lodged. This abstract element is supplemented with attributes of different connection types (see Figure 3). Further connection types can be added to the data model. To provide the required information for the time analysis a standardized data model is applied. In this regard, ADiFa project's "Application-specific data models", so called ADiFa Application Protocols, were used, which offer the integration of processes and data for different DM systems [13, 6].

The second fundamental object in the data model is the Item. It contains references to existing sub-assembly units, geometrical characteristics as well as AssemblyFeatures. The linking of AssemblyFeatures to product parts via ConnectedParts enables an illustration of a complete assembly with several parts. Each Item refers to the AssemblyFeature, which also refers to further used Items (see Figure 3). This construct is chosen to enable Data Mining methods to determine exact similarities between new parts and/or products and other existing parts. Furthermore, it makes comparison of the new and existing parts and products in any order and combination interchangeably possible.

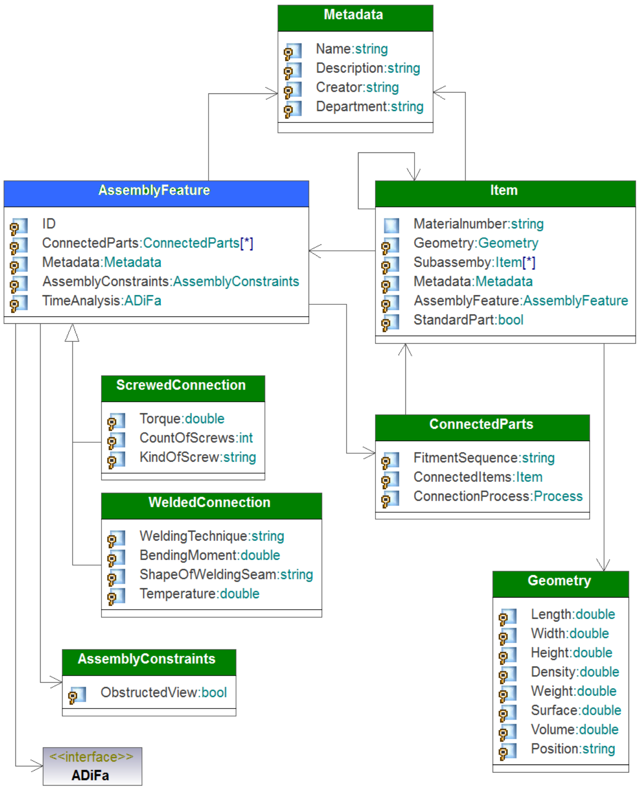


Figure 3: Assembly Feature – detailed view.

### 4.2 Data Mapping and Data Mining

After aggregating and appending the data subsets from different sources and systems, it is necessary to remove redundant data sets [14]. Data removal for the presented concept is only based on syntactic similarities of attribute structures and data sets. The next step is converting and porting data in the presented data model. Depending on data source the conversion is either fully automated or partially automated with further manual adjustment. Often value and scale of different attributes are often heterogeneous. In these cases a normalization of ratings prevents the undesired high or low impact of certain attributes on the results and evaluation process. In this regard a [0, 1] linear normalization has been used. Additionally, a further attribute prioritizing via weighting can be necessary to define the importance of each attribute for the evaluation. An automated learning of the weights via machine learning methods depends on the existing data sets and their quality possible. Otherwise they are determined based on expert knowledge or a combination of both methods. To prevent further expansion of scope and the complexity of existing problem expert knowledge was applied to determine the attribute weights. Furthermore, it is possible to have more than a single weight vector. This approach is useful, if there are various object types or parts, which have different prioritization for their attributes. [15]

To identify the objects with most similar assembly feature for a new object the classification algorithm k-nearest neighbor (kNN) [16] with Euclidean distance as evaluation function is used. From the identified objects a list is generated and the most related one can be manually chosen, which passes its assembly process data to new object. To assure the reliability of the presented method and prevent overfitting problem a cross validation [17] is used.

### 4.3 Aggregation of Information and Utilization of the Concept

The implementation of the presented approach was challenging due to high requirement for interconnection and the overall quality of the existing data in different DM systems. In particular the number of realized and existing assembly connections and thus necessary instances of an assembly feature as well as the quality of the data are important. As proof of concept, feasibility of the presented concept is verified with artificial test data. But in order to evaluate the quality of the results, it is necessary to rerun the analyses with production data. Furthermore, the selection of the properties and attributes for the analysis in particular also has to be determined based on production data to ensure the reliability of generated results. In this scope a special focus is on the characteristics of the parts and of the connection itself. In conformity with the presented objectives and concept a utilization of the methodology is described as follows:

**Suggesting assembly connections:** The designer creates a new module with already known and new assembly connections in the CAD system. He designs assembly connections and complements these connection properties in the context of the new module. Via the automated Data Mining process, he is provided with various information about the assembly connections. Moreover, for each assembly connection a list of alternative or ever realized connections can be created. Depending on the product properties the five most similar assembly features are made available to the designer as a prepared proposal list, which is generated through cluster analysis of existing product data. If the analysis is dispensed with the filtering of associated connections with the assembly feature, the designer can also be provided with other not associated connections as alternatives.

**Estimation of assembly process and information:** The production planner drafts an initial assembly process for a new assembly at an early stage of product development. Analogous to the use case of the designer, for known assembly connections that are implemented in the new product as well as in the old product data, the right assembly features and thus the assembly processes are found. For new unknown connections the most similar assembly features and related assembly processes from the database are determined and duplicated. Each of the founded assembly feature represents a single connection and the linked process represents precisely the assembly work content for this connection. The sum of the individual connections for the new product is its first assembly process. Thereby an initial draft of an assembly process of the new module can be generated. The founded individual connections, the individual process, as well as the overall process can be used in different ways to assist the designer and the production planner. The planner and designer also get a first estimation for the expected assembly time and cost in the automated process. In addition, the production planner can increase the quality of the process by manual intervention. On the one hand he adapts the assembly features, which are created by the designer, before the Data Mining analysis. On the other hand he can complete the assembly features in the attributes with practical knowledge. Thus he has an impact on the input of the Data Mining analysis and increases the quality of the result thereby. Furthermore, the designer has a first draft for the assembly process at one's disposal and a first estimated assembly time in the current CAD system. By a company-specific factor, the designer receives also information about the cost of the connection in the assembly. By verifying this information, the designer can evaluate and compare the alternatives for different connections.

## 5 CONCLUSION AND OUTLOOK

Through utilization of DM tools the quality of planning results and planning processes can be increased, while simultaneously time and cost reduction can be realized [18]. In this regard, the presented approach contributes an important added value to production design and planning through usage of knowledge in the existing systems. Thus the consequences are reduction of planning time, increasing availability of information in product design as well as easier cooperation between the designer and product planning teams.

The technical feasibility of the proposed solution has been shown by a prototypical implementation of the concept in CAD and PDM systems. However, to produce reliable outcomes the product data have to fulfill high requirements in regard to connection elements. Concurrently the necessary data model and some tool sets are provided to make the data integration easier. In the future further development of tool sets and methods could help to reduce the high initial effort for adjustment of the data even more. Besides the evaluation of the results based on product data it is important to investigate the behavior and results of the methodology for new and innovative assembly technologies. Furthermore, for analyzing more complex data sets as well as obtaining better results, it is important to develop and refine the concept and to apply further Data Mining methods.

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# Prioritisation of Influence Variables for a Flexible and Efficient Production

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**Abstract**
Influence variables can have a huge impact on the process and machine's behaviour during the production process and as a result on the product quality. Although process knowledge, methods for data base and regression analyses are available, it is still difficult to identify all relevant parameters and find their effect on the process.

The method, described in this paper, shows how all relevant parameters can be found by using a holistic approach. Through filtering, the total number of variables can be diminished as far as possible. For each variable a description about its impact on the process is designed and based on this, different actions can be derived to compensate or minimize the influences.

**Keywords:**
Process Control; Knowledge Based Optimization; Influences; Disturbances

## 1 INFLUENCE PARAMETERS IN THE PRODUCTION PROCESS

One of the most significant trends in nowadays production is the decrease of lot sizes. Modern production machines are designed for a high throughput, but the set up time is still high, which is extremely problematic for a flexible production. During set up time no saleable products are generated, which increases the total cost per sold part. Hence, to operate more economically, the set up time of production machines needs to be reduced.

This can be achieved by applying well-tuned controllers. A controller can be only tuned when the transmission behaviour of the plant is also known. When there are differences between the real and the calculated behaviour, then the system performance is not optimal. This results in a higher set up time and a waste of material and time.

So there is an adaption algorithm needed, which finds the actual plant transmission behaviour. There exist some algorithms like the model reference adaptive control, which uses a model for comparing the real behaviour with a model [1]. For this the measured control values needs to be known, which is not the case for all production machines, like offset printing machines. Hence other systems are needed, which identify the system by observing influence parameters like neuronal adapted fuzzy controllers [2]. For that kind of controller the designer needs to know which parameters influence the process to implement the adaption algorithm.

For each converting machine, an individual set of various factors may disturb the process. In general no parameters can be identified, which affect all processes in the same way. For example for printing machines the optical properties of the consumables is very important, but for milling machine it is less. They can affect the quality of the product, the stability of the process and the ramp-up speed to get an acceptable quality level.

There exist several methods for handling varying parameters. E.g. they can be held constant to eliminate their influence or their influence is compensated through the machine control system. It also needs to be considered, that there are some influences, whose relevance is small enough to be neglected.

In general it can be said that the level of knowledge about the influence parameters of a process is important for the design of the control system. Hence it is necessary to identify all relevant factors and find methods to integrate them into the control system or neutralize their influence.

There are already some spotted solutions for identifying influence parameters, like a regression analysis [3] but they are only applicable for a running production machine and it does not suggest how an influence variable should be considered.

To achieve a higher level of knowledge, this paper suggests a method, which can be used to identify all relevant parameters for a process, applying a holistic approach. It is also shown, how the parameters are investigated and described. Based on the process requirements, it is shown how appropriate and efficient actions are derived to compensate the effect of the influence parameters on the process. This method already has been applied for the design of a self-learning control for a printing machine.

## 2 CURRENT INFLUENCE PRIORITIZATION

Most control applications are designed for fix operational conditions. In reality it is difficult to ensure them. Hence there exist several concepts for a robust controller design. The variability of parameters and their effects on the control system are taken into account during the identification of the control parameters. So the stability of the control circuit can be assured. The influences, which should considered explicitly, depend on the application and the estimation of the user. [4]

In comparison, adaptive control systems analyse the system behaviour to known settings. Thereby the plant parameters are calculated continuously to get best fit parameters for the plant and also for the controller. Changing parameters are recognized, but there is no link to corresponding influence factors. Additionally you always need the process output and an accurate mathematical description of the process. [5]

The control systems of existing production machines mainly consider only a few influence parameters, which are well-known due

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to further experiences. Only seldom any methods are applied to find and prioritize influence parameters.

Controller concepts, based on the analyses of production data to establish a mathematical description of a system, address the prioritization of the influence parameters more strongly. Data sets are analysed by machine learning methods, for example by means of neural networks or support vector machines. To do this, all parameters must be collected, stored and analysed. As a result it can be derived which parameter impact the process stronger than others. This means, that full effort must be undertaken for all parameters, even some of them are not relevant for the process. [6, 7, 8]

The parameter sets, which consist of all influence factors and process output figures, are designed according to expert knowledge [9, 10], literature [11] or experiments [12].

For example, the influences for a weaving machine can be categorized into several classes. Based on a raw estimation of the impact on the process and their measurability, a first selection is done. This results in a large amount of remaining data, which are collected in a database and then taken to train a neural network. Only after the collection and the training a statement about the impact and therefore the need to consider this can be given. [13]

## 3 IDENTIFICATION OF RELEVANT PARAMETERS

### 3.1 Influence Parameters for Various Processes

Influence parameters are physical variables, which interact with the process. These parameters can be obvious. For example the specific weight of paper for the web offset printing process. Other effects, like the relative humidity of the air, appear as a disturbance.

It needs to be considered, that not every physical variable affects the process. Furthermore it needs to be distinguished between variables with a big and a low affect. The designer of a machine control needs to fulfil the requirements concerning the speed of the machine, the process stability, the maximum overshoot, the set up time and many other needs. In general it can be said, that the controller's speed can be increased by improving the knowledge about the process and the influence parameters. This means, that the number of known factors and the depth of knowledge determines the controller's performance. The more agile a system needs to be, the more effort in investigating the influence parameters must be done. This also means that the designer needs to know all relevant variables and to prioritise them.

### 3.2 Influenced and Considered Levels of a Process

Influence parameters affect several levels of a process and with this the quality of the product. For this, figure 1 shows a sketch of the influences affecting the process.

At first the consumables have to be observed. For different products, different consumables are needed. For example, in web offset printing machine different kinds of papers are used, which are unequal in their specific weight and glance. Each of these properties may affect the ability of the paper to absorb the ink and finally influences the printing quality. It is also important to recognize, that different lots of paper can also vary.

The product properties also need to be regarded, because it may affects the consumables and raw materials. In web offset printing, the printing image for example defines the amount of ink needed. When much ink is used, then the process itself behaves agilely, otherwise inertly.

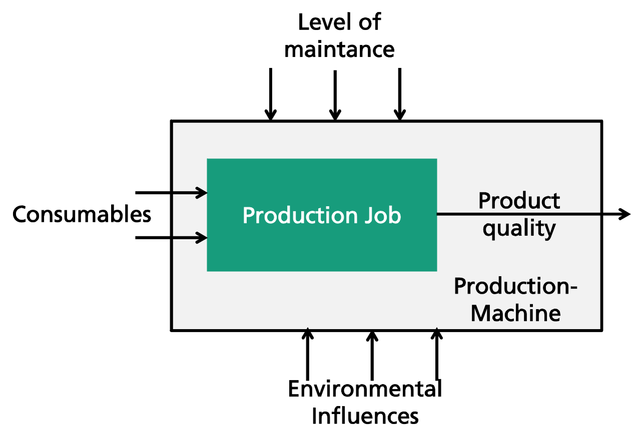


Figure 1: Parameters affecting diverse levels of the production.

The design of the machine can also change the production process. Although the principles of the process remain the same, especially the mechanical components affect the process. For example the width of the offset printing machine changes the flux of ink through a printing unit. In the middle the contact pressure between two rollers differs from the outer areas because of the mechanical sag of the rollers. The wider the machine is, the more important this effect becomes.

Furthermore the condition of the machine impacts its behaviour. When a single part of a machine ages, is substituted or renewed, it executes its task in a different way. At a printing machine the rubber of the roller becomes older over time. Its behaviour changes slowly, latently and continuously. When it is renewed, then the behaviour and so the flux of ink through the printing unit changes instantly.

Finally, environmental effects interact with the production process. They affect the consumables and the machine and influence their properties. In offset printing the air humidity changes the humidity of the paper. This factor can also describe the paper ability to absorb the ink.

### 3.3 Holistic Approach to Identify Relevant Parameters

In this method all relevant parameters shall be identified. For this task, not only the known parameters are investigated, but all, which are relevant for the process.

To be able to find all important influences for each level, all physical variables for each level are taken into account. There are different kinds of physical parameters, which are clustered as follows:

- Geometric (length, width, …);
- Kinematic (velocities, accelerations, …);
- Mechanic/Kinetic (forces, torques, …);
- Electric (voltages, currents, …);
- Magnetic (magnetic fields, …);
- Optical (light intensity, colours, …);
- Chemical (pH-value, concentrations, …);
- Radiation (frequency, strength, …);

Theoretically each parameter can have an influence on each level and so affect the process. Several variables do only have a small effect and can be neglected. Nevertheless there are several parameters that are not integrated in the machine control, because no holistic approach was chosen. This is illustrated in figure 2.

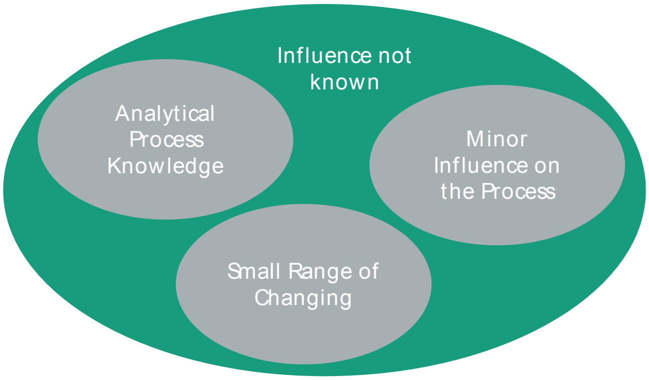


Figure 2: Holistic investigation of influence parameter.

In the first step for each of the five observed levels consumables, machine design, machine condition, process jobs and environmental factors, all physical variables can be used. To reduce the number significantly, several stages of filtering are applied.

In most cases there exist many parameters, whose influence is known as big and some other with small influence.

For example the printing process is strongly influenced by the printing image and it is known that magnetic variables do not affect the printing process. For many other parameters the knowledge about its influence is not clear and needs to be determined.

In the next step it is investigated, in which range the remaining parameters change during the production process. All parameters, which do not change over time, can be skipped as well. The temperature of the paper web does not change significantly and so it can be assumed, that it does not have an effect on the process. In many applications there exists a lot of literature describing the process and its influences. Often there are mathematical equations available, which describe the process behaviour.

In many production machines databases or complex data recording systems are installed. They are preliminary used to observe the current process and find ways to optimize it subsequently. This data can be used for investigations like data base research or regression analysis [3] [15]. With help of these tools the maximum range of the quality in dependency of the range of the influence parameter can be determined. An exact description of the correlation does not need to be investigated at this stage.

In the last step the remaining variables can be identified through experiments. These experiments can be carried out by varying only the investigated parameter and keeping all other parameters constant. At this stage also the exact correlation shall not be investigated.

## 4 CHARACTERIZING OF INFLUENCE PARAMETERS

So all parameters are identified, which have an influence on the process. In the next step it needs to be investigated, how big the influence is. Hence a characterization is performed, answering the following questions:

- How big is the effect of the variable on the process?
- How complicated is it, to control or to observe the variable?
- How good is the level of knowledge about the correlation between the influence parameter and the aim quality parameter?

### 4.1 Determination of the Relevance

The relevance describes the impact of a parameter on the process. In this paper $\Delta Q_{max}$ is defined as the maximum range of the changing of the quality during the production. $\Delta Q_{res}$ is the maximum changing of the quality, only caused by the observed influence parameter. The ratio of $\Delta Q_{res}$ and $\Delta Q_{max}$ is defined as the relevance r (see formula (1).

$$r = \frac{\Delta Q_{res}}{\Delta Q_{max}} \times 100\% \quad (1)$$

Every physical variable can affect the process theoretically. For this investigation it needs to be considered, that all variables can just vary in a predefined range. So for the determination of the relevance, only this range is investigated.

Both aspects can be taken into account, when the correlation between the influence and the quality parameter is known. This can be done with the help of different methods. The most holistic way is using mathematical formulas. By solving them or using a simulation model, the maximum or minimum quality in dependency of the influence parameter can be determined. Another way is using data base and regression analyses at existing machines to find relevant correlations. When none of these methods can be applied, then various experiments need to be performed.

It needs to be considered, that influence parameters can affect each other. For example the humidity of the air changes the ability of the paper to absorb ink. Low quality paper absorbs more water from the air than high quality paper. Thus it is more affected by this environmental factor. These cross correlations make it more difficult to find the absolute relevance of a factor for the process. Thus the total range observed needs to be reduced. Very interesting operation conditions are minimums or maximums. For example in offset printing process the factor “area coverage” describes the percentage of printed areas in an image. The possible range is between 0% and 100% and leads to an inert or agile machine behaviour. For the investigation it is sufficient to observe a range representing 80% of the daily production lots. So the effort for the investigation can be reduced significant. In offset printing the area coverage of common images lies between 3% up to 30% due to experts. All other values can be printed, but ca. 80% of all printing images is in this range. For the investigation of the influence of the area coverage only the values 1%, 3% to 30%, in steps of 5%, and 100% need to be observed. Summed up, only 30% of the whole range of all possible values of the area coverage needs to be observed. This reduces the effort by 70% and covers the whole possible range.

When the investigations are performed, the relevance of an influence has to be calculated due to formula 1. When the quality changes in the whole range of the influence parameter between 0% and 30% then the relevance is considered as low. When it changes between 30% and 100%, then it is middle and when it is above 100% then it is assumed as high.

These values were preliminary used for the validation of the control system for the printing machine. In further investigations they can be adapted.

### 4.2 Controllability of an Influence Factor

The next spotted item is the controllability. This factor describes, how easy it is to measure and set a parameter. When a parameter can be kept constant with low effort, then its controllability is high. This is e.g. true for pH-value of the fountain solution. This factor influences the process but, by keeping it constant, its relevance can be neutralized. Influences, which can just be measured, but cannot be controlled or only with high costs, are considered as observable. This is true for the area coverage. Calculating the area coverage is simple and this information is available for each image. Nevertheless it is difficult to change, since it is predefined by the desired product. When a parameter can hardly be changed or measured or measuring is cost-intensive, then its controllability is low. The parameter is in that case not observable. The aging of the ball-bearings of the rollers cannot be measured or controlled easily for example.

### 4.3 Level of Knowledge

Furthermore it is also necessary to know, how the correlation between the influence and the quality parameter is. The knowledge about the correlation is high, when the parameter and the quality depend on each other linearly. When this correlation is nonlinear, then the knowledge is middle. For example there exists an offset in the opening of the ink pot, which can be determined using data base analyses. When it is not possible to find a correlation because of its complexity, then the level of knowledge is assumed as low.

## 5 DERIVATION OF ACTIONS OUT OF THE CHARACTERIZATIONS

In this stage, each parameter is described fully. In the next step the information about the influence parameters is used to classify each parameter and derive appropriate and efficient actions for integrating the parameter into the control.

For this it is considered, how big the relevance and its controllability is. Out of these factors the best method for integrating the factor into the control system is derived. It needs to be regarded, that the actions need to be efficient so that the costs are low.

Figure 3 shows possible actions derived from the controllability and relevance.

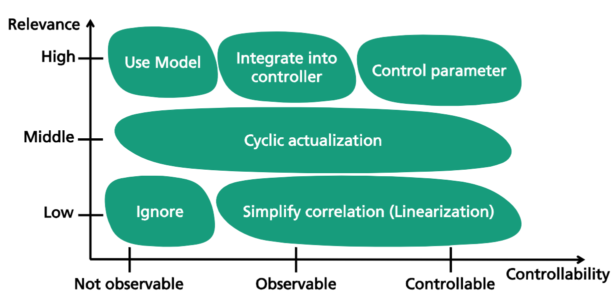


Figure 3: Decision Matrix.

When the controllability is low and the impact of the parameter is low as well, then it can be considered that the parameter can be skipped totally. This means that this parameter has an influence per se, but the benefit of considering is low and the costs are high.

It is recommended to keep parameters stable, which are easy to control and which have a big impact, so they do not have an influence anymore.

All other variables have either a low controllability and high impact or a high controllability and a low impact. These ones should be included in the machine control, e.g. using a model, which expresses the mathematical dependencies between the parameter and the quality. When it is complicated to measure the variables, then indirect measuring should be applied. This means that the value is calculated from various other measured variables. Also a model can be used, which simulates the variable. When a variable cannot be kept constant efficiently and its impact is low, it should be integrated into the machine control, using linearization and other forms of simplifications.

When it was designed that a variable should be directly integrated into the controller or via a model, then it should be identified, if an analytical description, a fuzzy or a self-learning system should be applied, depending on its complexity to describe its correlation to the quality parameter.

## 6 VALIDATION AND APPLICATION OF THE METHOD FOR A OFFSET PRINTING MACHINE

This method has been applied for the colour control system of a web offset printing machine. It is state-of-the art to consider only a few parameters like the area coverage, which are well understood and have the highest impact.

There exist several more influences, which have not been considered up to now, like the aging of the machine. This has led to the fact that potential is lost and that paper has been wasted.

Identifying all relevant parameters helped to design a model, which is used for tuning the machine. This method has been applied to design an adaptable control system for a web offset printing machine. For an area coverage of 3 % the wastage during the set up time could be diminished by 85 %.

## 7 CONCLUSION

In production one of the most important requirements is achieving the required quality as fast as possible. The speed and the agility of the machine depend on the design of the control system and the ability to adapt the system to the current machine state. The more precise the state can be described, the more agile the controllers can be tuned.

The machine state strongly depends on various parameters, which are affected by the consumables, the production job, the machine design, its condition and the environment of the production. For the design of a control system, all relevant influences and their correlations to the product quality have to be identified and prioritized.

For performing this, a method is suggested. It utilizes a holistic approach, considering all possible influences. Through filtering, variables are skipped, which are not relevant for the process. After this for each variable a description is designed, containing the most important data about its relevance for the process, its controllability and the level of knowledge about it.

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# Managing Complexity in Remanufacturing Focusing on Production Organisation

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**Abstract**

Due to individual requirements of economic actors, remanufacturing companies face the challenge of an increasing variety as well as the associated complexity. Therefore, a successful complexity management, created upon detailed knowledge of drivers and effects, is necessary. To close the lack of knowledge, the main complexity drivers and effects within the production organisation of remanufacturing companies are identified. Furthermore, common optimisation methods to manage this drivers and effects are assessed and the best ranked methods are shown within this paper. For the complexity effects, which occur the most and with a low number of available optimisation methods, new methods are presented.

**Keywords:**

Remanufacturing; Complexity Management; Production Organisation

## 1 INTRODUCTION

The individual requirements of economic actors lead to an increased variety in products and services. With every new variant, the effort of manufacturing increases. Thereby, the level of additional effort depends directly on the occurring complexity of the respective process. This process complexity is further co-determined by the number of variants of the products which have to be produced [1]. Additionally the resource efficient usage of capacities and the demand for minimum emission in the manufacturing of goods contributes to an increased process complexity.

Remanufacturing companies face similar challenges as companies from other industrial sectors. One challenge is the high variety due to the broad spectrum of Original Equipment (OE) brands (e.g., Bosch and Delphi), product groups (e.g., engines and alternators), generations (e.g., VW Golf 3, 4 and 5), configurations and varying core quality (e.g., degree of contamination and degree of wear or usage history) [2]. Compared to manufacturers of new parts, companies of the industrial sector of remanufacturing can only react passively to an increased complexity in products and processes instead of an active avoidance or reduction [1] [2]. For this reason a successful complexity management, based on detailed knowledge of complexity drivers, effects and optimisation methods is necessary.

Therefore, the project results of the quantification of complexity drivers and effects as well as of optimisation methods focusing the production organisation in remanufacturing companies are considered. Furthermore, new optimisation methods are presented in the course of this paper.

## 2 STATE OF THE SCIENTIFIC KNOWLEDGE AND NEED FOR ACTION

### 2.1 Remanufacturing

Remanufacturing is the industrial process to restore used products to an “as good as new” condition [3] [4] [5]. The worldwide remanufacturing industry represents about 100,000 companies with a turnover of approximately 100 billion Euros [2] [3]. The remanufacturing process of mechanical products can be divided into five main process steps (Figure 1) [6].

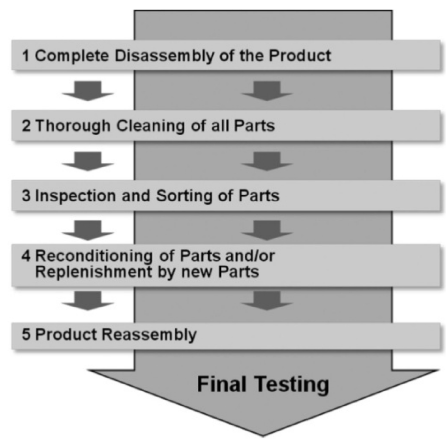


Figure 1: Main steps in the remanufacturing process [6].

### 2.2 Complexity

According to Ulrich and Probst [7], complexity is a system quality whose degree depends on the number of system elements, the plurality of the connections between these elements and the number of possible system states. In general, three main management strategies to manage the negative effects of complexity can be distinguished: avoid complexity, reduce complexity and handle complexity [2] [8].

### 2.3 Need for Action

Studies show that costs which are related to product and process complexity can make up to 25 percent of the total costs in manufacturing companies [8]. Progress regarding complexity reduction can be identified to a greater extent in the field of logistics, supply chain management and production techniques [9] [10]. Approaches for managing complexity specific to the needs of the remanufacturing industry do not exist so far [11].

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In their study “Industrial Challenges within the Remanufacturing System” Lundmark and Sundin found out that uncertainty and complexity are some of the most challenging factors in remanufacturing which have to be faced in the future [4].

Therefore, within the European research project reCORE (research for efficient configurations of remanufacturing enterprises), which is founded by the German Federal Ministry of Economics and Technology, scientists at the University of Bayreuth are searching for solutions to manage complexity in the remanufacturing industry.

### 2.4 Research Methodology

All shown results, except the new optimisation methods, have been determined within an empirical approach. The necessary data were collected by analysing company data and by questionnaires. The evaluation and validation of the results and solutions were done by expert interviews and workshops. The methodology to systematically identify, analyse and evaluate complexity drivers and effects as well as optimisation methods has already been presented in detail on the Swedish Production Symposium 2012 [11].

This paper shows the results of quantifying complexity drivers and effects, which can occur within the production organisation of remanufacturing companies, as well as the applicability of common optimisation methods to handle these drivers and effects. Furthermore new optimisation methods, which were developed within the research project reCORE to handle complexity, are presented.

## 3 ANALYSIS AND EVALUATION OF COMPLEXITY IN REMANUFACTURING FOCUSING PRODUCTION ORGANISATION

In the field of production organisation 26 drivers and 50 effects were identified, which leads to an evaluation of 1.300 combinations. The quantification of the drivers and effects allows the identification of the main drivers and effects and serve as a basis to derive a suitable complexity management. The top ten drivers in the field of production organisation are shown in Figure 2. The top ten effects within the production organisation are shown in Figure 3.

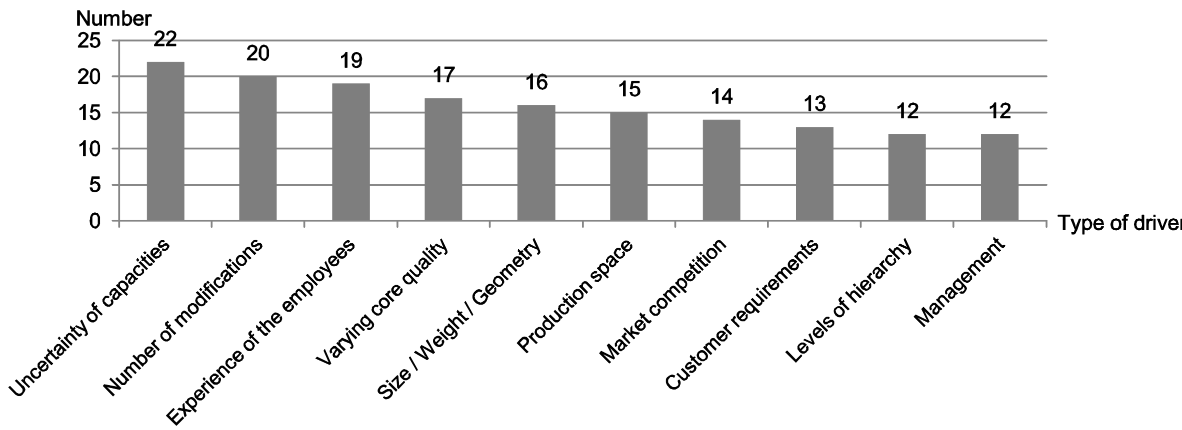


Figure 2: The top ten complexity drivers influencing production organisation in the field of remanufacturing.

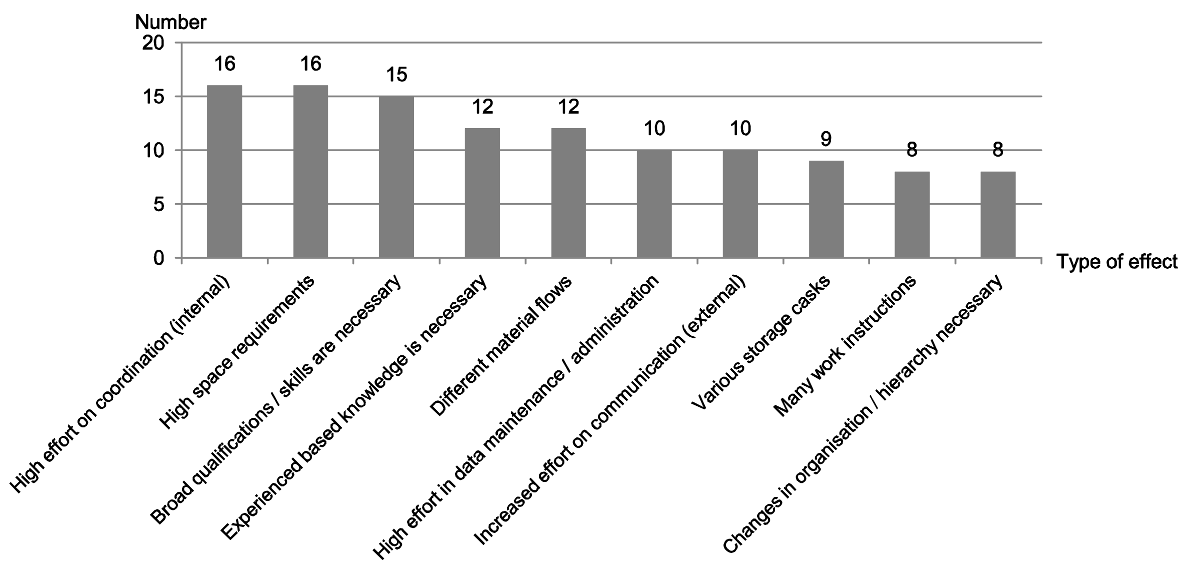


Figure 3: The top ten complexity effects influencing production organisation in the field of remanufacturing.

The chart shown in Figure 2 indicates that “Uncertainty of capacities” and “Varying experience of employees” as internal complexity drivers as well as “Number of Modifications” and “Varying core quality” as external complexity drivers cause the majority of the effects.

The chart shown in Figure 3 indicates that for a total consideration of the results within the production organisation, the effects “High effort on coordination (internal)” and “High spare requirements” with 16-fold occurrence each as well as “Broad qualification/skills necessary” with 15-fold occurrence and “Experience based knowledge necessary” with 12-fold occurrence represent a high proportion compared to the other effects turning up.

## 4 ANALYSIS AND EVALUATION OF OPTIMISATION METHODS

Besides the knowledge about complexity drivers and effects, remanufacturing companies also need suitable methods and tools to manage the complexity effects. Therefore 46 common optimisation methods are identified and assessed to each complexity effect. As mentioned before, for the assessment of drivers and effects a discrete evaluation was carried out for each combination of effect and optimisation method (or tool). The assessment evaluates whether a method is suitable or not to manage a complexity effect.

The top ten methods in the field of production organisation are shown in Figure 4. According to the results of the analysis, “Standardisation”, “Production planning and control (PPC)”, “Visualisation” and “Supplier management” are the top ranked optimisation methods to manage complexity in remanufacturing companies in the field of production organisation.

The results of this analysis are used to highlight the top optimisation methods as well as to detect gaps of available methods and thus to identify the need for further development.

| Effects | occurrence *(Number)* | applicable methods *(Number)* |
|---|---|---|
| High effort on coordination (internal) | 16 | 12 |
| High space requirements | 16 | 10 |
| Broad qualifications/skills necessary | 15 | 5 |
| Experienced based knowledge necessary | 12 | 5 |
| Different material flows | 12 | 12 |
| High effort in data maintenance/administration | 10 | 7 |
| Increased effort on communication (external) | 10 | 6 |
| Various storage casks | 9 | 4 |
| Many work instructions | 8 | 10 |
| Changes in organisation/hierarchy necessary | 8 | 5 |

Table 1: Number of applicable optimisation methods.

In Table 1, the numbers of optimisation methods which are applicable to the top ten complexity effects are shown. For the effect “High effort on coordination (internal)” a broad spectrum of optimisation methods is available whereas for the effects “Broad qualifications/skills necessary” and “Experienced based knowledge necessary” only five methods each are available. Hence for the complexity effects with a low number of available optimisation methods and on the basis of expert interviews, new optimisation methods, suitable for the production organisation of remanufacturing companies, were elaborated. A selection of the newly developed methods is presented in the following.

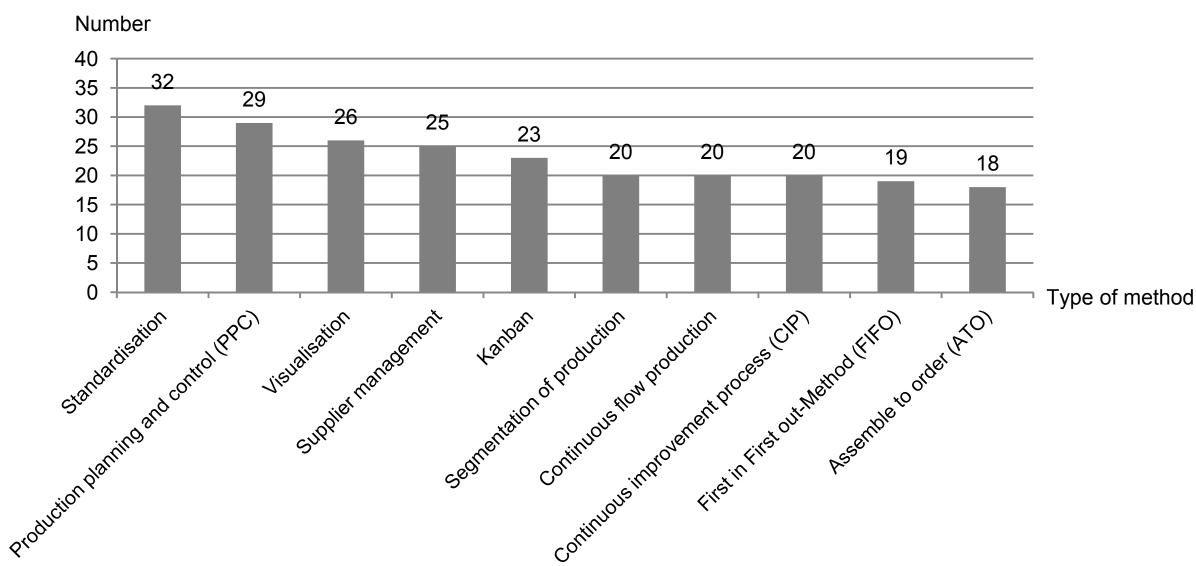


Figure 4: The top ten methods for managing complexity in production organisation in the field of remanufacturing.

## 5 DEVELOPED OPTIMISATION METHODS

### 5.1 Employee Knowledge Balanced Chart

As Figure 2 shows, the driver "Experience of employees" is one of the highest rated complexity drivers. This means that especially the employees are an influencing factor for the complexity.

Increasing work contents, strongly varying tasks and advancing expert knowledge are only the most important trends related to the employees in the production. In order to stay competitive the production staff must face this complexity by achieving a high degree of flexibility. This higher degree of flexibility can reached by a high level of expertise in as many job contents as possible.

In this case the job of the production management is to lead the staff to a high degree of flexibility by controlling the knowledge of the employees. Due to the fact that the most firm-specific knowledge and skills are only held in the minds of the employees, who are using this knowledge during their daily work, the production management can only have a supportive role.

For a highly efficient increase of the staff's knowledge and skills the method of the Employee Knowledge Balanced Chart was developed. The basic idea of this method is to give the production management an overview of the existing knowledge and skills of every employee of a department. Moreover, in contrast to well established methods like the qualification matrix, the Employee Knowledge Balanced Chart not only illustrates lacks of knowledge but also reveals potentials for synergies. This employee information is presented in the form of a single chart (Figure 5).

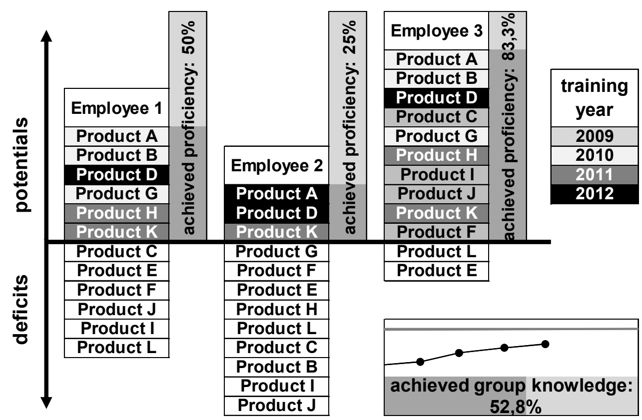


Figure 5: Example of an Employee Knowledge Balanced Chart.

In order to implement and work with the Employee Knowledge Balanced Chart in the production, the following five steps are necessary:

1. Collection of data: In the first step data about the existing knowledge and skills of every employee need to be collected. This can be done by interviewing the employees or if possible by a perusal of qualification documents. To prevent wrong or aged data this step should be done in close cooperation with the concerned employees.
2. Creation of the graphical representation: The existing knowledge and skills of each employee need to be depicted by using a diagrammatic representation for each department. A horizontal line separates the potentials and the deficits. For a better overview and to detect necessities of refreshment it is useful to colourise the existing fields of knowledge and skills whereby the colour represents the year in which the qualification was achieved. Afterwards the ratio of potentials and deficits can be added as a key performance indicator for each employee (achieved proficiency) and of course as well for a whole group or department (achieved group knowledge).
3. Decision about the needs for trainings: The complete representation of the Employee Knowledge Balanced Chart offers an overview of the deficits and potentials of every staff member. To act as efficiently as possible the most prevalent deficits should be focused in future trainings.
4. Training of the employees: The focused knowledge and skills are trained to the affected employees. The training should be given by employees, who already have experience in the relevant field and therefore serve as a multiplier. These experienced staff members can be detected by using the Employee Knowledge Balanced Chart. In order to verify the training success it is necessary to finish this step with a test, such as an independent and accurate proceeding in the trained field under supervision of the experienced employee.
5. Update of the Employee Knowledge Balanced Chart: In this step the achieved qualifications are cleared from the deficits and added to the potentials.

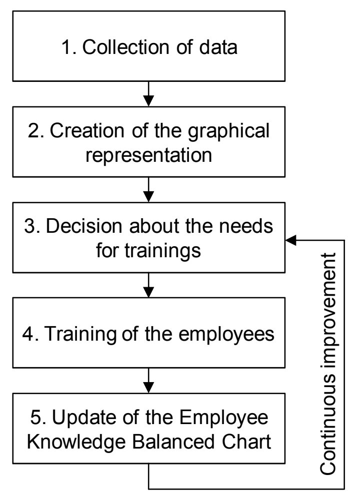


Figure 6: Procedure of the Employee Knowledge Balanced Chart.

To ensure a continuous improvement process it is advisable to return to step 3 ("Decision about the needs for training") after a successful treatment of step 5 ("Update of the Employee Knowledge Balanced Chart"). Figure 6 shows the procedure of the implementation of the Employee Knowledge Balanced Chart.

This continually recurring process can be repeated until a desired level of existing knowledge and skills is achieved. After reaching this high level of flexibility by a broad range of knowledge and skills of the staff it is recommendable to resume the repetitive process. But during the treatment of step 3 ("Decision about the needs for training") the management has to focus on the trainings with the oldest dates. This proceeding has the background of a continuous refreshment of knowledge and skills.

The diagrammatic presentation of the Employee Knowledge Balanced Chart provides an overview of the existing potentials and deficits of knowledge and skills. Due to this overview the production management and the employees are able to increase knowledge and skills in a high efficient way. Furthermore the targeted selection of trainings leads to decreasing training costs.

The inclusion of key performance indicators helps the production management to define objectives in close cooperation with the staff members. Due to the ambition of the employees to achieve the defined objectives the motivation to increase the knowledge and skills raises and also the company loyalty of the staff is improving.

In addition, the production management is able to detect less experienced employees and assist them to achieve a higher level of knowledge and skills. This can be used for restructuring measures like job enlargement which also improves the responsiveness to peaks of workload and work stoppages [12] and therefore positively influences the top complexity driver "Uncertainty of capacities".

Moreover, this method deals with different top ten complexity effects like the necessity of broad qualifications and skills as well as experience based knowledge.

In summary, the use of an Employee Knowledge Balanced Chart leads to a high degree of flexibility. This high degree of flexibility enhances the reactivity in the field of the production whereby the competiveness maximises.

### 5.2 Agile Production Area

Nowadays production must be able to handle highly volatile changes. As illustrated before, some of the most named complexity effects in the production organisation are high space requirements and different material flows. The following presented method was developed to manage these complexity effects. Most production areas are in operation with the same arrangement since many years. This means that the layout of the shop floor was also created many years ago. Due to the fact that the production is exposed to highly volatile changes, the conditions, which were existent during the set up of the consisting shop floor layout, became obsolete.

Usually the production management tries to increase the efficiency of the production by initiating changes. Practice, however, shows that only slight changes are usual. Due to the aspiration to keep the effort small the efficiency of the production is only improving with small steps.

However a general change would lead to an optimum of the production efficiency. Nevertheless the general realignment needs a high planning effort and due to the highly volatile change the implementation effort became obsolete after only a short time.

This means that a rapid change and adjustment of the production area must be possible with the lowest amount of planning and implementation effort.

The described method was developed to achieve a rapid change and adjustment with the lowest amount of time and effort. The method of the Agile Production Area deals with the intelligent arrangement of the production resources. According to Gienke and Kämpf the resources in the field of the production are personnel, equipment, materials, time and information [13]. Primarily this method deals with the personnel, equipment and materials. For achieving a rapid change and adjustment it is very important that the used equipment and materials are movable or can be made movable (e.g., by using wheels for a better mobility). Suitable areas in remanufacturing companies are for example the disassembly area, the inspection area and the reassembly area as usually no heavy machinery has to be moved in this area.

The procedure of the Agile Production Area has the following steps:

1. Development of the algorithm**:** First of all an algorithm must be developed. This algorithm must be able to generate an ideal layout by taking the forecasted work orders and the existing employee attendance into regard. Available equipment and material resources must be stored in a database. Beneath these functionalities the algorithm should consider several constraints like unmovable resources as well as the ratio of benefit and effort.
2. Update of the work list: The work list which contains information about the future work orders must be up to date.
3. Update of the attendance list**:** Besides the work list, it is necessary to maintain a list containing the current available employees.
4. Generation of the layout: In this step the updated work list and the updated attendance list are the input for the algorithm for generating the layout with the most efficiency for the upcoming conditions of production.
5. Arrangement of the resources: The employees have to implement the generated layout. Due to the movable equipment and materials it should be possible to do this step in a short time. Unused equipment and materials can be stored in an intended area.
6. Check of the arrangement: After the resources are in place it is important to check the completeness and the optimum of the arrangement. Small improvements can be done before the production starts.

After the steps are worked through the production is able to start with the work order. Figure 7 shows an overview of the procedure.

The production management has to take into account, that step 5 ("Arrangement of the resources") and the step 6 ("Check of the arrangement") are causing downtimes, which are required during the procedure of the Agile Production Area.

After the work order is finished, the production area can be rearranged. In this case the procedure starts with step 2 ("Update of the work list"). Due to the recurring process a permanent adaption of the production area is guaranteed.

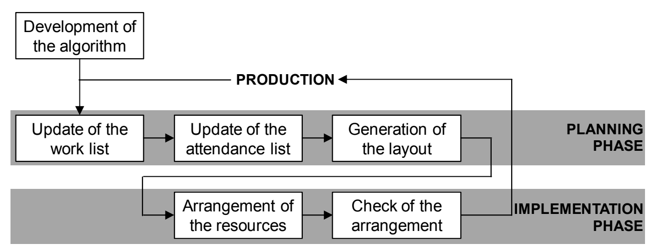


Figure 7: Procedure of the Agile Production Area.

The primary benefit of the introduction of this method is a quick adaption to high volatile changing conditions in a most efficient way. Because of the high efficiency in the production the cycle times as well as non-productive times for material handling and transportation are kept as small as possible. This leads to a reduction of the production costs.

Furthermore, as only necessary resources are available to the employees, the risk of failures caused by the use of wrong resources (e.g., incorrect tools and false material) decreases. This leads to an improved quality of the products and a reduction of the complaint rate.

### 5.3 Core Quality Oriented Supply Chain

The above presented results (Figures 2 and 3) show that for remanufacturing companies the varying core quality is one of the highest rated complexity drivers. Core is the international term for an old unit or used product [6]. The core quality depends on different factors (e.g., degree of contamination, reusability and completeness). This variety of core quality leads to an increasing complexity for the remanufacturing company.

Instead of checking the quality of the core at the beginning of the remanufacturing process the method of the Core Quality Oriented

Supply Chain recommends to source out the core quality check. Due to the fact that the cores are usually collected from different suppliers (e.g., Original Equipment Manufacturers (OEMs), core dealers, customers and recycling companies), it is very costly and time consuming for remanufacturers to subject incoming cores to an additional quality check.

The Core Quality Oriented Supply Chain suggests that the remanufacturer purchases the cores from a key supplier. This key supplier collects the cores from different suppliers and has to ensure a quality check and a presorting of different core qualities. Figure 8 shows the Core Quality Oriented Supply Chain with the key supplier between the different suppliers and the remanufacturer. This method manages not only the complexity, it also reduces the complexity.

The risk of the implementation of this method is the loss of knowhow to the key supplier.

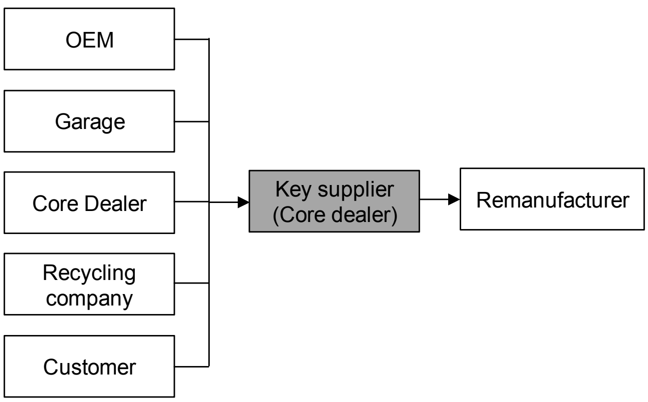


Figure 8: Core Quality Oriented Supply Chain.

The method of the Core Quality Oriented Supply Chain has different benefits:

- Unusable cores are scrapped previously in the supply chain.
- The effort which is caused by bad and variable core quality can be reduced.
- Downstreamed processes can be planned in a better way because of the stable core quality.
- Resources can be used to capacity, therefore dates and deadlines can be complied.
- The effort for communication (external) can be reduced.
- The core warehouse can be downsized, which also reduces the capital commitment.

## 6 SUMMARY

This paper shows for the first time the main complexity drivers and effects occurring in the production organisation of remanufacturing companies. The analysis and the newly developed optimisation methods enable the remanufacturing industry establishing a suitable complexity management. The implementation of the presented methods in remanufacturing companies enables them to reduce complexity (Core Quality Oriented Supply Chain) and/or to handle complexity (Employee Knowledge Balanced Chart, Agile Production Area).

As part of future research the presented optimisation methods will be verified by pilot trials.

Furthermore, it would be interesting to analyse the costs of complexity in remanufacturing to make complexity drivers and effects as well as optimisation methods monetarily assessable.

## 7 ACKNOWLEDGMENTS

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# Knowledge Based Configuration of Re-configurable Transfer Centres

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**Abstract**

The use of reconfigurable manufacturing systems (RMS) is seen as the strategy for producers to respond to variable market demands. The created possibilities for reconfiguration mean an increase in complexity for the process planning. This increased complexity of the planning process can be handled with knowledge based systems. Therefore, this paper describes how a knowledge model for designing an optimization process can be realized to be used in combination with a multi-agent system. The knowledge model describes the knowledge of the manufacturing planning experts to be deployed in the developed planning system. The great complex correlations, which have to be represented in this knowledge-integrated planning tool, can be integrated into an agent-based software system. Agents have the potential to process these complex data volumes and are used to construct the knowledge-integrated planning tool in this research work. A prototype has been developed, which is able to create the configuration of transfer centres by processing a given process plan.

**Keywords:**

Reconfiguration; Production planning; Knowledge management; Transfer centre

## 1 INTRODUCTION

### 1.1 Initial Situation

The surroundings of manufacturing companies have changed very much in the last years. This change is characterised by the effects of globalisation and its consequences. Manufacturing companies try to react to these changed conditions by increasing their productivity and flexibility. Several production paradigms have gradually developed in view of these constant efforts to take up the demands of the global market. The production paradigms presented in the last years, such as flexible or reconfigurable manufacturing, refer differently to these demands. They can be seen as change and transformation enabler at different levels [1].

The term most often discussed is 'flexible manufacturing systems'. It becomes clear from extensive literature studies, e.g., by Toni and Tonchia, which is based on more than 120 publications on this topic, that a distinction has to be made at first between static and dynamic flexibility. Static flexibility describes the capability of a stable production within a defined spectrum of products, processes and their quantities in view of quality, costs and delivery time. In contrast to that, dynamic flexibility describes the capability to change the manufacturing system quickly and without considerable costs regarding capacity, structure and processes [2]. Today manufacturing systems with dynamic flexibility are called „reconfigurable manufacturing systems“.

### 1.2 Technological Approaches to the Implementation of Changeability

Reconfigurable manufacturing systems offer changeable functionalities and a scalable capacity through the physical change of system components. These changes can comprise adding, removing or replacing machine modules, machines, manufacturing cells, handling facilities or entire production lines [3]. In 1999, reconfigurable machine systems were presented for the first time in an extensive CIRP keynote paper [4]. Whereas reconfigurable assembly systems can be regarded as state of the art, reconfigurable manufacturing systems are predominantly still in the research and development stage [5]. ElMaraghy provides an extensive overview of the state of the art regarding reconfigurable manufacturing systems [6].

The clear reduction in development time and the faster presentation of new product models and variants as driving forces for change were not carried out to the same degree in the field of the design and development of manufacturing systems. Manufacturing systems have to be developed in such a way that they can meet the special requirements and boundary conditions of a product. These are gradually changing, and the reconfiguration rates have increased recently [1]. This rise in reconfiguration processes and the high complexity due to the multitude of boundary conditions may only be dealt with information technology. In 2002, Michaelis already realised a prototypical planning tool to increase the flexibility of reconfigurable manufacturing systems [7]. The presented „technical library of knowledge represents a planning system for the configuration of reconfigurable machine tools. It is based on a resource model and facilitates the demand-orientated selection of modules, while including the knowledge of the planning engineer [8], [9]. Today knowledge management is regarded as important change enabler and is still a subject of research. For example, Abele describes an expert system for configuring reconfigurable systems [10].

The development of a software system for the knowledge-based reconfiguration planning of reconfigurable manufacturing systems takes up this strategy and intends to show the realisation potentials exemplarily applied to reconfigurable transfer centres.

## 2 CONCEPT OF KNOWLEDGE BASE CONFIGURATION OF TRANSFER CENTRES

### 2.1 Transfer Centres and Opportunities for Reconfiguration

Tightened conditions in the mass production of the automotive industry and its suppliers have promoted the use of the extremely productive transfer centres. In contrast to machining centres, transfer centres have an inverse kinematic structure. The workpiece carrier unit is moved in the working space of the transfer centre, taking the clamped workpieces to the individual stationary multi spindle heads and components for machining. A transfer centre is reconfigurable due to the integration and exchangeability of one or several components such as, for example, multi spindle heads, milling spindles, measuring or handling units. As no tool changes have to be carried out, it is possible to clearly increase the production time percentage of the machining time compared with the machining centres used because of the advantages of flexibility.

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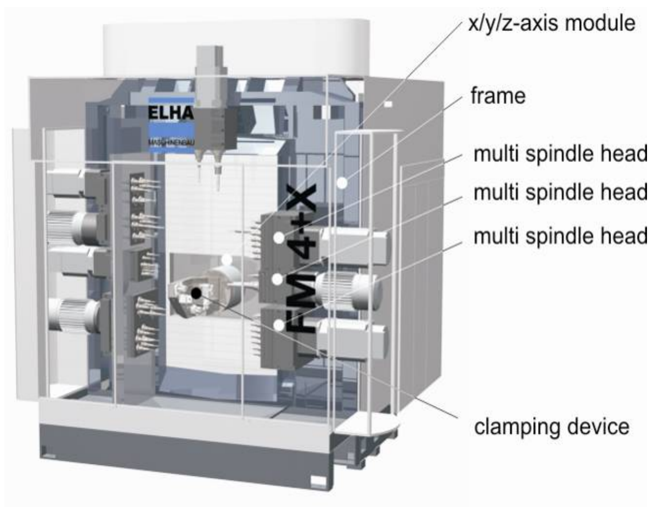


Figure 1: Structure of a transfer centre (photo credit: ELHA-MASCHINENBAU Liemke KG, Hövelhof).

Transfer centres are suitable for machining processes for middle-volume to high-volume parts of engine, transmission and chassis. The efficiency of transfer centres in mass production was examined, for example, by Brecher et al. in 2007 [11]. Due to the automation of the workpiece change, transfer centres are an alternative machine design to the various flexible manufacturing systems but have the disadvantages that workpiece change is not conducted within the production time and that the number of tools is limited [12]

This disadvantages could be eliminate by the planning assistance system for reconfiguration the transfer centres. Tool change that is not within the production time may be optimised by new kinematic linking concepts (cf [13]). The supposed disadvantage, that the available space for the integration of components restricts the number of possible machining operations in the transfer centre, can be avoided by considering the entire production process sequence and the machine properties. This possible solution of this challenge will be presented in the following.

### 2.2 Multi-agent Systems for Configuration Tasks

Agents are encapsulated (software) entities with defined goals ([14]). An agent tries to reach its objective by acting autonomously, but keeping to its scope of action. It interacts with its environment and with other agents, while keeping a persistent state. A system with several agents interacting with each other is called a multi-agent system (MAS). MAS are used for example to reduce the complexity in problems with many degrees of freedom, due to the fact that the agents are able to make their own decisions according to their knowledge.

In Blecker et al. an agent-based concept for the process configuration for mass customization is presented. They are using agents for representing platforms, modules, production constraints etc [15]. In Göhner et al. a system to support the test planning in software test is presented [16]. Here agents represent, for example, test cases and determine the importance of them. With this test importance and some other constraints, an ordering of the test cases is possible, in order to find as many bugs as possible in a given time span. This shows that multi-agent systems are suitable to deal with complex problems, where many constraints have to be considered.

## 3 ENGINEERING OF THE AGENT ORIENTATED KNOWLEDGE MODEL

### 3.1 Knowledge Model Description

Before the multi-agent system is developed, a suitable development methodology is chosen. By using the methodology, it is possible to exactly convert the objective of the multi-agent system into requirements, which influence the development of the multi-agent system.

It can be chosen from several agent-orientated development methods, created in the last years as a result from research works such as, for example, Gaia (cf. [17]), MaSE (cf. [18]) or Passi (cf. [19]). These methods support all stages of software development for an agent-orientated system, from the agent-orientated analysis of the problem through design up to implementation. Concepts such as role analysis, use cases and goal analysis are used here to systematically deduce subgoals or subtasks (roles) from the requirements. In the design, these subtasks and roles are assigned to the identified active elements of the system, i.e., the agents, and the interactions are defined, which are necessary for meeting the aims and roles.

The described Gaia, MaSE and Passi methods can all be assessed as well-suited for analysing and designing an agent system. The methods are primarily based on a role and interaction analysis and support the development of restriction conditions as well. In addition, the PASSI method provides information about creating an agent ontology. The methodical identification, structuring and modelling of expert knowledge in an agent system are, however, not described in any of the methodologies.

Hence the methodologies for developing knowledge-based systems are used for the methodical identification, structuring and modelling of the agent knowledge. The CommonKADS method is chosen as suited best for this task, because CommansKADS also provides information for identifying and describing agents and their channels of communication (cf. [20]). Fig. 2 shows the modified CommonKADS model suite with its parallel design of the knowledge and agent model.

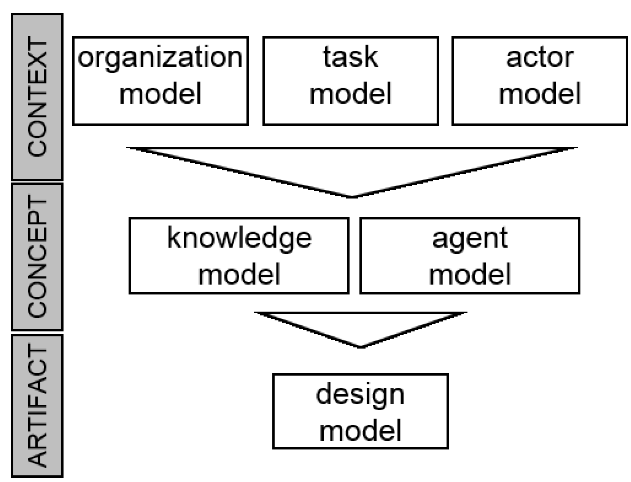


Figure 2: Modified CommonKADS model suite.

### 3.2 Context and Workflow Analysis

Equally to the CommonKADS methodology for knowledge engineering, an organisation, task and agent model is created to analyse the context in which the multi-agent system is to work. The organisation and task model constitutes the heart of the context analysis here. The agent model engineering is described below.

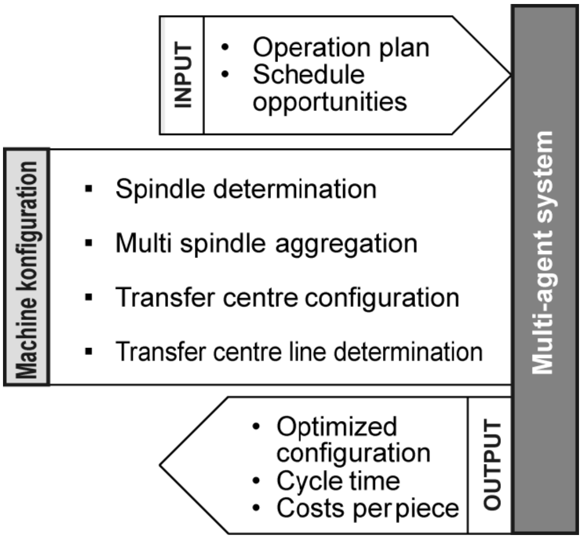


Figure 3: Summary of context analysis.

All corporate divisions and departments involved play a role in the development of the organization model. Then the involved corporate divisions are examined in more detail. Not only the structures, resources and staff qualifications are of interest here, but also particularly the processes and the specific process knowledge.

The task model is built in conjunction with the organisation model. Particular tasks have to be worked on within particular processes of business organisation. These tasks are represented in the task model and combined with the organisation model. In view of the findings from the modelling of the persons involved, the tasks of the task model can be combined and assigned to a process of the organisation model.

The context analysis can be summarised by Fig. 3. The concept of the agent system must be able to process information from different corporate divisions such as, for example, the departments of design, planning, sales and controlling. These data are the inputs of the multi-agent system and are made available to the system by specific interface definitions. The development of interface definitions enables to lead the input data back to the corporate processes. The machine tool design context contains all application tasks of the transfer centres to the machining task. The tasks modelled include spindle selection, spindle grouping in accordance with possibly available drilling patterns, the configuration of a transfer centre up to planning the production line.

## 4 DESIGN OF THE MULTI-AGENT FRAME WORK

The concept of the multi-agent system is an entity-based concept, which means that different entities (of the real world) are represented by agents.

In this case the workpiece to be produced is represented by the so called workpiece agent. It will provide all tasks, which are directly related to the workpiece and encapsulates information about the workpiece. It analyses for example the features of the workpiece and chooses corresponding production steps. For each production step a production step agent is instantiated for its representation. These agents choose a tool to perform the related operation and determine usable cutting parameters. After that, the production step agents communicate with each other in order to determine similar production steps which can be parallelized by a multi spindle head. When a group of production steps is created, a suitable multi spindle head is chosen and a corresponding spindle agent is instantiated. The spindle agent represents the multi spindle head and communicates with the transfer centre agents in order to get a mounting position in a transfer centre. These agents represent and manage a transfer centre. A production line agent represents the whole production line and e.g. coordinates capacity utilization the transfer centres. Fig. 4 shows an overview of the involved agents and their communication.

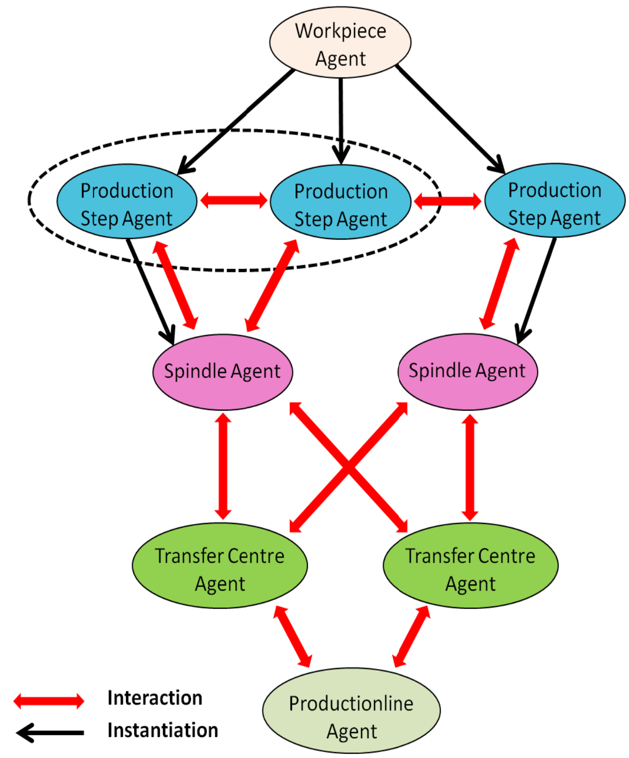


Figure 4: Agent-based concept for the planning tool.

## 5 STRUCTURE OF THE KNOWLEDGE MODEL

It is necessary to provide the agents with the required knowledge in order to implement agent properties such as, for example, goal-direction, autonomy and persistence in the multi-agent system. To enable the agents to process this knowledge within their interference mechanisms, the necessary knowledge must be collected, structured and processed.

Regarding the workpiece-based procedure, the knowledge necessary for reconfiguring reconfigurable manufacturing systems includes specialist knowledge from production and design engineering as well as industrial management. Corresponding to the many mutually dependent boundary conditions, the representation of this specialist knowledge is very extensively, and the links are difficult to determine.

The CommonKADS methodology offers several components for the knowledge modelling. The model distinguishes task, inference and domain knowledge (see Fig. 5).Using the example of multi spindle group assessment, the knowledge model engineering will be described below.

The goal hierarchy system is build up by the task decomposition in a hierarchical tree. Up to specific goals, the tasks are classified to different branches. The main goal of the spindle agents is to configure all necessary spindles. For example, this goal is decomposed in the subgoal ‘spindle pattern determination’. Machining processes for middle-volume to high-volume parts with transfer centres require the subgoal ‘spindle pattern determination’ to determine the hole

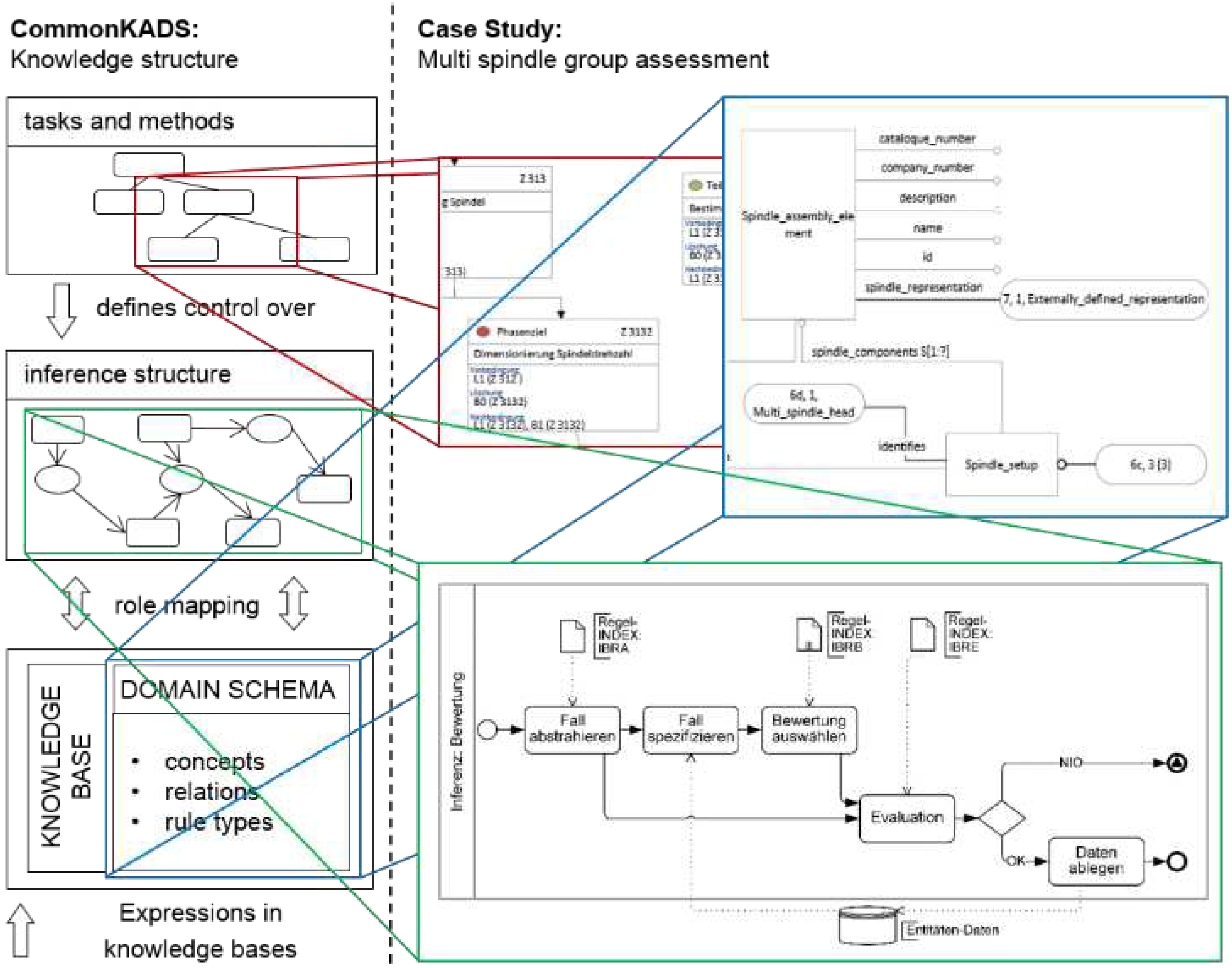


Figure 5: CommonKADS knowledge model structure by example of multi spindle group assessment.

pattern. The manufacturing of hole patterns with multi spindle heads in one shot is the great potential of effectivity. This advantage of transfer centres should be used in all applications. For this purpose the subgoal 'spindle pattern determination' is an important subgoal of the main goal 'spindle configuration'. The subgoal 'spindle pattern determination' could be achieved in different ways. In this case, the task model is subdivided into so called stage goals. The specific tasks for the configuration of the spindles are referred to these stage goals. For example, there is the task 'feature pattern determination' as one stage goal for the determination of spindle patterns.

These tasks could be solved by using the modelled inference knowledge. The inference knowledge is modelled in template sequences of assessment with specific requirements. The requirements depend on the respective goal and are collected in a list of rules. For running the inference sequences the attributes of the handled entities are also necessary. This data is provided in the form of the developed entity scheme.

## 6 MULTI-AGENT SYSTEM IMPLEMENTATION

The multi-agent planning tool was realized in a prototype using the Java Agent Development-framework (JADE) [21]. This prototype is able to read the features of the workpiece and the necessary production steps from a file and configure the transfer centres of a production line. As described in Chapter 4, the results of the first design step are the features and the corresponding production steps. These are presented to the user in order to have an overview over the production task. The automatically determination of the production steps is not realized in the prototype till now. In the next step, suitable tools are determined and the chosen tools are shown.

After that, the tools are assigned to spindles and multi spindle heads. The assignment of tools to spindles is done by comparing the tool's parameters like interface, rpms and forces. In order to group several spindles in a multi spindle head, the constraints concerning the order of the corresponding production steps have to be considered. Physical constraints like the dimensions, the rpms or the power have to be considered also. The results are presented to the user, which can be seen in Fig. 6. In the last step the multi spindle heads are mounted in the transfer centres. The result can be seen in a three-dimensional view, in order to have an imagination how the configuration looks like (see Fig. 7). This view is also able to show a simulation of the movement of the workpiece and enables a collision detection in order to avoid too narrow placement of the multiple spindle heads.

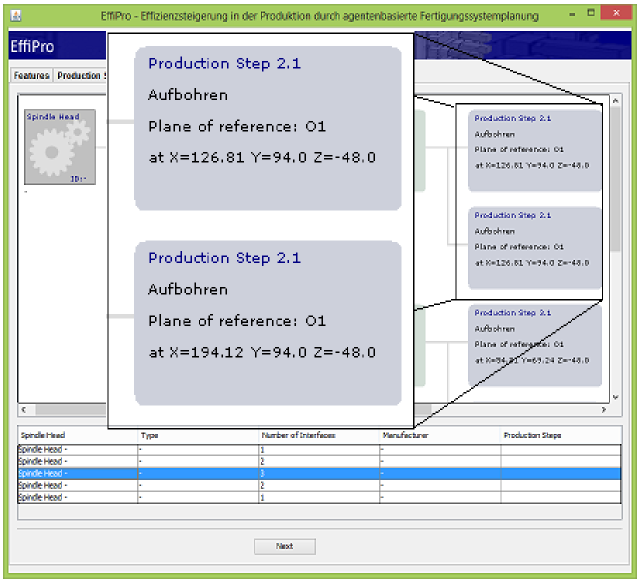


Figure 6: Screenshot of the prototype.

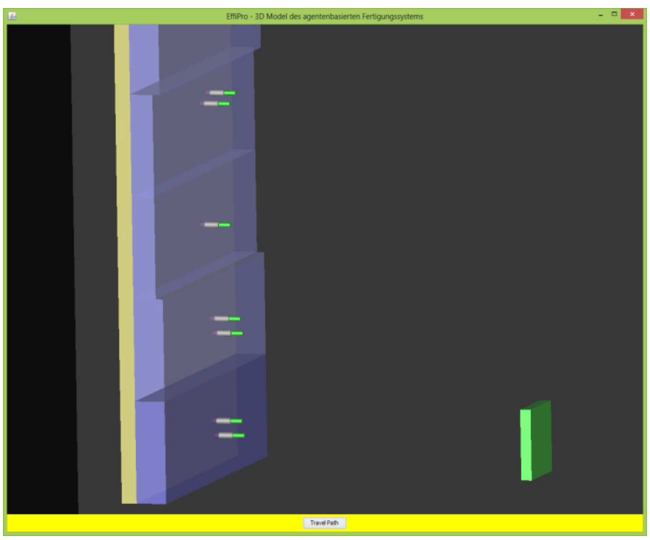

Figure 7: Simplified 3-dimensional view of the transfer centre.

The example workpiece, which was used to evaluate the prototype, has a medium complexity and needs about 50 production steps to be produced. The configuration of the transfer centres takes about 10 minutes with the actual version of the prototype. Fig. 8 shows an extract of the logged communication between the agents during the planning process.

## 7 SUMMARY

This paper presents an agent-based approach to support the planners configuring a production line built of transfer centres. Due to their inverse kinematic concept with fixed process spindles, transfer centres offer a huge potential for raising the efficiency of

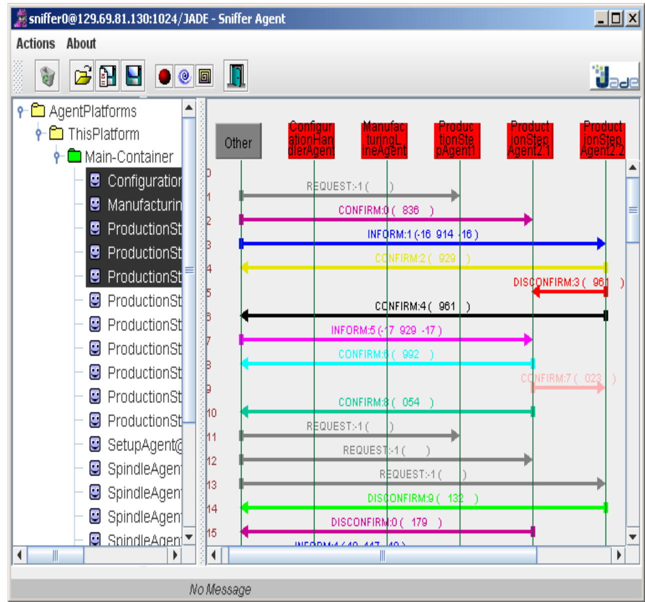


Figure 8: Logged communication of the agents.

production. The efficiency of these machine tools can not only be increased by improved processes, also spindle configurations, spindle positions and schedule tasks are important. The given flexibility raises the effort to plan or to configure such transfer centres. Therefore, the corresponding knowledge model and its creation process were described. The classic technology planning has to be expanded by design configuration aspects of the transfer centres and produces the strategy for solving the production planning of reconfigurable transfer centres. Therefore, the domain model also contains the information how the transfer centres, the spindles and tools are to be modelled. The CommonKADS methodology was used to develop these models. The entity-based agent concept and its realization in a prototype were presented, in order to show that the agents are able to deal with the given complexity. The prototype is able to plan the transfer centres of a manufacturing line in a very short time.

## 8 ACKNOWLEDGMENTS

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# Multi-Criteria Decision-Support for Manufacturing Process Chain Selection in the Context of Functionally Graded Components

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**Abstract**
In this contribution a methodology for a multi-criteria decision-support for manufacturing process chain selection in the context of functionally graded components is presented. The basis for this decision-support is provided by a framework for the computer-aided planning and optimisation of manufacturing process chains of functionally graded components, which is still under development. To distinguish between several alternative process chains it is necessary to consider those decision criteria that can not explicitly be specified within the CAD model. A matrix-supported algorithm guarantees a consistent weighting of these decision criteria while enabling a fine-granular rating scale. As a result, a ranking of the different process chains is achieved that constitutes the basis for the decision maker to select the favourite alternative.

**Keywords:**
Multi-Criteria Decision-Support; Functionally Graded Components; Sustainable Production

## 1 INTRODUCTION

Functional gradation denotes a continuous distribution of properties over at least one spatial dimension of a component made of a single material. This distribution is tailored with respect to the later application [1].

Application areas for the use of functional gradation can be found e.g. in the automotive industry. Car interior door panels for example are usually plastic materials that are supposed to absorb the impact energy of a lateral crash to a certain extent. The resulting deformation however must in no case lead to an injury of the passengers. To achieve a desired deformation behaviour it is necessary to assign exactly defined material properties to specific locations of the door panel. By functional gradation, e.g. of the hardness over the panel's cross section, the functionality of the component can be considerably extended. The formerly purely decorative interior door panel becomes a functional element of the passive vehicle safety.

Components with functional graded properties provide a resource-conserving alternative for modern composite materials [1]. However their production requires complex manufacturing processes, such as thermo-mechanically coupled processes [1]. While there are numerous material scientific approaches on how to design an isolated process step to achieve a certain material structure, the holistic design of connected process chains is much more difficult. For that purpose in section two a planning framework will be described that has been developed to suggest alternative manufacturing process chains based on an enhanced computer-aided design (CAD) component description. These resulting process chains are each capable of producing the component according to the component description but differ in criteria that are not specified in CAD models, as for example process flexibility or energy efficiency. To aid the decision maker in selecting the right process chain for the individual planning task, section three describes a methodology for a multi-criteria decision-support based upon a matrix-supported algorithm. Section four summarizes the approach and identifies the future research challenges.

## 2 FUNCTIONALLY GRADED COMPONENTS

### 2.1 Exemplary Manufacturing Process Chain

The manufacturing process chains of functionally graded components are characterised by strong interdependencies between the process steps. According to the presented interior door panel (cf. section 1), a manufacturing process chain for self-reinforced polypropylene composites is used here as an example. This process chain utilises a thermo-mechanical hot-compaction process to integrate the functional gradation into self-reinforced polypropylene composites by processing layered semi-finished textile products on a thermoplastic basis. The semi-finished textile products were previously stretched and provide a self-reinforcement based on a macromolecular orientation. This self-reinforcement leads to a sensitive behaviour regarding pressure and thermal treatments and is therefore essential for the functional gradation [1], [2].

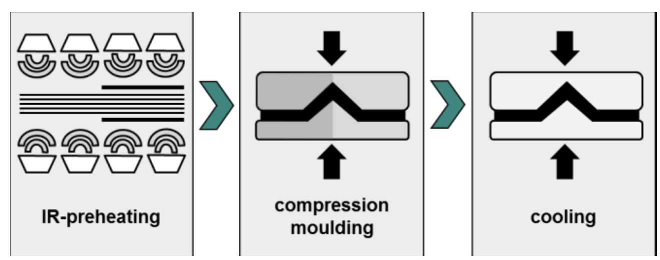


Figure 1: Manufacturing process chain of self-reinforced polypropylene composites by the process steps: IR-preheating, compression moulding and cooling.

Figure 1 shows the manufacturing process chain for self-reinforced polypropylene composites starting with a gradual preheating of the semi-finished products in a partially masked IR-preheating station. In the next step, the thermal gradation of the product will be enhanced due to consolidation by a special compression moulding forming tool. This tool also applies a mechanical gradation by a local reduction of pressure using a triangular geometry. A cooling phase is necessary before demoulding the component [3].


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### 2.2 Planning Framework

For the holistic planning of connected manufacturing process chains in the context of functionally graded components, the interdependencies between the component and the manufacturing processes as well as between the process steps themself need to be considered. Therefore the theoretical concept of a planning framework has been developed. The framework integrates several methods, tools and knowledge obtained by laboratory experiments and industrial cooperation projects in which the concept of functional gradation has been analysed. The planning process within the framework is continuously assisted by the three modules “Component Description“, “Expert System” and “Modelling and Process Chain Optimisation”.

The CAD model of the component and the intended graded properties provide the input information for the manufacturing process planning. Based on this information, alternative process chains for the manufacturing of the component are synthesised by means of the planning framework. After this, the process chains are ranked and optimised according to the individual planning task. The best process chain is described using a dedicated specification technique for production systems in the last step of the planning process (cf. Figure 2) [4].

The **Component Description** module enables the graded properties to be integrated into the CAD model of the component. The model usually consists of geometric features (e.g. cylinder or disc), which will be extracted after importing the model. These features allow the planning framework to consider the geometry of the component and to pre-select reasonable gradients according to the geometry. This pre-selection increases the efficiency since the manufacturing planner can directly provide the desired properties by modifying the parameters of the gradients proposed. If the CAD model does not contain geometric features or the user does not want to use one of the presented gradients, the component is divided into volume elements. These so called voxels enable the component to be locally addressed and can be used as supporting points for the function-based integration of the component’s graded properties [5].

Based on the enhanced CAD model, the **Expert System** synthesises several alternative process chains for the manufacturing of the component. Therefore the manufacturing process steps available in the knowledge base are filtered with regard to the component description such as material, geometry or the intended graded properties, e. g. hardness or ductility. To realise this, the content of the knowledge base is structured by an ontology, which classifies the process steps according to their characteristics and connects the information of the knowledge base via relations. An inference machine is applied in order to draw conclusions from the ontology, especially according to the interdependencies between the manufacturing processes.

In the presented manufacturing process chain for self-reinforced polypropylene composites, the initial material temperature that is adjusted during the preheating process in preparation of the compression moulding process, has for example a strong influence on the mouldability of the component. All those interdependencies need to be considered during the pairwise evaluation of the process steps to ensure the compatibility of the synthesised process chains. Process chains with incompatible process steps are disregarded. The ranking of the manufacturing process chains is described in section three. Thus the result of the Expert System module is a set of alternative process chains which are capable of producing the component according to the enhanced CAD model [1].

By means of the **Modelling and Process Chain Optimisation** module, the parameters of the preferred manufacturing process chains are obtained. To accomplish this, predictions of empirical models based on several experiments, measurements and simulations of research samples provide a convenient solution space (cf. [6]). Therefore modern empirical modelling techniques and also a hybrid hierarchical multi-objective optimisation are used to identify the optimal setup for each process step of a manufacturing process chain.

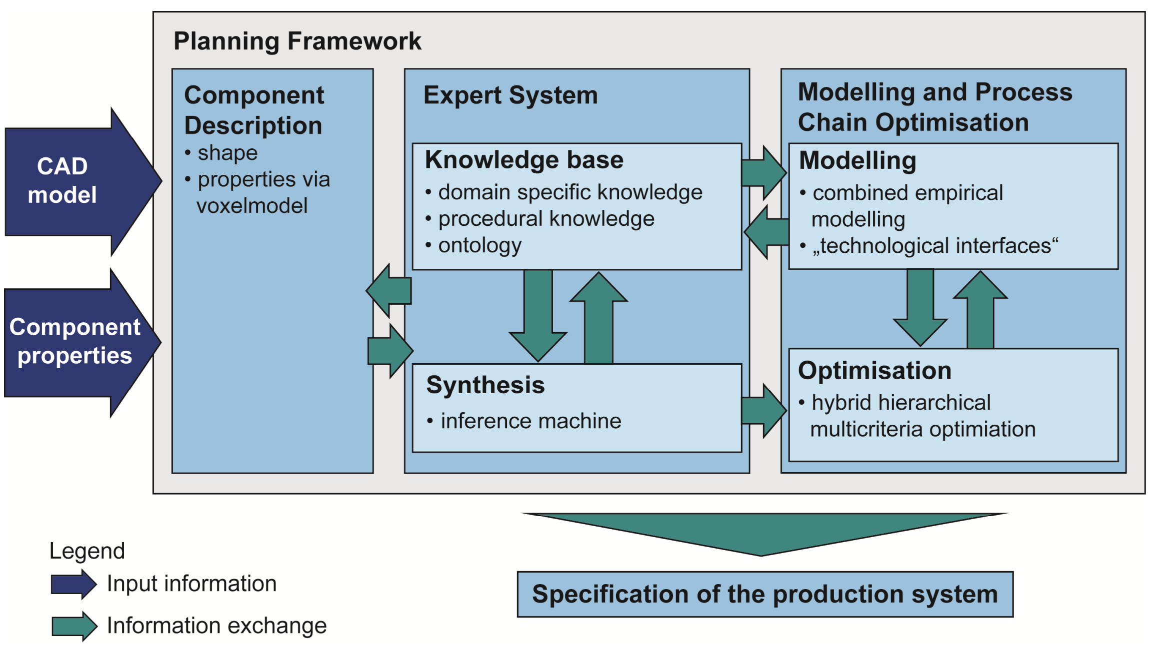


Figure 2: Planning framework for the computer-aided planning and optimisation of functional graded components.

Finally the process chain that is capable of manufacturing a functionally graded component in the best way with regard to the component description and the defined qualitative criteria is described using a dedicated specification technique. This fundamental specification is based on a process sequence and a resource diagram. Further information about the specification technique can be found in [7].

Figure 3 shows an extract of the optimised process sequence for the manufacturing of self-reinforced polypropylene composites with functionally graded properties. Also for the compression moulding, the four most significant process parameters are illustrated.

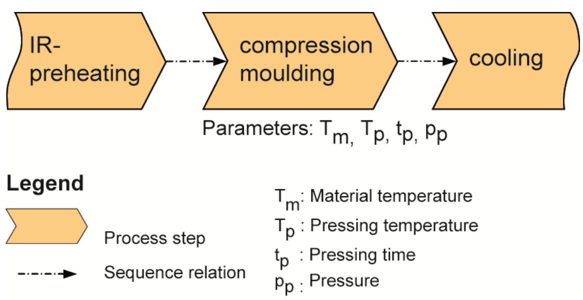


Figure 3: Part of the process sequence for the manufacturing of self-reinforced polypropylene components.

In the next section the procedure of the multi-criteria process chain selection will be described in more detail.

## 3 MULTI-CRITERIA DECISION-SUPPORT

### 3.1 Decision Requirements

After several alternative process chains have been identified, it is necessary to select the most suitable alternative with regard to the requirements that could not be specified within the CAD model. Initially each process chain has been set up to produce a single component mainly with respect to the technological interdependencies between the process steps. Although this objective leads to the desired results for a low volume laboratory manufacturing, high volume industrial production requires the consideration of more sustainable factors. Especially in the case of functionally graded components it is important to maintain a long-term reproducibility of the component properties even through mass production. While multi-criteria decision-support is available for isolated engineering decisions as for example the choice of material, other criteria besides engineering matters must also be considered [8].

### 3.2 Decision Criteria

Today one of the main challenges for companies is to establish a sustainable production according to the triple bottom line, i.e. satisfying social, ecological and economic criteria at the same time [9]. Since the development and production of functionally graded components is very cost-intensive, economic sustainability can only be achieved by high production volumes on an industrial scale. However increasing production volumes in general also mean higher emissions of pollutants and risen efficiency pressure on employees. Since these counter effects must be avoided in sustainable production environments, an individual trade-off point has to be identified for every new production task.

To balance the different kinds of requirements a set of criteria for each of the three clusters according to the triple bottom line of sustainability and based on empirical experiences as well as expert knowledge has been defined. Each of the criteria has been selected with regard to the overall objective of a sustainable production of functionally graded materials in an industrial mass production.

*Economic Criteria*

- Average lead time of single component in process chain
- Inventory volume of intermediate and finished material
- Consumption of scarce buffer resources, e.g. work space
- Flexibility regarding changes in customer demand
- Variance in component quality of production batch

*Ecological Criteria*

- Energy efficiency of process chain
- Generation of waste material
- Emission of pollutants
- Recyclability of process media
- Utilization of hazardous chemicals, e.g. coating

*Social Criteria*

- Emission of toxicants and vibrations
- Working environment temperature and humidity
- Process chain compatibility to ergonomic requirements

The value for each of the defined criteria must be determined by a comprehensive expression that specifies at least two discrete states of the criterion. Criteria values are not necessarily numeric and might combine several influence parameters. For instance the working environment temperature and humidity is a very important social criterion for the well-being of production workers. However the human comfort range cannot be easily expressed mathematically, since the temperature should neither be too hot nor too cold and the exact range heavily depends on the humidity. Human workers can perceive the same temperature as unpleasantly hot at high humidity or very comfortable at lower humidity. So rather than defining an extensive mathematical relation, the discretized criterion states are simply called ‘Freezing’, ‘Dry cool’, ‘Moist cool’, ‘Pleasant’, ‘Moist heat’ and ‘Dry heat’.

In contrast to the previous example there are also decision criteria that express clearly numeric characteristics. For example the average lead time of a single component in a process chain is directly expressed in minutes. Besides those criteria with obvious metrics another way of expressing discrete numeric states are normalized indices which integrate multiple input parameters, e.g. energy efficiency indices. Since there are many different approaches on how to differentiate discrete states of decision criteria, the chosen metric may be subject to change with new decision situations. Any specification of decision criteria must be carefully revised with respect to the decision objective and the expected values of the alternatives at hand.

### 3.3 Evaluation Method

With a given set of observable decision criteria and several different process chains the choice of the most suitable alternative depends mainly on the selected decision method. As has been described in the previous section, not all decision criteria are quantitative in nature and even those express very different characteristics regarding their evaluation. For example any value of the average lead time can be proportionally compared to another value, since double average lead time of a single component means the process chain is only half as good for this single criterion. Other criteria however do not display a similar behaviour, therefore inevitably requiring a human decision maker to decide which process chain is how much better.

After comparing different methods of multi-criteria decision-support the Analytic Hierarchy Process (AHP) proved to perform with the best results for the process chain decision problem. The AHP is a matrix-based approach for complex decision problems that is based on the pairwise comparison of the criteria as well as all alternatives [10]. With regard to the previously mentioned criteria characteristics there are three main advantages that particularly support the use of the AHP in the context of the manufacturing process chain selection:

- Mathematical foundation of the decision process increases acceptance among the stakeholders
- Automated consistency checks of input values reduce human errors and avoid distorted results
- A conversion of qualitative criteria scales to numeric scales is not necessary

In the next section the principle procedure of the manufacturing process chain selection with the AHP will be demonstrated by an example.

### 3.4 Weighting of Criteria and Assessment of Alternatives

Since it has already been explained how functional gradation can improve the functionality of a car interior door panel, the manufacturing process will be exemplarily demonstrated for this component. Figure 4 shows a possible shape geometry that has been designed to harmonise with the car interior in general and simultaneously provide acoustic protection as well as passenger safety during crashes.

Figure 4: Car interior door panel [11].

Once the product is fully specified the Planning Framework will support the production planner in setting up a suitable manufacturing process chain. The Planning Framework offers several alternative manufacturing process chains for the interior door panel which are all able to achieve the desired product specification and gradation.

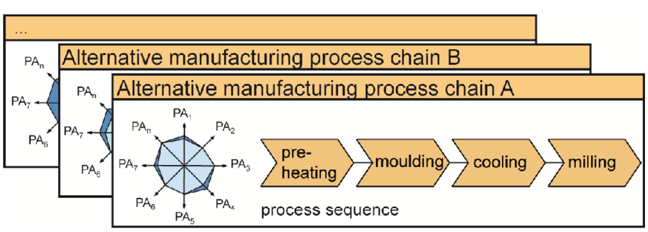


Figure 5: Set of alternative process chains given by the framework.

Figure 5 shows the general structure of each process chain which consist of a sequence of heating, cooling and processing steps. The alternative process chains differ in the exact number and order of their steps as well as their process parameters.

To select the best process chain with regard to a sustainable mass production the AHP contains three basic steps for the weighting of criteria and assessment of alternatives [12]:

1. Pairwise comparison of criteria importance for overall objective
2. Pairwise comparison of alternatives for each criterion
3. Ranking of alternatives

For the pairwise comparison of the criteria and alternatives, the AHP usually utilizes a linguistic scale which spans from equal importance to absolute dominance. Each point on the comparison scale is assigned a numeric value, i.e. equal importance corresponds to 1 and absolute dominance corresponds to 9, where values in between mean intermediate importance. For this demonstration example the scale is assumed to span from 1 to 5 meaning 5 expressing absolute dominance and 3 expressing medium dominance. The dominated criterion or alternative is formally assigned the corresponding fraction 1/3 or 1/5 respectively.

*1. Pairwise comparison of criteria importance for overall objective*

For demonstration purposes it is assumed that only three of all proposed decision criteria for the manufacturing process chain selection are considered during the AHP: average lead time of single component in process chain (LT), energy efficiency of process chain (EE) and working environment temperature and humidity (WE). Table 1 shows the relative importance of the three criteria with regard to the overall objective 'Sustainable mass production of functionally graded interior door panel' after pairwise comparison:

| Relative Criteria Importance | Economic Criterion | Ecological Criterion | Social Criterion |
|---|---|---|---|
| | **LT** | **EE** | **WE** |
| LT | 1 | 3 | 5 |
| EE | 1/3 | 1 | 2 |
| WE | 1/5 | 1/2 | 1 |

Table 1: Relative criteria weighting matrix for sustainable mass production of functionally graded interior door panel (example).

By calculating the eigenvector of the matrix the AHP allows the ranking of the criteria with regard to their importance concerning the overall objective:

1. LT - 64.8%
2. EE - 22.9%
3. WE - 12.3%

The AHP enables the evaluation of the criteria weighting matrix with an inconsistency factor that is based on the eigenvalue of the matrix. For the setting of Table 1 the inconsistency factor is 1.9% and therefore insignificant, since the AHP is robust enough to handle inconsistencies up to a factor of 10%.

*2. Pairwise comparison of alternatives for each criterion*

Once the ranking of the criteria importance has been obtained, all alternatives are compared with each other regarding their qualification for each criterion. For demonstration purposes two different process chains A and B are assumed, that differ in the sequence and parameters of their process steps (cf. Figure 5). While process chain A guarantees a fast and flexible production, process chain B is very energy efficient with more pleasant environmental conditions for the workers. The two process chains are now compared to each other for all three evaluation criteria, using the same linguistic scale as above.

| LT | A | B |
|---|---|---|
| A | 1 | 3 |
| B | 1/3 | 1 |

Table 2: Lead time assessment of alternatives.

| EE | A | B |
|---|---|---|
| A | 1 | 1/5 |
| B | 5 | 1 |

Table 3: Energy efficiency assessment of alternatives.

| WE | A | B |
|---|---|---|
| A | 1 | 1/4 |
| B | 4 | 1 |

Table 4: Working environment assessment of alternatives.

Since the assessment of each criterion only had two alternatives, the inconsistency is automatically 0% and therefore insignificant.

*3. Ranking of alternatives and sensitivity analysis*

With a complete assessment of the alternatives for each criterion and the obtained criteria ranking, the AHP calculates the final ranking of alternatives with regard to the overall objective based on a series of matrix multiplications. A detailed description of the procedure can be found in [10]. For the demonstration example of the car interior door panel the final ranking results as follows:

1. Process chain B - 58.7%
2. Process chain A - 41.3%

In this case process chain B would be selected since the shortcomings of the manufacturing process lead time compared to process chain A can be compensated by immensely superior energy efficiency as well as considerably better working environment conditions for the employees.

If any uncertainties are noticed during the weighting of the criteria or the comparison of the alternatives, a sensitivity analysis should be performed [12]. For that purpose the criteria weighting and the assessment values are varied within the uncertainty range to check whether the final ranking is affected. If the outcome is highly unstable, more information need to be acquired about the decision situation or additional decision criteria should be considered

## 4 CONCLUSION AND OUTLOOK

Functionally graded components offer a new and sustainable approach for customisable smart products. Therefore a planning framework for the computer-aided planning and optimisation of components with functional graded properties and a methodology for a multi-criteria decision-support of a sustainable mass production have been presented and demonstrated with an application example.

Although the expert system within the framework is able to automatically synthesise manufacturing process chains for the production of a functional graded component, the final selection must still be conducted manually with respect to the specific production objective. As the demonstration example illustrated it is not always obvious which alternative fulfils the diverse requirements of the different stakeholders in the best way. The Analytic Hierarchy Process proved to be the most effective method to handle the highly diverse characteristics of the decision criteria while not overstraining the decision process with data acquisition and examination.

Especially the mathematical foundation of the method improves the user acceptance drastically since the share of random decisions is obviously mitigated. However the mathematical principles are not self-explanatory and must therefore be openly communicated to gain sufficient recognition. If that is achieved, the method can play a vital role in supporting the user making the best decision.

Future work includes the integration of additional manufacturing processes and interdependencies into the knowledge base and thereby also the enhancement of the ontology. In addition, the inference-rules of the expert system have to be developed to realise the synthetisation of more complex manufacturing process chains and their pairwise evaluation. Considering that the system is still under development, the industrial applicability has to be proven. Likewise, a concept for the integration of the planning framework in common product lifecycle management (PLM) tools has to be developed.

Furthermore a cost estimation component could provide valuable information to support the decision making process by comparing efforts and benefits for each alternative. Especially the question of investment costs and variable expenses should be considered integrative with the manufacturing process selection. In that sense it would not only be possible to balance the economic decision criteria more appropriately but also incorporate them in the sustainability approach presented in this contribution.

## 5 ACKNOWLEDGEMENT

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# Model for a Decision Theory Based Inspection Planning

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**Abstract**
Within the framework of inspection planning, quality inspections for the entire production process from goods receipt to dispatch are established. As the quality inspections ensure that the manufactured product corresponds to the quality demands derived from the customer requirements, they have a significant influence on customer satisfaction and resulting economic success.

This publication presents a model based on decision theory for planning quality inspections in the entire production process. The model considers that decisions (e. g. with respect to inspection extend) need to be made during inspection planning, whose profitability depends on environmental states, that have a certain probability such as defect frequency, for example. The goal of the model is to enable cost-efficient decisions in consideration of the companies risk attitude regarding the outcome of the inspection plan (e. g. defects perceived by the customer).

**Keywords:**
Inspection Planning; Decision Theory; Quality Management

## 1 INTRODUCTION

International competition in mechanical engineering has intensified over the past few years. A promising approach of operating successfully in spite of increased competition lies in reducing costs while improving quality and productivity [1]. Inspection planning can make an important contribution in putting this approach into practice. Within the framework of inspection planning, quality inspections are established. During the production process, these serve to monitor the extent to which a unit fulfils stated and implied requirements (i. e. quality requirements) [2]. Thus, within the framework of inspection planning, there are trade-offs between inspection costs associated with quality inspections and failure costs resulting from lack of quality. The latter represent a considerable cost factor. On industry average, the share of failure costs expressed as a percentage of turnover lies between five and 15 % [3]; in production companies it frequently reaches as high as 30 % [4].

## 2 REFERENCE FRAMEWORK

### 2.1 Inspection Planning

The task of inspection planning is to define the testing for the different steps in manufacturing products, taking into account economic circumstances [2, 5]. In order to generate an inspection plan, based on of the VDI/VDE/DGQ guideline 2619 the following seven assignments need to be carried out [6, 7]:

- Selection of the inspection characteristics (what?)
- Determine the point in time of inspection (when?)
- Determine the type of inspection (how?)
- Determine the inspection extend (how much?)
- Determine the inspection location (where?)
- Determine the personnel (who?)
- Selection of the inspection equipment (whereby?)

When selecting inspection characteristics (i. e. what?), firstly the potential characteristics need to be identified using design drawings, process sheets technical delivery conditions etc. [2]. Afterwards, the potential characteristics are checked for inspection necessity to define the characteristics to be inspected. Reasons for the inspection necessity are statutory regulations safety issues and so on. The point in time of inspection (i. e. when?) describes at which point in the production process the inspection will be carried out. Here, a rough distinction can be made between the incoming, intermediate and final inspection. When establishing the type of inspection (i. e. how?), a basic distinction is made between an attribute and a variable inspection [7]. The attribute inspection permits the statement “Characteristic exists: yes / no”, for example. In the variable inspection, the quality inspection is carried out using qualitative characteristics, e. g. measured values of geometrical parameters, and comparing these with the specified tolerance zone. In principle, the variable inspection is preferable to the attribute inspection, as it has a greater statistical power and requires a lower sample size. The inspection extend (i. e. how much?) establishes the percentage of parts, which will undergo an inspection [6]. The inspection extend ranges from complete suspension (no inspection) to a 100 % inspection. The latter is used primarily in the case of safety-relevant characteristics, for characteristics whose production process does not have sufficient stability and during the phase of ramp up. Determining the inspection location (i. e. where?) is largely dependent on the inspection characteristics, the inspection equipment, the production flow and the size of the parts. Sometimes, the inspection location is also dictated by non-portable inspection equipment which is set up in laboratories or measuring rooms. The inspection personnel (i. e. who?) is usually determined by the choice of inspection equipment. According to certain circumstances, complex measuring instruments may only be operated by qualified personnel [7]. Inspection equipment (i. e. where by?) refers to all the devices and fixtures (measuring equipment) needed for conducting an inspection process. The selection of the measuring equipment is determined in particular by the availability and suitability of the inspection equipment.

### 2.2 Decision Theory

A decision problem may be characterized by the question as to which **action alternative** (i. e. alternative) should be selected from a number of alternatives [8]. At least two of the alternatives must differ from each other in a way that a goal may be reached better with one of them. The number of possible alternatives is limited by conditions,


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restrictions and circumstances [9]. Furthermore, the decision problem is characterized by the fact that the **result**, which is achieved from selecting an action alternative, is dependent on environmental **states** (i. e. states), i. e. on developments and circumstances which cannot be influenced by the decision-maker [10].

| state $s_j$ / alternative $a_i$ | $s_1$ | … | $s_n$ |
|---|---|---|---|
| | p($s_1$) | … | p($s_n$) |
| $a_1$ | $r_{11}$ | … | $r_{1n}$ |
| … | … | … | … |
| $a_m$ | $r_{m1}$ | … | $r_{mn}$ |

Table 1: Result Matrix [11].

The correlation between the possible action **alternatives** ($a_i$), the possible environmental **states** ($s_j$) and the **results** ($r_{ij}$) achieved can be represented in a result matrix (see Table 1) [10]. If the environmental states possess known probabilities of occurrence the parameter p($s_j$) is insert in the result matrix. This parameter describes the **probability of occurrence** of the environmental state ($s_j$). For the subsequent assessment and selection of the preferred action alternative, not only are the four named parameters (environmental states, probability of occurrence, alternatives and results) required, but also the objectives of the decision-maker [12]. Based on these objectives, utility functions can be formed with which the results of the action alternatives may be evaluated and weighed against each other [9].

A simple example of an utility function is the linear utility function [13]:

$$\mathrm{u}(x) = \frac{x - x^-}{x^+ - x^-} \tag{1}$$

At the interval [$x^-$, $x^+$] an utility value from 0 to 1 is allocated to the result $r_{ij}$ (i. e. u($x^-$) = 0 and u($x^+$) = 1). Here, $x^-$ and $x^+$ represent the two extreme values of the results $r_{ij}$. In reality, however, many decisions are not made based on the result values alone, but are also influenced by the risk attitude of the decision-maker. A utility function, which takes into account the risk attitude of the decision-maker, is represented by the following exponential utility function [13]:

$$\mathrm{u}(x,c) = \frac{1 - \mathrm{e}^{-\mathrm{c}\frac{x-x^-}{x^+-x^-}}}{1 - e^{-c}} \tag{2}$$

With this utility function, the risk attitude is accounted for by the parameter *c*. For *c* < 0 the utility function develops in a strictly concave manner. The marginal utility thereby increases as the result value increases, and the decision-maker is called risk-averse. For *c* > 0 the utility function line develops in a strictly convex way. The marginal utility thereby decreases and the decision-maker is identified as risk-seeking. Although the function is not defined for *c* = 0, the function converges to the linear function for $c \rightarrow 0$. Therefore in the case of a risk-neutral decision-maker (e. g. *c* = 0), the linear utility function is employed (constant marginal utility) [9, 10].

On the basis of the utility values of the various alternatives, which are determined by the utility value function, the optimum action alternative may be selected using the optimization criterion. If maximization of the utility value is used as the optimization criterion, it is referred to as utility maximization [9].

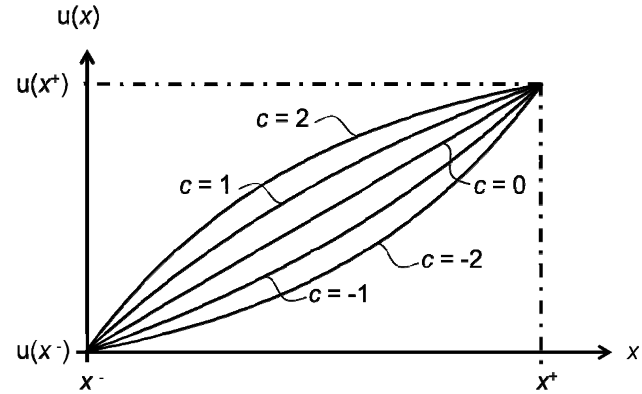


Figure 1: Exponential utility value function [13].

## 3 MODEL

Based on the fundamental goal of a company to maximize the return of capital invested, the task of inspection planning is to plan the inspections for the production process in such a way that costs within the framework of inspection planning are minimized. Here it should be noted that inspection planning determines not only the costs for the inspections themselves but also has a decisive influence on the quality of the product experienced by the customer and thus an effect on failure costs (cf. Figure 2). The underlying idea presented in Figure 2 is, that while the costs for inspection rise (e. g. because of a higher inspection extend) the quality, that is perceived by the customer, increases (i. e. graph inspection costs). Further more, if the quality perceived by the customer increases the failure costs decrease (i. e. graph failure costs).

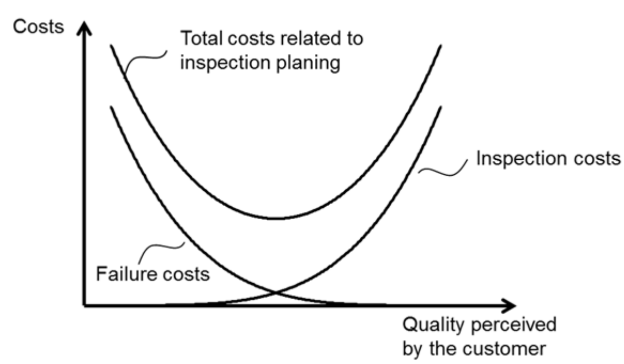


Figure 2: Balance between Inspection and Failure Costs [14].

In principle, costs within the framework of inspection planning may be sub-divided into inspection costs and failure costs. Inspection costs primarily include the costs incurred when inspecting the quality of the product. The failure costs may be sub-divided into internal and external failure costs [7]. Here, internal failure costs refer to internal operating costs for remedying a defective product or process. By contrast, external failure costs refer to costs which are incurred after dispatch. The total costs which are controllable through inspection planning $K_G$ are the sum of the inspection costs $K_P$, the internal failure costs $K_F$ as well as the external failure costs $K_{FF}$:

$$K_G = K_P + K_F + K_{FF} \tag{3}$$

The equation (3) implies, that all three summands have the same importance. However, for example for a company that strives for quality leadership, due to the higher external failure costs, the case depicted in equation (4) is less preferable than the case depicted in equation (5).

$$K_{G,1} = K_{P,1} + K_{F,1} + K_{FF,1}$$
$$= 10\ Mio.\$ + 5\ Mio.\$ + 5\ Mio.\$ = 20\ Mio.\$ \quad (4)$$

$$K_{G,2} = K_{P,2} + K_{F,2} + K_{FF,2}$$
$$= 13\ Mio.\$ + 6\ Mio.\$ + 1\ Mio.\$ = 20\ Mio.\$ \quad (5)$$

In order to account for this, the aim of the presented model is to enable cost-efficient decisions in consideration of the companies attitude regarding the outcome of the inspection plan.

### 3.1 Basic Concept

Within the framework of the seven inspection planning assignments of the VDI/VDE/DGQ guideline 2619, a range of decisions (e. g. with respect to inspection extend, equipment and location) must be made. These decisions involve various action alternatives (e. g. 100 % inspection vs. complete suspension of inspection), as well as environmental states (such as defective product vs. defect-free product), that occur with a probability, and results (such as inspection costs).

Consequently, these decisions are decision problems as defined by decision theory, which may be depicted using a result matrix and solved by means of an utility function. In the model presented here, the decision theory approach was taken and combined with a monetary perspective in order to facilitate cost-efficient inspection planning in consideration of the companies risk attitude regarding the outcome of the inspection plan (e. g. defects perceived by the customer).

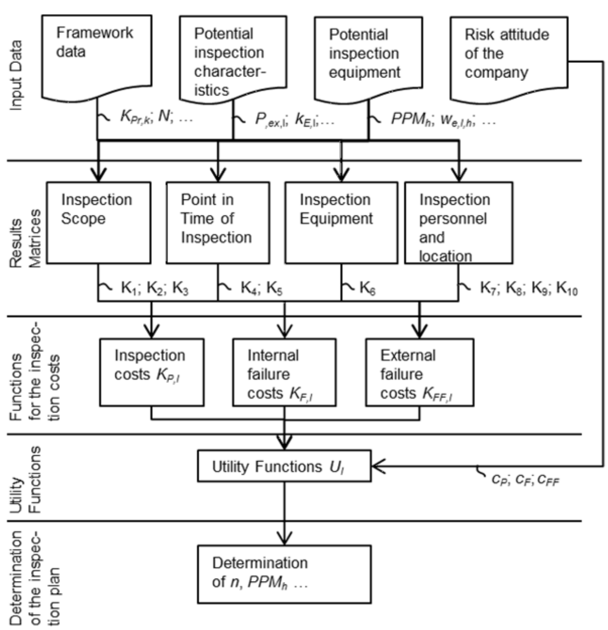


Figure 3: Basic concept.

The basic concept of the model (cf. Figure 3) provides, that a range of framework data (such as the quantity of units to be produced and the personnel costs) is included, as well as potential inspection characteristics and potential inspection equipment. On the basis of the input data, result matrices are generated for the decision problems of inspection planning. These matrices contain the action alternatives, environmental states, the probability of occurrence and the relevant results. Finally, functions for the various cost components (e. g. Inspection costs, internal failure costs) are derived based on the results of the individual result matrices. They are then weighed using the utility functions in order to enable cost-efficient inspection planning based on the companies risk attitude. The inspection plan, consisting of all seven inspection planning assignments (i. e. what, when, how, how much, where, who, whereby), can be determined on base of the utility functions by calculating the utility values for each individual alternative and choosing the highest value.

### 3.2 Input Data

*Framework data*

To generate the result matrices of the model, the framework data first needs to be recorded. Here, in particular, the following cost factors are relevant for the model:

- $K_{Pr,k}$: accumulated production costs per piece at the point in time $k$
- $K_{Pr,G}$: total production costs per piece
- $K_{EL}$: replacement delivery costs per piece
- $K_{SE}$: compensatory costs per piece
- $K_{FP,k}$: personnel costs of an employee of the production station $k$ per minute
- $K_{QS}$: personnel costs of an employee of quality assurance per minute

Furthermore, the number of production steps and the number of units to be produced in the lifecycle ($N$) are also examples of significant factors.

*Potential Inspection Characteristics*

Other important input data within the framework of the model are the potential inspection characteristics. In principle, all product characteristics may represent an inspection characteristic. As part of reducing costs, a pre-selection must therefore be made in which the number of potential inspection characteristics is limited. Criteria for selecting a product characteristic are the relevance of the characteristic for [7]:

- Safety
- Customer requirements
- Functionality
- Statutory regulations
- Internal company regulations
- Adjustment of a production process
- Economic necessity

Identifying potential inspection characteristics is achieved using design drawings, for example, or process sheets and technical delivery conditions.

With respect to potential inspection characteristics, properties such as "time of origin of the characteristic $l$ ($k_{E,l}$)" and "inspection possible until ($k_{Z,l}$)" are important for the subsequent decisions. This information is recorded in the **list of potential inspection characteristics**. In Table 2, an excerpt of the list is shown, using the example "diameter".

| characteristic | location on work piece | nominal dimension | range of tolerance | … | time of origin of the characteristic *l* $k_{E,l}$ | inspection possible until $k_{Z,l}$ | costs from re-working per piece $K_{n,l}$ | costs for external inspection per piece $K_{P,ex,l}$ |
|---|---|---|---|---|---|---|---|---|
| diameter | ⋮ | ⋮ | ⋮ | … | $k_{E,1}$ | $k_{Z,1}$ | $K_{n,1}$ | $K_{P,ex,1}$ |
| ⋮ | ⋮ | ⋮ | ⋮ | … | ⋮ | ⋮ | ⋮ | ⋮ |

Table 2: List of potential inspection characteristics.

*Potential Inspection Equipment*

To select suitable inspection equipment for an inspection characteristic, the suitability and availability of inspection equipment needs to be determined in advance. An inspection characteristic/ inspection equipment allocation matrix, may be used as an instrument for selecting suitable inspection equipment for the relevant characteristics. Available measuring equipment may be identified with the aid of an inspection equipment database (inspection equipment catalogue). This database usually lists all available measuring equipment with its specific performance data. In addition, new procurements also need to be considered. The suitable and potentially available measuring equipment and its properties (e. g. fixed inspection costs ($K_{PF}$) and duration of inspect-ion ($t_P$)) are recorded in the list of potential inspection equipment. In Table 3, an excerpt of such a list is shown as an example.

| potential inspection equipment | … | fixed inspection costs $K_{PF}$ | variable inspection costs $K_{PF}$ | duration of inspect-ion per piece $t_P$ | probability that a defect of characteristic *l* is recognised |
|---|---|---|---|---|---|
| ***PPM₁*** | … | $K_{PF,l,1}$ | $K_{PV,l,1}$ | $t_{P,l,1}$ | $w_{e,l,1}$ |
| **…** | … | … | … | … | … |
| ***PPMₕ*** | | $K_{PF,l,h}$ | $K_{PV,l,h}$ | $t_{P,l,h}$ | $w_{e,l,h}$ |
| **…** | … | … | … | … | … |

Table 3: List of potential inspection equipment for characteristic *l*.

### 3.3 Result Matrices

*Inspection Extend*

If the reason for the inspection of characteristic *l* does not render a 100 % inspection necessary, the inspection extend has to be determined. A distinction can be made between three alternatives (with *n*: number of parts to be inspected and *N*: number of units to be produced in the lifecycle) [7]:

- Complete suspension of inspection ($n = 0$)
- Sampling inspection ($n \in ]0, N[$)
- 100 % inspection ($n = N$)

| state $s_j$ / alter-native $a_i$ | defect 1: diameter too small | defect 2: diameter too big | no defect |
|---|---|---|---|
| | $p_1 = w_{a,1,1}$ | $p_2 = w_{a,1,2}$ | $p_3 = w_{a,1,3} = 1 - p_1 - p_2$ |
| **suspension inspection ($n_l = 0$)** | $K_1(n_l, w_{a,1,1})$ | $K_1(n_l, w_{a,1,2})$ | 0 |
| **sampling inspection ($n_l \in ]0,N[$)** | $K_2(n_l, w_{a,1,1})$ | $K_2(n_l, w_{a,1,2})$ | $K_2(n_l, w_{a,1,3})$ |
| **100 % inspection ($n_l = N$)** | $K_3(n_l, w_{a,1,1})$ | $K_3(n_l, w_{a,1,2})$ | $K_3(n_l, w_{a,1,3})$ |

Table 4: Result Matrix for the inspection extend of characteristic *l*.

The environmental states are the possible defect states (defect 1 and defect 2) and the defect-free state. These states have the probability of occurrence $p_j = w_{a,l,j}$ (with $w_{a,l,j}$: probability of occurrence of the state *j* of the characteristic *l*). This probability may either be determined based on data from production of previous products or must be estimated based on experience. In the case of a **complete suspension of inspection**, no inspection costs are incurred. For this reason, only the subsequent failure costs are taken into account through the cost function $K_1$:

$$K_1 := N \times w_{a,I,j}\left(K_{\mathrm{Pr},G} + K_{EL} + K_{SE}\right) \tag{6}$$

With respect to the cost function $K_2$ of the **sampling inspection**, both the inspection costs as well as the subsequent failure costs are taken into account:

$$\begin{aligned} K_2 := &\left(K_{PF,I,h} + n_I \times K_{PV,I,h}\right) + \\ &\left(N - n_I\right) \times w_{a,I,j}\left(K_{\mathrm{Pr},G} + K_{EL} + K_{SE}\right) \end{aligned} \tag{7}$$

with:

- $K_{PF,l,h}$: fixed costs for inspecting characteristic *l* with measuring equipment *h*
- $K_{PV,l,h}$: variable costs for inspecting characteristic *l* with measuring equipment *h*

As the costs for defects, which remain undetected during inspection, are taken into account by $K_6$ (result matrix for inspection equipment), theses costs are not considered by cost function $K_2$ and $K_3$. The cost function $K_3$ for the **100 % inspection** can be derived from the cost function $K_2$ (with $n_l = N$):

$$K_3 := K_{PF,I,h} + N \times K_{PV,I}, h \tag{8}$$

On the basis of the cost functions from Table 4 (i. e. $K_1$, $K_2$ and $K_3$), the inspection extend cannot be determined at this point, as the inspection equipment and hence the cost for the inspection equipment ($K_{PF,l,h}$ and $K_{PV,l,h}$) have not yet been determined. Rather these functions represent cost scenarios whose results may only be established once all result matrices and the utility functions have been defined (cf. Figure 3).

*Point in Time of Inspection*

To assign the point in time of inspection in the production process, the parameter *k* is introduced based on COLLEDANI, TOLIO 2012 [15]. This counts through the individual production steps in the production sequence. The possible point in time of inspection $k_l$ of the characteristic $I$ is limited by the point in time of origin of the characteristic ($k_{E,I}$: earliest possible point in time of inspection of characteristic $I$) and, generally by the point in time ($k_{Z,I}$: latest possible point in time of inspection of characteristic $I$) from which the accessibility is no longer ensured.

| state $s_j$ / alter-native $a_i$ | defect 1: diameter too small | defect 2: diameter too big | no defect |
|---|---|---|---|
| | $p_1 = w_{a,1,1}$ | $p_2 = w_{a,1,2}$ | $p_3 = w_{a,1,3} = 1 - p_1 - p_2$ |
| $k_{E,I}$ | $K_4(k_{E,I}, w_{a,1,1})$ | $K_5(k_{E,I}, w_{a,1,2})$ | 0 |
| … | … | … | 0 |
| $k_{Z,I}$ | $K_4(k_{Z,I}, w_{a,1,1})$ | $K_5(k_{Z,I}, w_{a,1,2})$ | 0 |

Table 5: Result Matrix for the point in time of inspection for characteristic $I$.

The numerous possible points in time of inspection (i. e. [$k_{E,I}$, $k_{Z,I}$]) represent the action alternatives in the result matrix for the inspection extend (cf. Table 5). The environmental states and their probability of occurrence are depicted analogue to the result matrix for the point in time (Table 4) by means of the possible defect states (defect 1 und defect 2) and the defect-free state.

With respect to the cost functions in the results fields of the matrix, a distinction is made between the case where reworking is possible upon detecting a defect and the case where no reworking is possible. Here, it is assumed that defects which remain undetected during inspection arise in the form of type II error (i. e. the defect is not detected by inspection) but not in the form of type I error (i. e. although there is no defect, the result of the inspection states a defect) [16]. The additional costs arising from this are taken into account in the result matrix for the inspection equipment (Table 6).

In case no reworking is possible, the costs are accounted for with the function $K_4$:

$$K_4 := n_I \times w_{a,I,j} \times w_{e,I,h} \times K_{\Pr,k} \quad (9)$$

with:

- $w_{e,I,h}$: probability that a defect of characteristic $I$ is recognised employing the inspection equipment $h$

In case reworking is possible, it is assumed that the costs for renewed inspection following reworking may be disregarded, and so, within the framework of the model, the costs of rework are calculated as follows:

$$K_5 := n_I \times w_{a,I,j} \times w_{e,I,h} \times K_{n,I} \quad (10)$$

with:

- $K_{n,I}$: cost for reworking the defect of characteristic $I$

*Inspection Equipment*

When determining the inspection equipment, the defects which remain undetected during inspection are taken into account within the framework of the model, as these are directly influenced by the inspection equipment. In this decision matrix (Table 6), the different inspection equipment represents the action alternatives, while the two results "defect detected" and "defect not detected" represent the environmental states. The environmental states occur with the probability of detection ($w_{e,I,h}$) that is dependent on the measuring equipment.

| state $s_j$ / alter-native $a_i$ | Defect Detected | Defect not Detected |
|---|---|---|
| | $p = w_{e,I}$ | $p = 1 - w_{e,I}$ |
| $PPM_1$ | 0 | $K_6$ |
| … | … | … |
| $PPM_h$ | 0 | $K_6$ |
| … | … | … |

Table 6: Result Matrix for the inspection equipment for characteristic $I$.

As the costs of the inspection equipment were already taken into account in $K_2$ and $K_3$, this result matrix only considers the costs which are incurred due to defects remaining undetected during inspection using the relevant inspection equipment.

$$K_6 := n_I \times w_{a,I,j} \times \left(1 - w_{e,I,h}\right) \times \left(K_{\Pr,G} + K_{EL} + K_{SE}\right) \quad (11)$$

*Inspection personnel and location*

Determining the inspection location and inspection personnel are closely linked to each other. Whereas the inspection location is usually defined by the inspection equipment, the inspection personnel are defined in most cases by the inspection location. These interactions are shown in Table 7.

| Inspection personnel / Inspection location | Quality assurance personnel | Manufacturing personnel |
|---|---|---|
| in-line | $K_7$ | $K_9$ |
| off-line | $K_8$ | $K_{10}$ |

Table 7: Interaction of Inspection personnel and location.

Whilst inspection which takes place at a distance from production incurs transportation costs ($K_T$), this is not the case with inspection that is close to production. The different qualification level and hence the different costs of the employees is taken into account by means of the two cost sets $K_{QS}$ (personnel costs of an employee of quality assurance) and $K_{FP,k}$ (personnel costs of an employee of the production station $k$). These case distinctions are depicted in the model by means of the following cost functions.

- Inspection in-line by quality insurance personnel:

$$K_7 := t_{P,I} \times K_{QS} \quad (12)$$

- Inspection off-line by quality insurance personnel:

$$K_8 := t_{P,I} \times K_{QS} + 2 \times K_{T,k} \quad (13)$$

- Inspection in-line by manufacturing personnel:

$$K_9 := t_{P,I} \times K_{FP,k} \quad (14)$$

- Inspection off-line by manufacturing personnel:

$$K_{10} := t_{P,I} \times K_{FP,k} + 2 \times K_{T,k} \quad (15)$$

### 3.4 Decision Rule

In order to be able to make a decision, a decision rule is necessary. A simple decision rule would be the minimisation of overall costs. However, this decision rule does not consider the strategy of the company with respect to customer perception of quality. Due to quality leadership, for example, the consequences resulting from subsequent failure perceived by the customer may, thus, lie far above the costs that can be accounted for by the replacement delivery costs and the compensatory costs. It is often difficult to account for the costs that come along with failures perceived by the customer. Nevertheless most of the time it is well-known that fulfilling the particular product characteristic is very important. For this reason, the concept of an exponential utility function is reverted to and each cost factor (inspection costs $K_P$, internal failure costs $K_F$ and external failure costs $K_{FF}$) is individually weighted. The utility function is therefore as follows:

$$U_I = u(K_{P,I}, c_P) + u(K_{F,I}, c_F) + u(K_{FF,I}, c_{FF}) \quad (16)$$

with:

- $c_P$: parameter for the inspection costs
- $c_F$: parameter for the internal failure costs
- $c_{FF}$: parameter for the external failure costs

The parameters (i. e. $c_P$, $c_F$ and $c_{FF}$) allow to allocate different weighting to the individual terms of Equation (16) depending on the risk attitude of the company.

The decisions within the framework of inspection planning (i. e. with respect to inspection extend, point in time of inspection, etc.) are made on the basis of the utility value $U_I$. In order to determine the optimal value of the independent variables (e. g. $n$, $k$, $PPM_h$) the utility value $U_I$ needs to be calculated for each possible value of the independent variables (i. e. for example for $n$: for each value [0, 1, …, $N$] the $U_I$ needs to be calculated). Finally, the value of the independent variable that leads to the highest value of $U_I$ is selected (utility maximization).

## 4 SUMMARY

Within the scope of this paper, a model for achieving cost-efficient inspection planning, that takes into account the risk attitude of the company, was presented. Whereas the monetary assessment of the different alternatives is depicted through the cost function, the risk attitude of the company is integrated in the model via the concept of the exponential utility function. By taking risk attitude into account, it is ensured that inspection planning does not include risks that are monetarily non-tangible or that are difficult to assess monetarily, such as threat of image loss through less costly errors. The Model presented is theory based, i. e. was derived on the base of theoretical foundations. The next step is to enrich the model with more details and to represent the model using software in order to enable verification and enrichment in an industrial context.

## 5 ACKNOWLEDGMENTS

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# Hamburg Model of Knowledge Management

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**Abstract**
Knowledge management within manufacturing networks allows an efficient integration of distributed business processes in order to realise a common value creation. There are enormous potentials to accelerate the common innovation development or to cut costs through the harmonisation of cross-company value chains. Although the science and industrial community is aware of this, the potentials arising from a collaborative use of knowledge in networks have not been entirely exploited yet. The Hamburg Model offers a general guideline for developing a systematic management of knowledge within value creation networks, which is supplemented by a context-dependent, dynamic qualitative model that takes the relevant impact factors of a specific case of application into account.

**Keywords:**
Knowledge Management; Distributed Manufacturing; Co-operation Networks

## 1 INTRODUCTION

The intention of many companies to achieve a stronger concentration on their core competencies results in an increasing outsourcing of business processes. The overall aim is to cut costs as well as to raise the flexibility of the organisation through streamlining. This decentralization of processes disturbs or even breaks the already existing interconnectedness between the actors. Knowledge, which has been developed within the organisation over years or decades, is distributed to autonomous partners [1]. Consequently, knowledge is often not directly accessable and experiential knowledge gets lost.

In order to cope with these circumstances and to integrate the decentralised activities in efficient business processes, a common management of the resource ‘knowledge’ within value creation systems becomes more and more important. However, in comparison to knowledge management (KM) within single enterprises, inter-organisational knowledge management poses an even greater challenge. The different institutional embedding of the actors and its resulting structural barriers as well as mistrust evolving from power asymmetries between the actors of the network are just two examples evolving in the context of KM in value creation networks.

KM can be basically understood as “the identification, generation and transfer of a strategically critical and scarce resource” [2]. ‘Knowledge’ as a phenomenon of interdisciplinary interest has been defined in many different ways often resulting in very widely drawn, blurry conceptions. “If knowledge is everything, than maybe it is nothing” stated SCHREYÖGG/GEIGER [2] meaning that a too broad definition of the term makes it impossible to capture the phenomenon and is therefore not suitable for an efficient KM. But where are the lines to be drawn?

In the context of KM the qualification and selection of knowledge plays an important role [2]. The precondition for qualifying and selecting knowledge is that it needs to appear in a codified, communicable form in order to be validated or negotiated in discourses of specific fields [2]. Consequently, we are excluding concepts such as *tacit* or *embodied knowledge* [3, 4] from the scope of our investigation, because they rather refer to “skills” or individual mental models that are not directly communicable (transferable) and are more subject to the field of cognitive science [5]. However, knowledge can still appear in different forms and the boundaries between these forms are fluent. It can be fixed in an object (i.e. documents) which is not linked to an individual (*informational knowledge*) or it can be manifested in and transferred through narrations. The latter is always linked to an individual and its personal experiences; we therefore refer to it as *experiential knowledge* [6]. The realisation of the knowledge management tasks depends on the form in which knowledge appears and its differing modes of transfer.

## 2 THE HAMBURG MODEL OF KNOWLEDGE MANAGEMENT

### 2.1 Overview

The Hamburg Model of knowledge management (HMKM) is an integrative model for the design and implementation of knowledge management systems (KMS) which focuses on the inter-organisational co-operation.

The HMKM has been developed within the framework of the project ‘Development of a Knowledge Management System for the Aeronautical Cluster in Hamburg’ (sponsored by the Federal Ministry of Education and Research (BMBF)). The regional cluster initiative *Hamburg Aviation* (HA) consists of 300 small and medium-sized enterprises (SMEs), the core companies AIRBUS and LUFTHANSA Technik, Hamburg Airport, several federations, as well as research institutes and universities. Due to the heterogeneity and the large number of actors within the cluster as well as the diverse and varying relations among them, the development of a generally applicable and scalable KMS poses a highly complex task. The development of the HMKM has been based on findings from systems theory and cybernetics [7, 8, 9].

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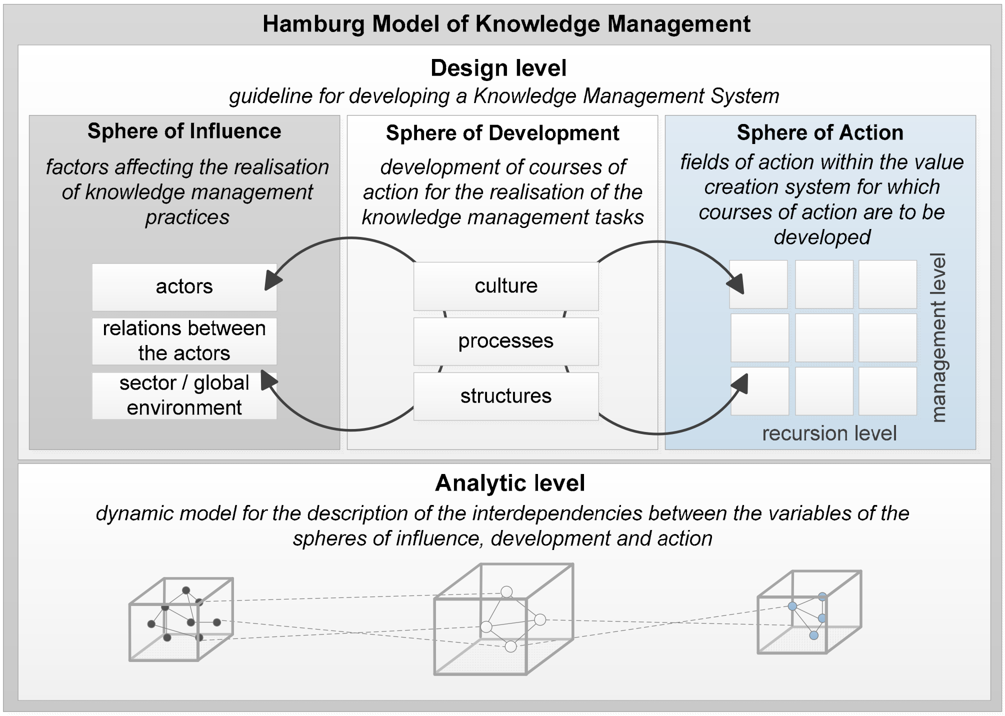


Figure 1: Levels and Spheres of the Hamburg Model of Knowledge Management.

Grasping and mastering the complexity of the various forms of co-operation within a value creation system cannot be achieved through a constructivist approach, which aims at a rather static system with specific instructions and directives [8, 9]. According to Malik, the viability of the inter-organisational co-operation within a cluster evolves rather evolutionary, because it is far too complex than it could have been entirely managed or directed by humans [9, 11].

The HMKM takes this complexity into account and offers a framework for design (design level), which relies on an understanding of the system's internal interdependencies (analytic level). The combination and constant interaction between these two levels serve as a base for the development of courses of action that enable the actors to efficiently fulfill the tasks of knowledge management (see figure 1). In the following, the design and analytic level of the model will be further described.

### 2.2 The Design Level

The design level corresponds to a general guideline for developing a KMS for specific contexts. The basis for the development is the awareness of the respectively relevant factors affecting the realisation of the KM processes within the system (*sphere of influence*). This awareness allows the design of efficient processes, structures and a 'culture' to perform the knowledge management tasks (*sphere of development*) in the specific fields of action of the value creation system (*sphere of action*).

In an initial stage of the development of the model, qualitative expert interviews with representatives of the clusters' sectors (research institutions, SMEs, original equipment manufacturer (OEM), public authority, cluster management) have been carried out. People were asked about the specific way and characteristics of the inter-organisational co-operation within the cluster and the related opportunities of support through a common KMS [12].

The subsequent process of systematic data preparation and analysis has been conducted according to the methodological principles of the Grounded Theory [13]. The aim of the application of this approach is to create a grounded theory, which is derived inductively from the examination of the phenomenon it represents [13]. "Grounded theories, because they are drawn from data, are likely to offer insights, enhance understanding, and provide a meaningful guide to action" [13]. Within an iterative process, semantically identical or resembling statements of the interviewees have been developed into categories. The further densification and abstraction of the sets of developed categories led (amongst other things) to the key demand of the interviewees: the KMS should provide a systematic support for the actors, in a way that the viability of co-operation networks can be ensured and the aim of the co-operation can be achieved together. This claim implies the demand for an integrative approach, which considers KM not isolated from more general management tasks, but rather integrates KM in the existing management processes.

The abstracted results of the qualitative-hermeneutic analysis have been aligned with already existing models for KM and models for general management. We refer mainly to the Viable System Model [14], the St. Gallen Model [9, 15] and the KM model according to PROBST [16] in order to raise the general validity and applicability of the HMKM's design level. This finally led to three domains, which are crucial to the realisation of KM: the sphere of influence, the sphere of development and the sphere of action.

The **sphere of influence** contains factors, which affect the processes of KM in value creation systems. This general set of factors can be further divided into factors, which result from the actors participating in the cooperation (e.g. structural barriers); factors, which take the relations between the actors into consideration (e.g. the dominance of an actor) and finally factors, which are derived from the industrial sector respectively the global environment the actors are embedded in (e.g. the rate of economic growth in the aviation industry) (see figure 2).

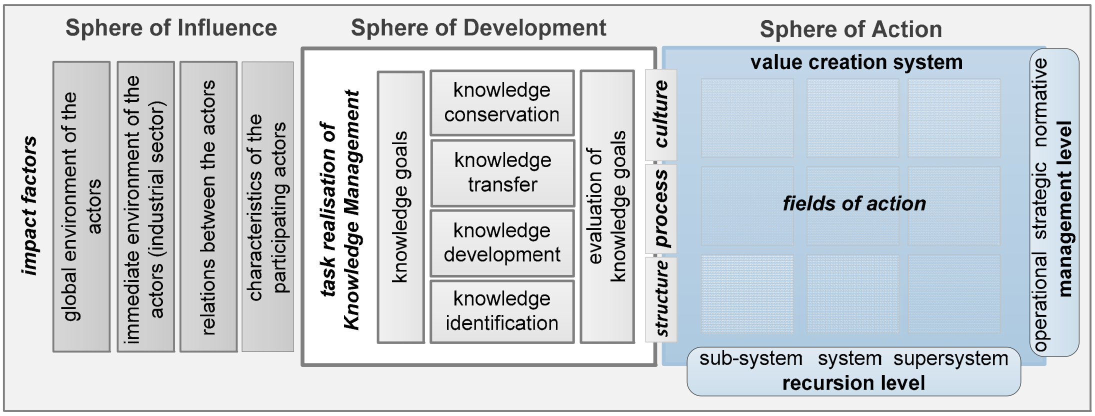


Figure 2: Design Level of the HMKM.

The **sphere of development** aims at the conception of courses of action (structures, processes, culture) for the task realisation of the KM (knowledge management goals, identification of knowledge, knowledge development, distribution and sharing of knowledge, knowledge evaluation, knowledge conservation and the evaluation of the KMS) [16].

The **sphere of action** finally describes the concrete fields of action that are to be supported by the KM and for which the courses of action of the sphere of development are to be developed specifically. The demarcation of the fields of action arises from the consideration along the levels of 'management' and 'recursion' (see figure 2). The distinction inspired by the Viable System Model [14] allows a general description for each field of action.

The *management level* divides the activities within the value creation system into the areas of normative management (a common framework for action), strategic management (external view and future planning) and operational management (harmonisation and optimisation of internal operations) [15].

The *recursion level* refers to the interleaving of the value creation system. This approach enables us to take the interfaces between the different levels of recursion into account and to avoid isolated solutions. The system to be investigated is surrounded by a supersystem and is itself further divided into several sub-systems [7]. Based on the consideration of an inter-organisational research project as a system, the cluster or the network would form the supersystem, whereas single teams of researchers in the project would be defined as sub-systems. These sort of interleaving structures follow explicitly no hierarchical order [10, 14].

### 2.3 The Analytic Level

The development of a KMS according to the design level of the Hamburg Model requires a deeper understanding of the interdependencies between the sphere of influence, the sphere of development and the sphere of action of the considered system. In order to capture the key factors affecting the fulfillment of knowledge tasks, a cybernetic perspective has been chosen. This perspective takes the high variety and existing dynamics as well as the complexity of the research object into account [9, 14, 17, 18]. The cybernetic research perspective is based on the presupposition that one can only understand a system by analysing its internal patterns or more specifically the relations between the system`s elements and their dynamic (reciprocal) interactions [10, 14].

| | impact of variable on variables ↓ → | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | ... | 51 | ... | 81 | ... |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **impact factors** | | | | | | | | | | | | | | | |
| **1** | willingness to share knowledge | **X** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ... | **65** | ... | 0 | ... |
| **2** | ability to share knowledge | 0 | **X** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ... | **35** | ... | 0 | ... |
| **3** | interpersonal trust | **35** | 0 | **X** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ... | 0 | ... | 0 | ... |
| **4** | continuity of collaboration | 0 | 0 | **15** | **X** | 0 | **20** | 0 | 0 | 0 | 0 | ... | 0 | ... | 0 | ... |
| **5** | face-to-face communication | 0 | **40** | **25** | 0 | **X** | 0 | 0 | 0 | 0 | 0 | ... | 0 | ... | 0 | ... |
| **6** | common identity | 0 | 0 | **10** | 0 | 0 | **X** | 0 | 0 | 0 | 0 | ... | 0 | ... | 0 | ... |
| **7** | power asymmetries between the actors | 0 | 0 | **-15** | 0 | 0 | 0 | **X** | 0 | 0 | **15** | ... | 0 | ... | 0 | ... |
| **8** | common innovation development | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **X** | **25** | 0 | ... | 0 | ... | 0 | ... |
| **9** | apparent added value | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **X** | 0 | ... | 0 | ... | 0 | ... |
| **10** | mutual dependence between the actors | 0 | 0 | **-10** | 0 | 0 | 0 | 0 | 0 | 0 | **X** | ... | 0 | ... | 0 | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | **knowledge tasks** | | | | | | | | | | | | | | | |
| **51** | transfer of knowledge | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ... | **X** | ... | **50** | ... |
| **...** | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | **fields of action** | | | | | | | | | | | | | | | |
| **81** | common scenario analysis (strat. mgmt) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **30** | 0 | 0 | ... | 0 | ... | **X** | ... |
| **...** | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| | **sum of impacts** | **...** | **...** | **75** | **...** | **...** | **...** | **...** | **...** | **...** | **...** | ... | **...** | ... | **...** | ... |

Figure 3: Extract of the Interdependency Matrix.

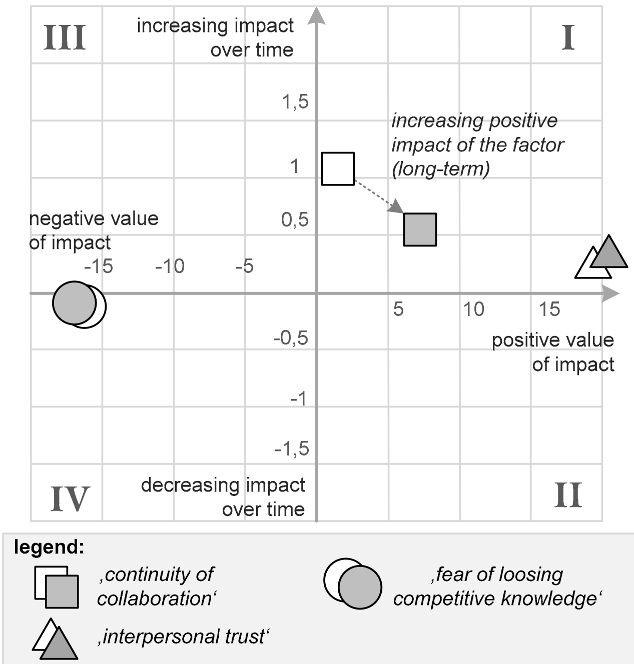


Figure 4: Insight matrix of the variable 'transfer of knowledge' for selected impacts.

On account of permanent changes through feedback loops, complex dynamical systems are hardly tangible. A cybernetic perspective makes the detection of the system patterns feasible and can furthermore be the basis for deriving regulatory mechanisms [8, 10]. In order to detect the complex interactions of the research object and to develop possible mechanisms of regulation (courses of action), the analytic level of the HMKM relies on a qualitative interaction model. This model describes – with regard to a specific case of application – the effect of the impact factors on the realisation of KM tasks within the different fields of action over time. The method of qualitative modeling, also used in the field of scenario management [19] as well as in the field of integrated management systems [9, 15], is based on a procedure developed by NEUMANN/GRIMM [20], which refers to insights of the sensitivity model developed by VESTER [21].

*Development of the Analytic Level of the HMKM*

The overall aim of qualitative modeling in this context is to recognise the direct and indirect interdependencies between the factors of the three different spheres of the design level [21]. Through the variation of the input parameter of independent factors (impact factors which are not affected by any other factor within the interaction model) the system performance can be simulated [20, 21, 22].

In a first step, impact factors on the co-operation and the realisation of the KM tasks in the cluster were identified on the basis of the results from the qualitative interview study and the concomitant heuristic analysis. These results served as a base for the determination of the direct impacts between the factors with regard to their intensity and their temporal dynamic, which were collected in an interdependency matrix (see figure 3: white = instantaneous effect; grey = medium-term inserted effect; black = long-term unfolding effect) [20, 22].

In order to determine an accurate weighting, those factors affecting an investigated variable directly were identified and weighted in percentages. If the impact factors described in the model fully cover the different impacts of the analysed factor, the sum of the impacts is 100%. If there are impacts, which have not been taken into account in the scope of the model, because they were irrelevant to the investigation, the sum of the impacts is under 100% [22]. The percentage weighting has been also based on the interview study results and the supplementary heuristic analysis.

The further refinement of the model regarding the specific weighting and the temporary impact of the factors has been accomplished in interdisciplinary workshops (with actors of different academic backgrounds) as well as separate individual sessions in order to avoid group thinking [22]. Figure 3 shows a small extract of the interdependency matrix. Column 3 shows the intensity of impacts of the factors 'continuity of collaboration' (15), 'face-to-face communication' (25), 'common identity' (10), 'power asymmetries between the actors' (-15) and 'mutual dependence between the actors' (-10) on the variable 'interpersonal trust'.

In a next step, the intensity of selected factor's effects and their change over time can be determined more precisely based on the interaction between the variables. Figure 4 shows the effect of selected factors on the 'knowledge transfer' within a short as well as a long-term observation. The factors in sector I have a positive impact on 'knowledge transfer' which is reinforcing over time, whereas the factors in sector II have a positive impact, which decreases over time. Sector IV shows factors that have a negative impact that is prospectively reinforcing and the factors of sector III have a negative impact, which decreases in the future.

This example illustrates that 'interpersonal trust' has a strong positive impact on the 'transfer of knowledge' and the value of this impact is almost constant over time. The impact of the factor 'continuity of collaboration' has got a weaker positive impact than 'interpersonal trust', because the effect on the 'transfer of knowledge' is only indirect, however the impact value is increasing over time. The reason for this is a reinforcing retroactive effect of 'continuity of collaboration' (positive feedback loop), which evolves from interdependencies between the factors. Figure 5 shows an example for the reinforcing loop between 'continuity of collaboration' and 'transfer of knowledge'.

The qualitative model (analytic level) thus allows the identification of direct and indirect impacts as well as reinforcing and compensating feedback loops on the realisation of the KM tasks and their implementation in concrete fields of action. The current development and validation of the HMKM takes place in the context of a regional, aeronautical cluster.

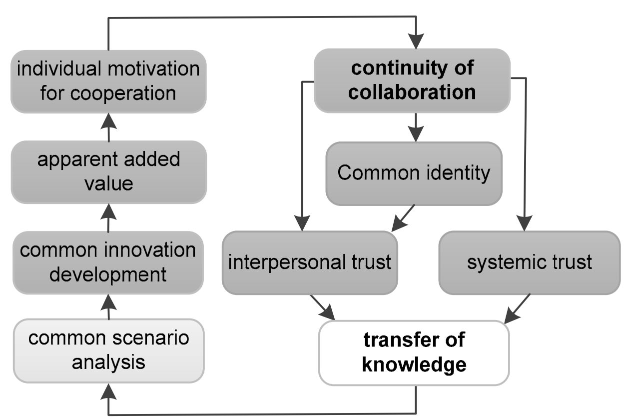


Figure 5: Positive feedback loop of the variable 'continuity of collaboration' within the qualitative interaction model.

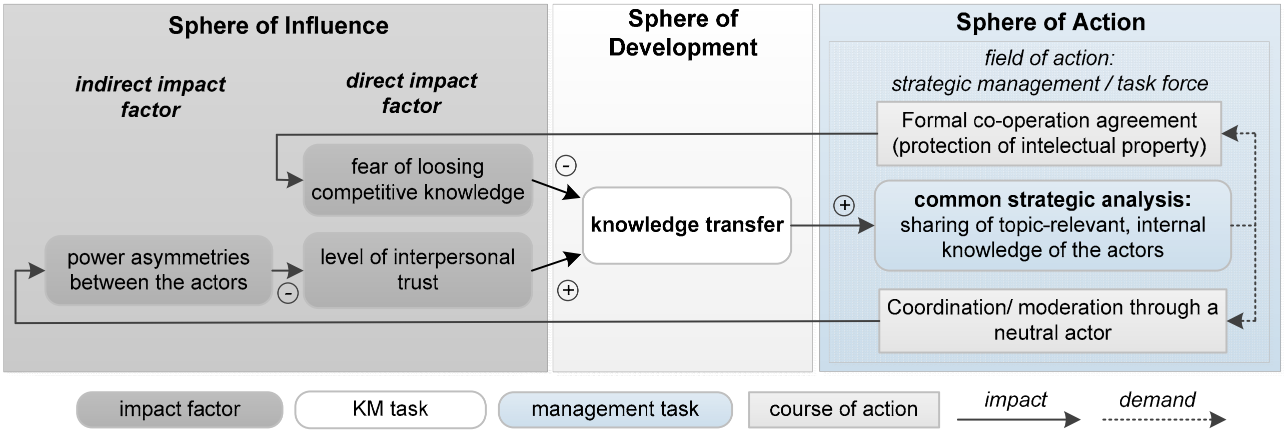


Figure 6: Deriving procedure for the development of courses of action.

A large number of the identified interdependencies between the variables of the three spheres will be also valid in other contexts of application. However, each case of application needs an initial phase of exploration in order to link and weight the relevant factors and to adapt them to the qualitative model of the analytic level. Whereas the design level serves as a context-independent general guideline, the analytical level of the HMKM is considered to be a dynamic, qualitative basis, which can be adapted to different cases of application or to changes that may occur on account of new findings during the research process.

### 2.4 Case Example: Inter-organisational Innovation Development in the Cluster *Hamburg Aviation*

The consolidation and expansion of the competitive position of an enterprise requires a constant development of innovative and customer-oriented products [23]. The base for an efficient innovation management is a holistic view of the product development process. Due to the increasing decentralisation of value creation processes and the distribution of activities on a high amount of autonomous actors [24], there is first of all a need for establishing an integrated common innovation process. The success of this process depends directly on the prudent management of the common resource ‘knowledge’. The actors of the cluster *Hamburg Aviation* (enterprises, universities, federations) are facing that exact challenge.

In the following section, we are explaining step by step how we applied the HMKM in order to establish and support the development of a common, integrated innovation process.

The application of the HMKM starts with the definition of the fields of action (*sphere of action*) for a respective context (see figure 2). In order to define the relevant and context-specific fields of action, one must take the *level of recursion* and *general management* into account (see figure 2 “sphere of action”). Nine different fields of action arise from this distinction within the sphere of action.

In the given case, we focus on inter-organisational task forces which develop ideas for innovations in a specific thematic framework (e.g. manufacturing in the aviation industry). The inter-organisational task force forms a system on the *recursion level*, which is interleaving with the surrounding supersystem (i.e. the cluster) and several sub-systems (i.e. single teams in the task force). The second dimension of the sphere of action is specified by the *management level* (i.e. operational, strategic, normative). In the course of further application of the HMKM one must now identify the knowledge-intensive business processes for each field of action.

If we consider for instance the following field of action:

- *recursion level:* inter-organisational task force (system)
- *management level:* strategic

‘The execution of a scenario analysis in order to develop a common project portfolio’ represents one knowledge-intensive process in this strategic field of action. It implies the sharing of topic-relevant internal knowledge between the group members and is therefore based on an efficient transfer of knowledge. The analytical level of the HMKM allows the further determination of impact factors that affect the realisation (positive – negative; increasing – decreasing) of the knowledge-intensive processes of the sphere of action. The awareness of the impact of the factors serves as a base for deriving appropriate courses of action to support the processes of the task force.

Figure 6 shows an example of the deriving procedure. ‘Executing a common strategic analysis’ is strongly influenced by an efficient transfer of knowledge. There are several factors that affect these tasks significantly. Power asymmetries between the actors have for instance a direct negative impact on the interpersonal trust among them, which is directly affecting the knowledge transfer (willingness to share) in a positive way. In order to reduce the negative impact of the power asymmetries we suggest for instance to assign a neutral actor for the coordination of the task force.

Through this procedure, we are able to develop context-specific courses of action in terms of processes, structures and culture for each of the nine fields of action. The common qualitative model takes the interdependencies between the three spheres into account (see figure 1 *analytic level*), so we can avoid conflicts between processes of KM in the different fields of action while developing a KM concept for a specific case.

The development and evaluation of a scalable KMS for *Hamburg Aviation* is still ongoing. On the recursion level of the task force, the group “Aerospace Production” has been institutionalised at the Center of Applied Aeronautical Research (ZAL) as a neutral organisation. They are addressing problems and future challenges for manufacturing in the aviation industry. The group consists of heterogeneous representatives of the aviation industry as well as from related scientific research fields. The goal of the support through KM is to align the academic research stronger on the demands of the local and regional industry and to identify and use synergies between the research activities of the local universities and research institutions. Table 1 shows just a little extract of the results of our current work in this task force.

| Initial situation (impacts) | Courses of action |
|---|---|
| task force level | |
| heterogeneous goals / expectations of the actors | *common strategy development and goal-setting* |
| lacking common identity | *development of common guiding principles and name* |
| fear of loosing competitive resources | *formal co-operation agreements (NDAs, etc)* |
| unilateral domination of the cluster internal cooperation through the OEM | *neutral moderation of the collaboration within the task forces* |
| structural communication barriers (cultural, functional, hierarchical) | *e.g. direct interconnectedness of the operational level across organisational boundaries* |
| uncertainty about interfaces and redundancies between the research activities of the actors | *development of an inter-organisational competence matrix / project portfolio mgmt* |
| insufficient conservation of developed working results | *routines of knowledge work (standardised documentation, common IT platform)* |

Table 1: Extract of impact factors of the case example and respective courses of action.

## 3 SUMMARY AND OUTLOOK

The Hamburg Model of Knowledge Management is based on a design and an analytic level. The design level serves as a context-independent general guideline for the development of courses of action (structures, processes, culture) that enable autonomous actors to efficiently realise the KM tasks within inter-organisational value creation systems. The analytic level of the HMKM corresponds to a context-dependent, dynamic qualitative model that can be expanded and adapted to different cases of application. It is considered to be the base for the development of the specific courses of action, because it illustrates the interdependencies between the different spheres of the design level.

The current implementation and evaluation of the model takes place in the context of inter-organisational innovation development in the aeronautical cluster *Hamburg Aviation* and has shown first positive results. The task now is to explore other contexts of application such as the coordination and harmonisation of value chains or the realisation of an inter-organisational quality management. Further empirical research needs to be carried out in order to test and validate the model in different contexts and to proof and refine the efficiency and applicability of the design level as well as the validity of the analytic level so that it can be adapted to different cases. However, we are just starting to take advantage of the enormous potential lying in inter-organisational knowledge management.

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# Change Management through Learning Factories

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**Abstract**
In today's ever faster changing economy it is crucial to adapt the production of a company in shorter intervals. Many change processes fail, often due to the resistance of the workforce. Approaches on the field of change management address this issue, but do often not consider the special circumstances in production. Learning factories are designed to meet these requirements, but usually focus on the aspect of qualification. This paper describes how change processes in production can be supported by learning factories by offering a test bed for new ideas, qualification and communication through participation.

**Keywords:**
Change Management; Learning Factories; Participation

## 1 INTRODUCTION

Change has become the only constant in the life of many organisations. In the past, changes tended to be incremental and continuous (first-order change), but today transformational, revolutionary changes that alter the organisation at its core and its values (second-order change) have become more frequent [1]. The triggers for change processes are innumerable: economic difficulties arise, the demands of the market are above or below the capacity, or new managers identify potential for optimisation. Often the competencies for the change needed are not available within the organisation, so external consultants come in and analyse the weaknesses and potentials to devise how the company should be transformed. Plans are made and approved, but when it comes to implement them, problems arise [2]. Schreyögg describes the paradigm behind this management style which perceives change management primarily as a question of planning and goal-setting [2].

This approach has led and still leads to many unsuccessful attempts of change. Studies have investigated the percentage of change projects that fail. A study by the Standish Group in the US found that 31% of change processes were abandoned, and 53% failed to keep the budget or the timeframe or did not fulfil their function [3]. An IBM study found that 16% were abandoned and 46% labelled as a partial success [4]. It has to be taken into consideration that the delicate issue of failure is probably subject to a strong underreporting which explains why an expert like Moldaschl estimates a much higher failure rate of 70% [5].

Why do change processes fail to deliver the anticipated results? One of the reasons mostly mentioned for the failure of change processes is resistance of the employees (see Figure 1).

This issue is also investigated at length in change management research. Doppler describes resistance to change as inevitable. He even states that the lack of resistance is a more dangerous sign than its appearance: if there is no resistance, no one believes in the realisation of change [7]. Most authors agree that dealing with resistance in the right way is a critical factor for successful change [7, 8, 9, 10].

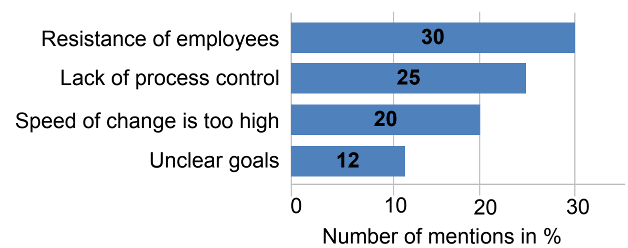


Figure 1: Reasons for failed change [6].

## 2 APPROACHES IN CHANGE MANAGEMENT

### 2.1 Dealing with Resistance: Top-Down vs. Bottom-Up

How is resistance dealt with? These strategies can be distinguished by the level of involvement of the staff [9, 10, 11, 12].

In the classic top-down approach there is little involvement – managers try to break resistance by power and coercion [7]. This is a relatively quick method because it requires no time consuming analysis of the reasons of resistance to avoid or minimize it, which can be important in some situations. On the other hand, it can lead to very adverse effects in the long run. The workforce will most likely comply with the change just until the attention of the management shifts to other issues [11], after that the changes will erode and there will probably come a slow return to the way things were before the change [13].

A paradigm opposed to this approach was created by the psychologist Kurt Lewin in his field theory [13]. He is often credited as the first one to address the issue of resistance to change and as the creator of the basic phase model underlying most change processes [2, 14]. His model starts with "unfreezing" to break up accustomed patterns of behaviour and to make "moving" to a new state possible that is then "refrozen" to stabilise the level reached [13].

There are four "golden rules" for successful organisational change that characterise Lewins paradigm [2]:

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- Active participation and early information facilitate identification with change
- Groups should be used as a means of change
- Cooperation with the parties involved rises their interest in the change process
- Change processes need an "unfreezing" to create willingness for change and "refreezing" to stabilise the gains against old routines [2].

Based on Lewins paradigm, many bottom-up strategies were developed, that try to involve as many people as possible into the change process from the very beginning to avoid or minimize resistance. Including the employees into the change process takes time and other resources and often leads to an incremental change. On the other hand, the changes made are often much more sustainable because the employees are more likely to develop commitment [8].

Assuming that both basic strategies have a right to exist, the question arises which criteria should be taken into account when choosing a strategy.

### 2.2 Choosing a Strategy for Dealing with Resistance

Kotter and Schlesinger identify four key situational variables that determine how to position oneself on a continuum that ranges from little to lots of involvement of others (see Figure 2) [10].

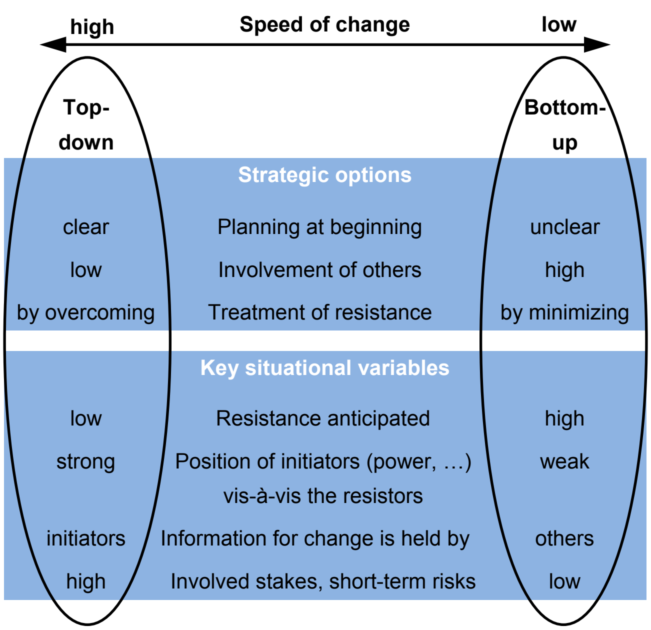


Figure 2: Strategic continuum on the basis of Kotter and Schlesinger [10].

Kotter and Schlesinger advise to move as far to the right as possible because of the negative effects of forcing people to change [10].

Hayes argues that neither of both strategies in a pure form will produce the optimal result, but a combination of both which he calls "combined drive and develop approach". While the top management sets the vision and strategic direction for change, employees throughout the organization are included in the process of operationalising both [11].

Rank and Scheinpflug suggest that the level of involvement might be different depending on the state of the change process. Mergers and acquisitions are a good example: although change is probably top-down during the acquisition of another company, it might become more bottom-up when the two companies are merged later on [8].

Almost all authors recommend involving the employees in the change process if possible to reduce resistance or to avoid it in the first place [8, 15]. To implement such a strategy, one has to analyse the sources of resistance in order to address them [10].

### 2.3 Sources of Resistance

Since the sources of resistance are uncountable, it is important to find a classification in order to derive strategies to address them. One can distinguish sources of resistance on the level of the individual or on the level of the organisation [2, 14, 16].

The stronger the culture and norms of an organisation are, the stronger the resistance towards change [2]. Schreyögg defines an organisation as a "defined pattern of social interaction which is replicated through the actions of its members" [17]. Simon states that constant activity is necessary to keep an organisation alive, and it can be understood as an autopoietic system for this reason [18]. The effort necessary to keep the status quo is in contrast to the requirement to change the system in order to adapt it to its environment [17, 18].

Reiß distinguishes two basic barriers that lead to resistance: ability and willingness [19]. These become obvious in four situations of which each one is characterised by a specific deficit (see Figure 3).

Employees will resist a change if there is not enough information about the change or if they feel that they lack the power or are not allowed to implement the change autonomously [20]. There will also be resistance if the demands exceed the qualification or if the staff feels that the change will be associated with losses. The different reasons for resistance can be distinguished but are interdependent and hold valuable information on how they can be addressed [19].

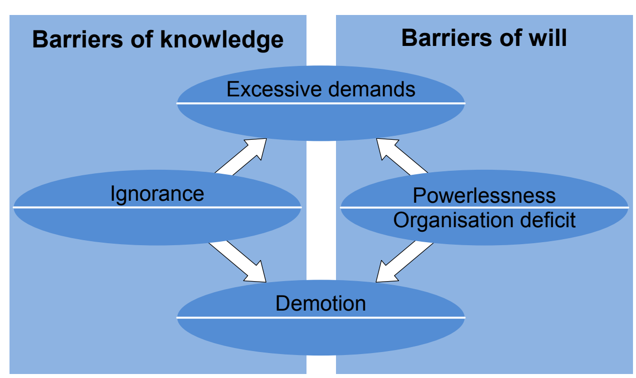


Figure 3: Sources of resistance by employees [19].

While it suggests itself that the first three situations can be improved by information, qualification and in particular, participation [21], the fourth case, in which there is a demotion, is much harder to deal with.

One cannot expect an individual to participate freely in a process if the results will be negative for the individual from a neutral point of view. However, the evaluation whether an outcome will be negative is hard to make prior to the planning and implementation of the change. Schreyögg and Koch even argue that opposition against a demotion should not be labelled as “resistance against change” because the reasons for this behaviour are obvious [17]. Since such measures can probably only be enforced by coercion, they will not be further discussed in the participative approach outlined in this paper.

Resistance to change is often regarded [8] or even defined [7] to be a mostly emotional issue – which misleads to the conclusion that resistance is almost entirely irrational. This is very critical because this kind of attitude, especially when held by the initiators of change, will tempt them to not take people seriously that are concerned with the best for the whole organisation [22]. One has to keep in mind that even a perfectly rational evaluation of a situation is highly dependent on the information available. It is simply impossible for the relatively few decision makers at the top to have all the information available within the organisation. On the other hand, the staff will often not possess all the information available to the managers [10] – which shows that both groups are dependent on each other. There is a need to find ways of exchanging information and work together which take into account the surrounding conditions.

### 2.4 Instruments of Change Management

How is it possible to involve the staff in the change process? A multitude of instruments has been developed over the years (see [14]), often called tools or methods. In systemic coaching these instruments are called interventions. They can be defined as purposeful communication between psychological or social systems that respects the autonomy of the system that is the objective of the intervention [23].

The plethora of instruments can be clustered according to the phases of the change process [14] or their main objective into the categories communication, qualification, and participation [24]. The following section gives a short impression on what kind of measures are discussed in change management.

In the field of communication, it is important to distinguish between unidirectional and bidirectional media [14]. Unidirectional media, such as newsletters, speeches or bulletins, offer little to no basis for a dialog as bidirectional media, like meetings, chat rooms etc., do. Since communication is the basis of both qualification and participation as well, the distinction from the latter two can be difficult, which is reflected in the definition of interventions cited above.

Qualification aims at building competencies to perform new tasks that will be assigned after the change process is completed, or at competencies needed during the change process. While the training requirements concerning the situation after the change are very specific for each workplace, the abilities needed during the transformation are more universal. An example is Stolzenberg’s and Heberle’s concept of a “change workshop” that combines elements of trainings and workshops to develop the change management capabilities of managers [24]. The development of competencies needed for or during a transformation has also been the focus of learning factories for industrial engineering [25, 26].

Rank and Scheinpflug distinguish three main instruments of participation: Surveys, big events (conferences) and workshops [8]. An example for the use of surveys is the survey-feedback-method, which uses surveys to collect data that is then fed back to the organisation as a basis to draw conclusions and plan actions [2]. Hayes describes “whole system interventions” which include large parts of the staff (up to 500 people or more) in conferences to develop possible visions or strategies [11] (see also [14]). Workshops are usually much smaller in scale. Bastian defines a workshop as a group-dynamic event, which follows set goals during a limited period of time outside the routine of daily work while providing information and using selected techniques to involve the participants [27].

## 3 APPROACH FOR PRODUCTION

### 3.1 Requirements of Production

The multitude of instruments of change management which address communication, qualification and participation focus mostly on “soft” issues, which appear in some way in any organisation that is object to change. In production, there is often a special set of circumstances such as:

- Heterogeneous levels of qualification ranging from unskilled workers to highly trained professionals
- High technical restrictions
- Strong identification with job profiles
- Very specific skills
- Large number of employees
- …

Some of these factors are present in other parts of companies as well, but the combination of these factors is specific for production. Since the framework is set by technical solutions, there are many “hard facts” that define the type of work to be done. This often brings forth a culture in which the importance of “soft facts” is underestimated. There is a tendency to treat people like machines that are supposed to function, not to think or act on their own. Although this tayloristic view has been in decline for a considerable time, its legacy is still often found [11].

This suggests that the optimal solution for production is a concept that combines “hard” with “soft facts”. The creation of learning factories can be seen as an attempt to implement such an approach. Learning factories have been created as realistic production environments and represent the “hard facts” of production with the goal to create “soft facts” like competencies [25, 26].

### 3.2 Potential of Learning Factories in Change Management

Several learning factories have been created in recent years [26, 28]. They can be characterised by various dimensions, for instance by the competencies they develop, the physical facilities or the didactic concept.

The concept outlined in this paper is intended for learning factories that aim at developing the trainee’s intellectual capabilities to apply methods of lean production and industrial engineering [25, 26]. Such learning factories do not focus on teaching manual skills or craftsmanship. A physical, realistic production environment is used to implement a didactic concept based on learning-by-doing [25, 26, 29].

The potential of learning factories to develop “softer” competencies, for instance in the field of change management, has been identified by Wagner, Heinen et al. [28]. Their approach focuses on the possibilities of the qualification for change management in learning factories, not on how they can be used as a part of an on-going change process or to design that process.

Improvements in production can be experienced "live" in learning factories. This shows the big potential of learning factories in terms of communication, just like pilot lines. In a changeable learning factory, the cost and risk associated with creating a pilot line is reduced to a minimum.

Learning factories offer learning-by-doing, the trainees are expected to participate as much as possible. It is the goal to reduce the guidance by the trainer step by step during the training [25]. Participative planning is an integral principle in most learning factories.

To enhance this strong initial position for learning factories to be used in the change management process, there is another issue that has to be taken into account.

A frequent concern of managers interested in using simulation games or learning factories to qualify their employees is the question if the offered initial state and framework represents the individual situation of their company. Learning factories are usually designed in a way to cater for the needs of a target group and illustrate a common set of challenges.

Since this original setup is improved during the training, there is the danger that this "didactic illustration" [28] is optimised for the application of the method that is supposed to be transferred. Reiß advocates the concept of "balanced resilience learning" to reduce the likelihood of raising unrealistically high expectations and blank out risks, which make failure more likely. This is achieved by exchanging best practice and worst case scenarios for realistic models that adequately illustrate barriers and potentials [30]. This concept of "balanced resilience learning" can be realised by depicting the actual situation of a real individual production in a learning factory. This step creates the basis of a new way to use learning factories for change management.

### 3.3 Concept for Using Learning Factories as a Tool for Change Management

To tap the full potential of learning factories to facilitate the change process, it is necessary to go beyond qualification as the originally intended use of learning factories. The basic idea is to use learning factories as an environment in which a participative planning process is possible, new ideas can be developed, tested and communicated. The result should be motivated participants, solutions that can be demonstrated, and a blueprint of how the production should work in the future and how to get there.

This requires a thorough analysis of the state as-is, which is necessary in almost all change projects anyway. The idea is to transform the results of the analysis into an abstract problem in a learning factory (see Step 1 in Figure 4).

Since existing learning factories have different equipment and levels of changeability, it is necessary in practice to check if a certain situation of a factory can be displayed in the learning factory at hand. This includes restrictions like the product mix, degree of automation, cycle times of machines and so on. These aspects go hand in hand with the question of how high the level of abstraction should or can be, which depends on the level on which most problems arise. The higher the level, the higher the abstraction that is necessary.

The next step is the qualification of the employees in the learning factory: for this step, there are well-proven approaches at hand [26, 30]. This qualification can combine "soft" with "hard" topics. Both the "hard" topics like methods of lean production and industrial engineering and the "soft" topics, such as change management or methods for involving everybody in the process, can be applied to the situation at hand right away. This step will also automatically facilitate teambuilding, which is especially important if the members of the team come from different departments. Since the trainees do not work on a hypothetical scenario, but on one that includes the challenges that await them, they can design an abstract solution to the individual situation in their company (see Step 2 in Figure 4). Once this abstract solution has been developed, it is implemented and tested in a production run in the learning factory. Some of the difficulties of implementation can be recognised and learned from and further adjustments can be made to the abstract solution.

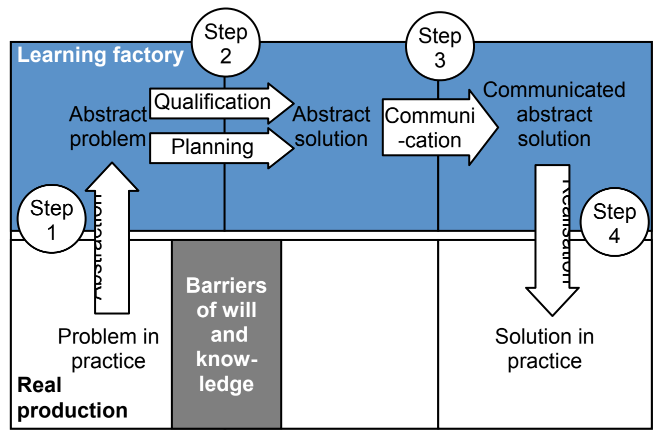


Figure 4: Planning, qualification and communication through learning factories.

This new state depicted in the learning factory can now be used as a kind of pilot production line to communicate the changes to other employees that were not part of the initial group (see Step 3 in Figure 4). The learning factory resembles a pilot project in several ways: it allows experiments and revisions, demonstrates that change is possible, and provides a physical manifestation of change [15]. The following model to foster communication is imaginable: employees that were not involved so far can work in the initial and new state and experience the improvements first hand. On this basis, it is possible to discuss if and how the real production can be improved. There could be additional restrictions in place that have been overlooked and need to be taken into account. This approach might be suitable, for instance, for those responsible for the implementation on the shop floor. The end of this step will merge into the last one.

The abstract solution has to be developed into a realised solution in the real production (see Step 4 in Figure 4). This step is supported by the communication that took place in Step 3 and by the "soft" and "hard" methods trained in the learning factory.

## 4 SUMMARY AND PROSPECT

Avoiding and dealing with resistance of employees is a central issue for change management. Many generic strategies and instruments have been developed over the years. The existing potential of learning factories as a platform for qualification, participation and communication during the change process is not tapped today, although the basic paradigms behind both change management and learning factories are similar.

The approach depicted in this paper will be further elaborated in an upcoming dissertation. Especially the abstraction of the condition of an actual production into a depiction in a learning factory is a crucial step. The translation of the optimised state of the learning factory into a redesign of the production is another challenging aspect.

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# Pricing Policies of Excess Capacity in Make to Order Production Systems

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**Abstract**

The research concerns a make to order manufacturing environment and two classes of customers who submit orders. The core customers have a contract with the firm at fixed services level (price and due date). The short-term customers submit the orders based on the price set by the firm. In this paper, it is proposed a pricing policy based on fuzzy logic to set the price for the short-term customers. The fuzzy approach captures the state of the manufacturing systems in terms of congestion in order to set the price. The policy proposed is compared to a fixed price, and to a state-dependent policy based on three levels of price. A discrete event simulation environment is used to test the proposed approach in a static, dynamic environment and considering the reliability of the manufacturing system. The simulation results show how the proposed approach outperforms the other policies in all conditions tested.

**Keywords:**

excess capacity; make to order; fuzzy logic; discrete event simulation

## 1 INTRODUCTION AND MOTIVATIONS

The development of Information and Communication Technology (ICT) leads to numerous opportunities in the fields of marketing and supply chain management. The integration of marketing area and supply chain management can increase the knowledge of the individual customers' behavior and adjust dynamically the price.

In several industry sectors (metal parts production for power generation industry, steel industry, electricity industry, etc.) [1,2], the customers can be divided into two classes: core customers and short-term customers. The core customers place orders with a fixed negotiated price and a determined service level (as the due date). The core customers have a long-term contract with the enterprise to determine the specific characteristics of the orders. The short-term customers place order depending on the price and service level proposed by the firm. In this case, the short-term customers don't have any contract with the enterprise.

The firms in order to satisfy the core customers' orders and adsorb disruption of the production system, uncertain and demand fluctuations are characterized by a variable level of excess capacity. The strategy to take the as many possible short-term orders to allocate all the excess capacity can reduce the service level both for core and short-term customers. The pricing strategy can be used to increase the short-term orders when the capacity utilization is low and reduce them when the capacity utilization is high. The objective is to maximize the revenue driving from the fixed capacity of the firm.

The development of a dynamic pricing policy concerns the following problems: the relationship between the pricing strategy and the manufacturing system state; how the manufacturing state is evaluated; how the core and short-term orders are loaded in the manufacturing system. The context of excess capacity concerns the problem of how the firm can use the unutilized capacity to improve the revenue. In the time horizon considered the capacity and the contract with the core customers are fixed constraints.

The scientific literature investigated the pricing policies for excess capacity in two main contexts: Inventory and pricing decision [3,4] and the pricing policies for the manufacturing systems. In the last context, the research is focused on the policies based on the Markovian queue models [2].

Yano and Gilbert [5] provided a comprehensive review of analytical models on this topic, focusing on models in which external demand is price-sensitive. They reviewed models in both continuous and discrete-time frameworks, considering both constant and time-varying demand functions, with and without demand uncertainty.

Plambeck [6] considered two classes of customers: delay sensitive and de-lay insensitive. He proposed a heuristic to set a static price for each class considering the lead times.

Savin et al. [7] considered the allocation of capacity in a system in which rental equipment is accessed by two classes of customers. They formulated the problem as a continuous-time analogue of the one-shot allocation problems found in the more traditional literature on revenue management, and we analyze a queue control model that approximates its dynamics. Moreover, they proposed a heuristic based on fluid approximation.

Anderson et al. [8] developed an approach for selling contracts to network users. In particular, the contracts enable buyers to use a certain proportion of a network link over a given time period, with payments at the end of the period based on actual usage.

Katta and Sethuraman [9] considered the problem of pricing and scheduling the customers arriving at a service facility, with the objective of maximizing the profits of the facility, when the value of service and time-sensitivity of a customer are his private information. The problem is modeled by the Markovian queue theory.

Sinha et al. [10] considered a queuing model wherein the resource is shared by two different classes of customers, primary (existing) and secondary (new), under a service level based pricing contract.

Teimoury et al. [11] investigated a service/make-to-order firm with heterogeneous price and delivery time-sensitive customers as an M/M/1 queuing system. The objective of this profit-maximizing firm is to determine optimal price, delivery time, and capacity for different market segments.

Jang [12] considered a setting of two firms and one capacity agent. Each firm serves a primary market, and the capacity agent sustains

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a common market to draw demand for capacity from the external firms. He developed a mathematical model of the environment and find the market equilibrium to optimize the profit of the firms.

Ulrich et al. [13] proposed a model to allocate scarce resources to products for different customer segments combining methods from both revenue management and customer relationship. The model was applied in a semiconductor industry serves.

Zhang et al. [14] studied the setting in which a one-of-a-kind production firm offers two types of orders (due-date guaranteed and due-date unguaranteed) at different prices to the sequentially arriving customers. They proposed a dynamic pricing approach based on the dynamic Bellman problem.

The main limitations of the scientific literature regard the following issues: the most part of the papers investigates the pricing related to inventory; the recent models proposed are based on queue theory that are not able to capture the fluctuations and unforeseen events (as the failures of the production system); the function of the demand behavior of the short-term is simplified in order to obtain a numerical solution.

The research proposed in this paper concerns a fuzzy based methodology to capture the manufacturing state and set the price for the short-term orders. This approach can be adapted to several contexts and can capture the fluctuations of the customer demand. The proposed approach is tested considering dynamic customer demands and the reliability of the manufacturing system. Moreover, the demand of the short-term customer is modeled as a function of the past orders' satisfaction level in order to consider a more realistic scenario. The proposed approach is tested by a discrete simulation environment that allows to include the dynamic conditions and the reliability of the manufacturing system.

The paper is organized as it follows. Section 2 presents the reference context and the proposed approach based on fuzzy logic. The simulation environment developed by the discrete event simulator is described in Section 3. The discussion of the numerical results is provided in Section 4, while the conclusions and future development paths are discussed in Section 5.

## 2 THE PROPOSED MODEL

The problem addressed concerns a firm that operates in a Make To Order and serves two classes of customers. The core customers have a long-term agreement with the firm with a pre-established price and due date as expected service level. The short-term customers have immediate needs and submit orders to the firm that proposes price and due date acceptable.

The customers input orders following statistical distributions. The core customers input the orders following a distribution that is independent of the time because these orders are related to long-term contracts. The distribution of the short-term customers depends on the price proposed by the firm, and the service level obtained by the past orders. Therefore, if the firm tries to attract the short-term customers with low price, but the service level is poor, then the demand of short-term orders decrease drastically in the next periods.

The firm manages the orders in queue processing first the core orders. The firm sets the price of the short-term orders in order to maximize the profit and the increase the utilization of the manufacturing system.

The policies tested in this research are the following:

1. The firm sets a fixed price that is independent of the manufacturing system utilization. This approach is used as a benchmark to test the proposed methodology (Benchmark Model).

2. The firm sets the price considering the manufacturing system state; the price depends on the range in which the manufacturing state is attributable. This approach is used to evaluate the value added by the fuzzy engine. (*Thre* Model).

3. It is developed a fuzzy approach that considers the manufacturing system state. The manufacturing congestion is the input and the price to set is the output (Fuzzy Model).

The state of the firm is evaluated considering the congestion of the manufacturing system. In particular, it is computed the workload of the orders that wait to be processed by the manufacturing system:

$$cong = \sum_{i \in queue} ProcessTime_i + residualtime \quad (1)$$

where,

*cong* is the congestion level of the manufacturing system computed as the workload of the orders in queue and the residual time of the order in progress (*residualtime*);

$ProcessTime_i$ is the processing time of the customer order *i-th* in queue.

*queue* is the queue of the customer orders that wait to be processed both core and short-term.

*residualtime* is the time to complete the order in progress in the manufacturing system.

The *cong* index is general because can consider core and short-term orders characterized by different typology of products and therefore, different processing times.

In order to set the price for the short-term customers the firm computes the following expression:

$$avail = Max(duedate - cong - ProcessTime_o; 0) \quad (2)$$

where,

$ProcessTime_o$ is the processing time of the order requested by the short-term customer.

The value of *avail* evaluates the difference between the due date (*duedate*) requested by short-term customer and the available time to complete the order. This evaluates if the service level requested by the short-term customer can be satisfied. Then, it is computed the following index:

$$index = Max\left(\frac{avail}{ProcessTime_o}; index_{max}\right) \quad (3)$$

The *index* value relates the availability of the manufacturing system to the processing time of the short-term order requested. The index value is cut to a maximum value possible in order to define a finite range of this index, because this value is the input of the models: *Thre* Model and Fuzzy Model. The *Thre* Model uses the value of the index to identify the interval correlated to a price value. The *Thre* Model considers three intervals as shown in table 1.

| | Interval 1 | Interval 2 | Interval 3 |
|---|---|---|---|
| **Threshold** | $[S_1 – S_2)$ | $[S_2 – S_3)$ | $[S_3$-$S_4]$ |
| **Price** | $P_1$ | $P_2$ | $P_3$ |

Table 1: Model 2 Intervals.

The firm sets the price considering in which interval the index value belongs. The main benefit is the limited computational complexity, while the main drawback is the identification of the range for each interval. The range of each class needs to be revised when the manufacturing system changes or the market conditions are modified.

The submission of the short-term orders depends on the price proposed by the firm, and the service level obtained by the past orders (due date in this research).

In particular, the information considered are the following:

-$P_{min}$; it is the minimum value of the price that the firm can set;

-$P_{max}$; it is the maximum value of the price that the firm can set;

-$I_{min}$; it is the minimum value of the expected inter-arrival of the short-term orders. This is the inter-arrival value when the firm sets the lower price and the satisfaction of the past orders is high.

-$I_{max}$; it is the maximum value of the expected inter-arrival of the short-term orders. This is the case when the firm sets the higher price and the satisfaction of the past orders is very low.

The exponential parameter of the inter-arrival of the short-term orders ($\lambda short$) depends on the price that the firm sets and the satisfaction level (the tardiness performance) of the past orders by the following expression:

$$\lambda short^{-1} = coeff\_ang \bullet price + coeff \qquad (4)$$

where, the *coeff_ang* is computed by the following expression:

$$coeff\_ang = \frac{I_{max} - I_{min}}{P_{max} - P_{min}} \bullet K_p \qquad (5)$$

and *coeff* is computed by the following expression:

$$coeff = I_{min} - p_{min} \bullet \frac{I_{max} - I_{min}}{P_{max} - P_{min}} \qquad (6)$$

finally, $K_p$ is computed by the following expression:

$$K_p = 1 + K \bullet \frac{delay_{av}}{ProcessTime} \qquad (7)$$

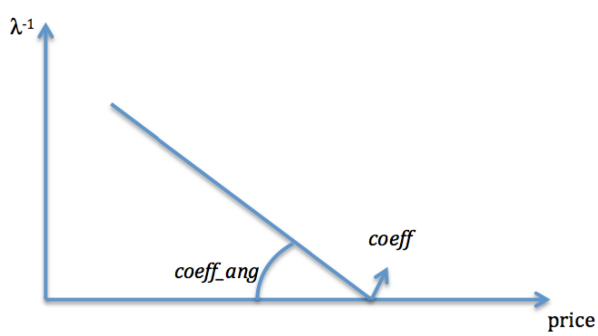


Figure 1: Inter-arrival parameter short-term orders.

Figure 1 shows the linear dependence of the expected inter-arrival time of short-term orders. The expressions (4-7) define a set of straight lines that have different angular coefficient by the parameter $K_p$. The parameter $K_p$ takes into account the service level in terms of delivery time ($delay_{av}$ is the average delay of the past orders) obtained by the past orders. The parameter *K* is the weight of the service level of the past orders (in this research, *K=1*). Therefore, if the service level of the past orders is low the angular coefficient increases. In this way, the inter-arrival parameter decrease with higher rapidity when the price increases. This means that if the firm proposes a low price, but the service level is poor the firm looses potential profit in the next periods because the short-term customers don't input orders. The value of $\lambda^{-1}$ can assume value between $I_{min}$ and $I_{max}$. The modeling of the inter-arrival time can include other service level parameters; this can be realized only modifying the function of $K_p$.

The innovative approach proposed in this research concerns the development of a fuzzy logic system to set the price. Four modules characterize a fuzzy logic system: *fuzzifier*; inference engine; rule base and *defuzzifier*.

The input of the fuzzy engine is the index value computed in expression (3).

The firs activity is the fuzzification of the input; the fuzzy value of the index value considers three membership functions: low, medium and high (see Figure 2). The triangular membership is the more suitable in this context for the following reasons: it is more adapt to the concept of "*close to..*" and the mathematical simplicity for the fuzzy operations. In this research, the value of $Index_{max}$ is set to 4 as shown in figure 2.

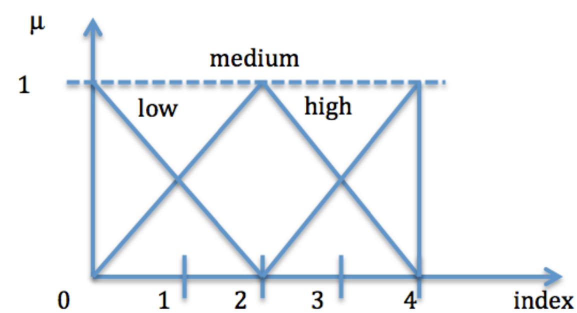


Figure 2: Index fuzzy sets.

The second module is the elaboration of the rules base. In particular, the following three rules are considered:

IF THE INDEX IS HIGH THEN THE PRICE IS LOW

IF THE INDEX IS MEDIUM THEN THE PRICE IS MEDIUM

IF THE INDEX IS LOW THEN THE PRICE IS HIGH

The above rules control the price considering the congestion level of the manufacturing system of the firm. If the short-term orders are promoted when the congestion level is low, this increases the profit without reduces the service level of the core and short-term orders.

The inference engine applies the rules provided by the rule base in order to obtain the qualified consequence of each rule depending on the degree of support. The membership function of the price (the output) is shown in Figure 2.

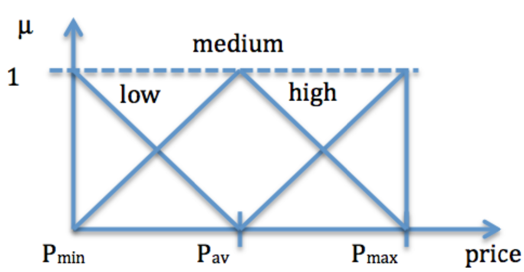


Figure 3: Price fuzzy sets.

For each rule, it is computed the related area; then, the output of the price is computed by the center of gravity methodology (defuzzification module). The fuzzy approach allows to obtain a gradual variation of the price when the manufacturing system state changes, through the evaluation of the index value. Moreover, the fuzzy logic system can easily include other inputs on the state of the manufacturing system.

## 3 SIMULATION ENVIRONMENT

The objective of the simulation experiments is to measure the performance of the proposed approach in a static and dynamic environment. The authors selected the Arena® discrete event simulation platform by Rockwell Software Inc. [15]. The fuzzy logic system is developed by the Visual Basic for Application (VBA) code.

In order to evaluate only the price policy, the process time of the orders is equal to 10 unit times for all orders requested by the customers. The inter-arrival of the core customers is considered in two conditions: static and dynamic. In static condition, the inter-arrival of the core customer is considered for two levels of the manufacturing system congestion: EXPO (15) for low level and EXPO (11) for high level of congestion.

In dynamic condition, the exponential parameter changes every 500 unit times as reported in expression (8):

$$\lambda core^{-1} = 13 \bullet UNIF[K_1; K_2] \quad (8)$$

K1 and K2 define the level of uncertain of the inter-arrival of core customers. The distribution uniform is used to model a dynamic condition where all the values occur with equal likelihood. The parameters of the simulation model are reported in table 2.

| Simulation parameters | | | |
|---|---|---|---|
| $P_{min}$ | 2 | $I_{min}$ | 20 |
| $P_{max}$ | 10 | $I_{max}$ | 100 |
| | **Low uncertain** | **High uncertain** | |
| **K1** | 0.8 | 0.6 | |
| **K2** | 1.2 | 1.4 | |

Table 2: Model parameters.

Moreover, the dynamic conditions are tested when machine breakdowns occur in the manufacturing system. In this case, the following parameters are considered for the reliability of the manufacturing system. The Mean Time Between Failure follows an exponential distribution EXPO (500), while the Mean Time To Repair is fixed to 50 unit times. These parameters are related to the processing time of the orders; therefore, the failure of the manufacturing system has an expected value of 50 products and the time to repair is related to 5 times the processing time of a part.

The core orders have the priority in the queue of the manufacturing system. For each experiment class, a number of replications able to assure a 5% confidence interval and 95% confidence level for each performance measure have been conducted. The replication length is fixed to 5000 unit times.

The performance measures investigated are the following:

- the total profit obtained by the short-term orders (*Profit st*); it is the total profit reached by the satisfaction of short-term orders. The profit of core orders is related to the long-term contract with these customers.

- total delay of the core orders (*Tdelay co*); it is the sum of unit times of delay of the core orders.

- total delay of the short-term orders (*Tdelay st*); it is the sum of unit times of delay of the short-term orders.

- average delay for part of core orders (*Adelay co*); it is the index of the service level for the core customers.

- average delay for part of short-term orders (*Adelay st*); it is the index of the service level for the short-term customers.

The following performance measures concern specifically the production system of the firm:

- throughput time of the core orders (*Thr co*);
- throughput time of the short-term orders (*Thr st*);
- number of orders that wait in queue (*Queue*);
- average utilization of the manufacturing system (*Av util*);
- throughput of the manufacturing system (*Thr*).

## 4 NUMERICAL RESULTS

The simulation results are reported as a percentage difference using the fixed price as base. Several simulations are conducted to obtain the best interval (see table 1) for the threshold (*Thre Model*) approach. The better values of the threshold model are the following: S1=0; S2=1; S3=3; S4=4.

Table 3 reports the simulation results in case of fixed exponential inter-arrival time of the core orders. There are considered two levels of congestion of the manufacturing system.

| | EXPO (15) | | EXPO (11) | |
|---|---|---|---|---|
| | **Thre %** | **Fuzzy %** | **Thre %** | **Fuzzy %** |
| **Profit st** | 1.23 | 16.25 | 6.89 | 29.87 |
| **Tdelay st** | 2.31 | 30.49 | -30.42 | -10.38 |
| **Tdelay co** | -37.89 | -37.89 | -16.67 | -83.33 |
| **Adelay st** | 4.57 | 6.02 | 0.14 | -1.46 |
| **Adelay co** | 1.59 | 3.17 | 0.00 | 0.00 |
| **Thr co** | 2.20 | 2.86 | -0.15 | 0.18 |
| **Thr st** | -14.38 | -6.90 | -22.66 | -21.19 |
| **Queue** | 9.01 | 17.12 | -17.79 | -8.14 |
| **Av util** | 4.05 | 0.00 | 0.00 | 0.00 |
| **thr** | 4.11 | 5.30 | -0.20 | 0.24 |

Table 3: Simulation results.

The simulation results show that the proposed approach outperforms the fixed price and the threshold methodologies. The fuzzy approach works better when the manufacturing congestion is higher for all performance measures considered. The increment of the short-term profit does not reduce the performance of the core orders, because the fuzzy approach sets the price capturing the state of the manufacturing systems in a better manner. In this way, the short-term orders are attracted when the manufacturing system has the better conditions to satisfy these orders. In fact, the profit of the short-term orders increase and the service level of the core orders increase.

Table 4 reports the simulation results when the inter-arrival of the core orders is affected by a degree of uncertain. Two levels of uncertain are considered in order to evaluate the effect of fluctuations of the inter-arrival core orders.

| | Low uncertain | | High uncertain | |
|---|---|---|---|---|
| | Thre% | Fuzzy% | Thre% | Fuzzy% |
| Profit st | 4.76 | 21.45 | 4.27 | 22.02 |
| Tdelay st | -20.46 | 0.67 | -28.86 | -11.54 |
| Tdelay co | -31.04 | -31.63 | -29.75 | -29.60 |
| Adelay st | 0.30 | 0.08 | -0.82 | 1.36 |
| Adelay co | 1.25 | 1.25 | 0.00 | 0.00 |
| Thr co | 0.58 | 0.88 | 0.02 | 0.71 |
| Thr st | -23.40 | -15.72 | -29.19 | -20.56 |
| Queue | -4.55 | 2.07 | -12.61 | -5.21 |
| Av util | 1.22 | 2.44 | 1.19 | 2.38 |
| thr | 1.62 | 2.43 | 1.16 | 1.85 |

Table 4: Simulation results – demand fluctuations.

The fuzzy approach allows to increase the level of profit due to the short-term orders and this level has a low fluctuation when the degree of uncertain changes. In case of high uncertain, the average delay of short-term orders increase compared to the threshold approach, but this is due to higher throughput of the fuzzy approach. The lower throughput of the threshold approach leads to obtain lower value of throughput time of the short-term orders and parts in queue for this approach. The performance of the core orders is the same between the fuzzy and threshold approach. The benefits of the fuzzy approach are confirmed in the case of demand fluctuations.

Table 5 reports the simulation results in case of machine breakdowns of the manufacturing system. The fuzzy approach has an important increment of the profit due to the short-term orders. The performance measures of the core orders are very similar between the two approaches. The better performance measures of the threshold approach for the short-term orders are due to the lower throughput of this approach. Then, the fuzzy approach reacts to the failures of the manufacturing system keeping a high level of performance.

| | Low uncertain | | High uncertain | |
|---|---|---|---|---|
| | Thre% | Fuzzy% | Thre% | Fuzzy% |
| Profit st | 6.19 | 25.09 | 4.49 | 22.60 |
| Tdelay st | -27.23 | -8.27 | -38.27 | -11.43 |
| Tdelay co | -0.73 | -1.52 | -1.81 | -0.93 |
| Adelay st | -20.41 | -22.87 | -21.90 | -21.49 |
| Adelay co | 0.00 | -6.67 | 0.00 | 0.00 |
| Thr co | -0.20 | -0.52 | -1.06 | -0.37 |
| Thr st | -23.93 | -16.60 | -22.99 | -17.29 |
| Queue | -10.76 | -5.38 | -13.80 | -8.19 |
| Av util | 0.00 | 1.25 | 0.00 | 0.00 |
| thr | 0.44 | 1.04 | 0.37 | 0.99 |

Table 5: Simulation results – failures.

From the analysis of the above numerical results the following issues can be drawn:

- the fuzzy approach allows to improve the profit gained by the short-terms order in all conditions tested (congestion levels, fluctuations of the core orders and reliability of the manufacturing system). Therefore, the proposed approach is robust to the external (demand fluctuations) and internal (failures) disturbances.

- Compared to the benchmark the fuzzy approach does not reduce the performance of the core orders in all conditions tested. Therefore, the improvement of profit due to the short-term orders has a low effect on the core orders.

- In some conditions, the performance measures of the short-term orders (throughput time, average delay and queue) are better in the case of the threshold approach. This is due to the lower throughput of this approach.

- The simulation environment developed allows to include fluctuations, reliability and other disturbances (core orders fluctuations) on the manufacturing system compared to the Markovian queue approaches proposed in literature.

## 6 CONCLUSIONS

The research presented a fuzzy approach to set the price in a Make To Order Environment to allocate excess of capacity to short-term customers. The value of the price and service level of the past orders regulates the arrival of short-term customers. The fuzzy approach is implemented in a discrete simulation environment development in ARENA package. The results of this research can be summarized as follows:

- The proposed fuzzy approach outperforms the benchmark for the performance of the profit reached by short-term orders in all conditions tested. The benefits are obtained keeping the same level of performance for the core orders.

- The fuzzy approach proposed can be easily extended to other information on the manufacturing/firm state, because the fuzzy engine proposed can include other information as the reliability information.

- The simulation environment allows to consider different conditions to test the proposed approach. In particular, it has been considered the level of congestion, the fluctuations of the core customers and the reliability of the manufacturing system.

Future research paths can be the following: the fuzzy approach can be extended including other manufacturing/firm state information: reliability, more complex manufacturing system modeling, outsourcing possibility, etc. The segmentation of the customers can consider other classes; this leads to modify the rules of the fuzzy engine and evaluate the benefits obtained; the collaboration among the firms can be considered in order to evaluate the pricing methodology in this environment.

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# Dealing with Seasonalities – An Observation of Different Branches in a Seasonal Environment

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**Abstract**
Varying demand and supply mark challenges for production planning. Particularly in seasonal environments, the major part of production concentrates in short periods of time during the year. The volume of demand and supply and the timing of the seasonal changes are hard to predict.

In the following, different braches that unterly seasonal fluctations are presented. Based on expert interviews causes for seasonalities are classified and practices for an adequate handling are explained.

**Keywords:**
Seasonalities; Changeability; Uncertainties

## 1 INTRODUCTION

Today's companies' environment is characterised by increasing turbulences [1][2]. In order to ensure future competitiveness, companies need to set up changeable processes [3][4]. The changeability of processes is of specific importance in sectors with seasonal variations. Apart from structural and economic uncertainties, companies within these sectors have to deal with changing demand or varying supply of raw material during the year [5]. This environment implies diverse effects on production and logistics systems that need to be adjusted to the repeating fluctuations in demand and supply. Variations in the product mix with deviating capacity requirements enforce shortages and delays.

Although the seasonal effects might be known to companies, their impact and timing depend on various factors that can not or just in parts be influenced by the companies. Consequences are varying and unpredictable production levels and lead times or changing stock levels. This makes production and capacity planning difficult and causes, among others, high storage costs and late delivery.

In order to improve operations planning and management in a seasonal environment, it is necessary to understand the factors influencing the seasonalities. Based on the seasonal patterns, production and processes can be designed to optimise results. One basis is concepts of changeability, e.g. flexible working hours, early increase or reduction of stocks, and outsourcing or insourcing of processes.

Reliable information on future demand and supply are the basis for setting up robust production processes. If there is a great difference between expected and actual demand and supply, it the difficulties for an adequate dealing increases [7]: if there is a reaction to every event although its impact my be compensated and thereby undid by a second upcoming event. This reaction may cause additional fluctations, that are unintentional and occasionally hard to control again. Shortages and free capacity lead to inefficient processes and delays. One goal of production planning is to balance capacity utilisation during the complete planning horizon [7]. The maximum available personnel capacities and machine infrastructure mark limiting factors.

This paper firstly provides theoretical aspects of seasonalities. In the proceding part, different sectors and their seasonal influences are presented. The seasonal influences are characterised by particular factors. After that, the impact of seasonalities on production planning is described. The paper closes with an outlook on further research activities.

## 2 SEASONALITIES

In the following discussion, the term "seasonalities" (or "seasonal variations") is used economically rather than statistically. While the statistical view regards seasonalities as regular variations, the economic interpretation also includes irregular patterns. For use in our analyses, the timing as well as the power of the seasonalities can vary. Even if the causes of the seasonalities are fixed at a specific date and predictable, the seasonal effects to the economy can vary. Reasons for this are, among others, technical developments and changes to the demand preferences [8].

Seasonal variations can affect supply and demand. Seasonalities in demand are caused by events like holidays and vacations and the time of the year. Demand for toys increases shortly before Christmas and Easter, whereas demand for clothes, sports goods and barbecue equipment changes according to the weather and holiday times [9].

Supply-side seasonalities especially occur with agricultural products such as vegetables and crop with fixed natural growing periods and limited shelf-life. However, due to technical developments like cooling and freezing systems as well as heated greenhouses, these products can increasingly be supplied independent of the natural conditions [8][10].

Seasonalities need to be distinguished from fluctuations due to general economic trends and business cycles that influence demand in the medium term (see figure 1 and [11]. Depending on the causes, seasonalities appear in different frequencies. Apart from yearly intervals, seasonal variations e.g. repeat monthly, weekly or daily. Demand for Christmas trees shows a yearly pattern [9], whereas the electricity market presents daily or weekly fluctuations [12].

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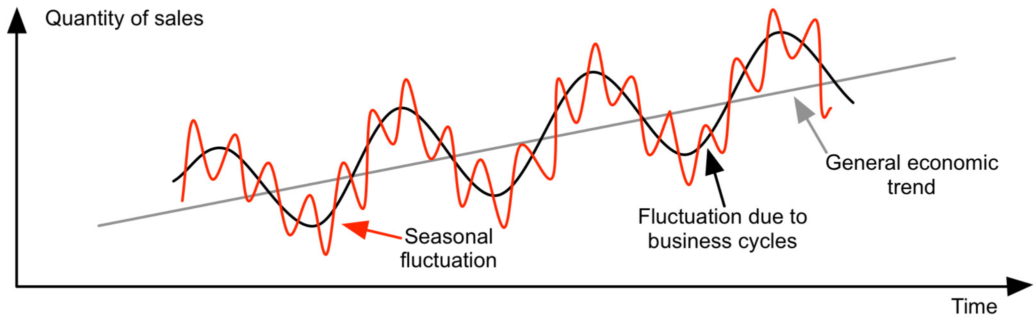


Figure 1: Comparision of seasonal fluctations, fluctuations due to business cycles and general economic trend (based on [11]).

Based on Hylleberg, seasonalities in this article include the following effects:

Seasonalities are repeating, systematic, not necessarily constant intra-year variations of supply or demand due to external influences [13].

## 3 SEASONALITIES IN THE BUSINESS ENVIRONMENT

Seasonal environments induce diverse challenges for companies in different branches. In the following chapter, the causal relationships with regards to the timing and strength of the seasonal variations are described for the industries municipal and agricultural machinery, luxury food, the printing sector and medical solutions. Starting point for the analyses are natural and institutional causes of seasonalities [8]. Based on these analyses, specific impacts of the seasonalities on companies‘ operations are presented.

### 3.1 Municipal Machinery

Demand for municipal machinery is highly seasonal as the weather determines when the machines are used. Spreaders and anti-icing machines are required in late autumn before the beginning of the freezing season. Delivery dates are concentrated in a short time period and demand strongly decreases as soon as the winter has started. This induces high production volume and required capacity as the winter approaches.

There is a great number of products offered which can be varied according to customer specifications. The great number of varieties induces specific challenges as it makes forecasting the required products and varieties extremely difficult. Modular production is usually not possible so that only a small part of production volume can be processed before the order was placed and the major parts of the specification are known. Minor parts of the specification can be changed up to several days before delivery.

Machines that are not sold by the end of the high season can either be stored for sale in the next year or be reconfigured to meet customers' requirements in markets with different seasonalities, e.g. Australia. Both of these options come along with very high costs, i.e. storage costs or reconfiguration costs.

The strength of demand depends on the expected intensity of the upcoming winter which is based on the experiences during the preceding year. As the main group of customers consists of public sector authorities such as communes and towns, demand for these machines is also determined by the public budget and subsidies. Further influences are technical progress and depreciation of existing machines. The demand for new machines as replacement investments depends on the inventory, age and usage of the existing machines.

The relationships between these factors and the seasonal variations in demand for municipal machinery are displayed in figure 2.

For a manufacturer of municipal machinery, the seasonal variations increase the need to coordinate purchasing, production and sales activities, especially with respect to capacity planning. Purchasing of raw materials and components is planned according to the expected demand specifications. In order to receive the necessary materials and components on time, it is necessary to place the orders with the suppliers ahead of time. This implies that means of production are ordered at a point in time when the true demand and thus the volume and mix of materials and components for production are not yet known.

As demand and production approach the seasonal peak, product specifications are fixed and necessary shortages of materials and components become clear. Additional orders for means of manufacturing are placed with the suppliers. At these times, the suppliers also face high demand so that delivery might be delayed. Late delivery of means of production is especially critical during the peak season as production is operating at full capacity and is thus inflexible with hardly any possibilities to adjust production workflow and planning.

At this point in time, modifications of the production plan often result in late deliveries of machines. In order to avoid that the supply with materials and components becomes the bottleneck of production, purchasing is adjusted as soon as demand specifications or production planning change.

According to the time of the year, material and component shortages are solved in different ways. During the peak season, the supplier with the shortest delivery time is preferred, even if this comes along with higher costs. This is due to the fact that during the peak season late delivery is extremely costly and customers might switch to a competitor for future orders. In the low season the costs are a more important factor when selecting a supplier although this might imply longer delivery times.

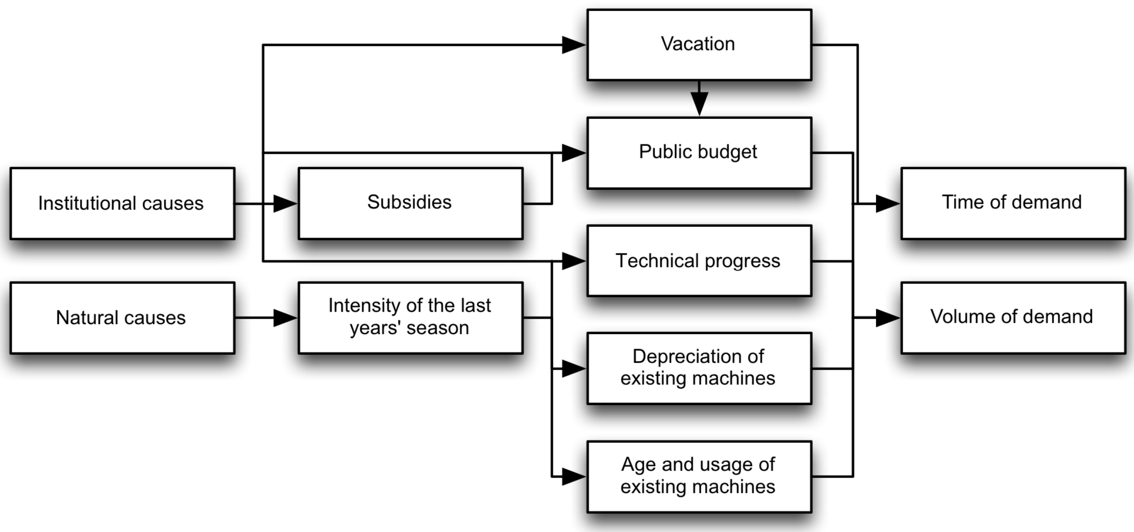


Figure 2: Relationships of seasonal factors in the municipal machinery sector.

### 3.2 Agricultural Machinery

Demand for agricultural machinery changes according to the harvesting times of agricultural products. As grain harvest approaches, the required grain harvesters need to be delivered. As soon as the harvesting time starts, demand falls rapidly.

In this industry it is extremely important to deliver the machinery before the harvesting time starts. The agricultural machines are built for harvesting specific crop that are mostly harvested during a few days of the year. Missing the optimal harvesting period is extremely costly for customers as this means reduced crop, quality and earnings.

As these machines need to fulfil specific customer requirements. Different characteristics with each various possibilities result in a high range of variants. As these components are very costly, they cannot be produced in advance. Customers' specifications are fixed as the harvesting season approaches. Manufacturers of agricultural machinery face the challenges of customer-specific production and the concentration of delivery dates in a short time period. The delivery dates are determined by the harvesting times that can be varying from year to year. The harvesting and delivery dates can be forecasted to lie within a period of a few weeks. As the harvest approaches, the delivery date can be narrowed down to a few days.

The harvesting times and therefore the seasonality depends on the weather conditions during a specific time of the year as well as the farmers' growing habits and investment decisions. Further factors are the cultivated area, the type of grains and the way of fertilisation. The way of cultivation is influenced by local regulations, subsidies and technical developments.

As an example, the Renewable Energy Law (EEG) that supports the operation of biogas plants with corn in Germany, induced an increase of demand and thus prices for corn. This resulted in an increase in the cultivation of corn and rising demand for corn harvesting machinery. In return, alternative crops are cultivated less intensively so that demands for harvesters for other crops decreased.

Figure 3 shows the described relationships.

A manufacturer of agricultural machinery faces the challenges that production of these machines comes along with long lead times and high requirements for customer-specific production. Manufacturing is designed on separate lines with preproduction of specific components. Different varieties are built in the same lines.

Depending on the machine, the necessary components and the delivery date, there is a critical date when the configuration needs to be fixed in order to realise the delivery date. While the vehicle chassis needs to be known at the beginning of the production process, parts of the cabins can be changed shortly before the delivery day. As changes of the specification are very time-consuming, they can only be carried out if production capacities allow for it. As production runs at high capacity when the seasonal peak approaches, specification changes are often not realised during this time of the year.

Planning production according to demand would imply concentrating production in a few months of the year while keeping capacities on hold during the rest of the year. This is extremely costly and would not enable efficient production. Therefore, capacities are not provided according to peak demand but to a lower degree. For increasing the utilisation of capacity in the low season, the company offers new machines at attractive terms when buying in a special period. Special discounts lead to early incoming orders. The ordered machines are produced customised in low season. This balances capacity utilisation, increases flexibility and reduces lead and delivery times during the peak season.

In order to secure sufficient personnel capacity during the peak season, a no-vacation-rule is in place during this time of the year. Contrary, during some weeks of the low season production is closed down completely. The low season is also used for personnel trainings, machine maintenance and repair.

This production design aims at balancing capacity utilisation and shortening delivery times through preproduction. As capacity smoothing and on-time delivery are key factors especially during the peak season, these advantages make up for the increasing storage costs that occur due to preproduction.

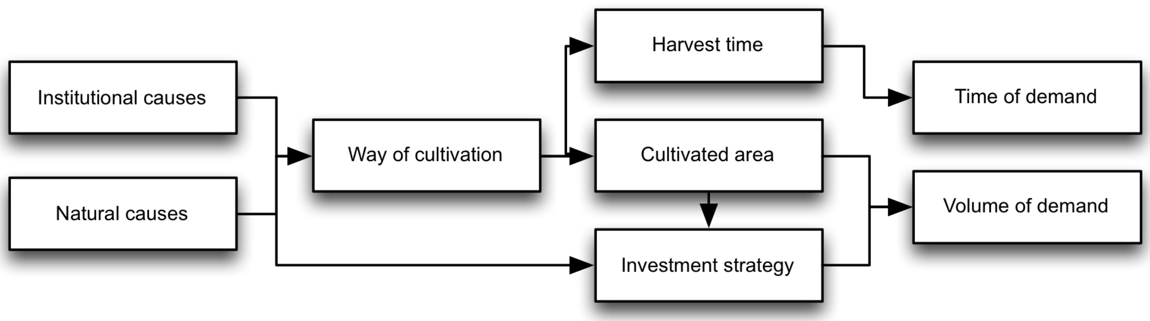


Figure 3: Relationships of seasonal factors in the agricultural machinery sector.

### 3.3 Luxury Food

Customer-specific luxury food as chocolates shows a strong demand concentration a few days before Easter, Christmas, Valentine's Day and Mother's Day. Shortly before these events, production volume rises up to ten times within a few hours. As these items are given away as gifts on these occasions, they need to be delivered before the events occur. Items that are delivered afterwads are of no value to the customers. After these events, demand falls rapidly.

Demand for these products also depends on the time of year and the weather that influence habits, transport and storage conditions. During winter, the demand for chocolates, especially dark varieties, is higher than in summer. In summer, the demand for white chocolate products is stronger than in winter. The described relationships are shown in figure 4.

Production is labour-intensive and planned according to the actual demand on short notice. Due to the customer specifications that determine the composition of the entire products, production cannot take place in advance. The number of employees and the working hours are adjusted to demand. As demand increases, flexible and temporary workers are called in and working hours are extended. Employing flexible and temporary workers is possible as some parts of the manufacturing process require only short training.

As soon as demand falls, working hours are cut back and the employees take overtime. Moreover, the low seasons are used for restructuring and maintenance.

Even though a great number of varieties is handled in the customer-specific production process, the capacities are occupied evenly independent of the required product mix. This is possible as different varieties can be produced using the same facilities and personnel. Manufacturing different varieties in the same production line does not require set up time and costs. If sufficient personnel capacity is provided, production can adapt to changing demand extremely fast and flexible as the lead times only amount to a few hours for each variety.

### 3.4 Printing Industry

The printing industry is influenced by events like book fairs, Easter, Christmas and holidays. In Germany, the most important events are the Leipzig Book Fair and the Frankfurt Book Fair that take place each year in March and October, respectively.

Book fairs imply rising demand for print work before the events start as publishers need samples of new releases for exhibition at the fairs. These products are mostly ready for print on short notice before the beginning of the fairs but still need to be delivered by the start of the events. These print works involve low quantities and wide varieties of book covers, sizes and colours. With respect to these jobs, digital printing is the preferred procedure as it does not involve set up costs when switching between styles.

Book fairs also induce high demand following the events. This is caused by the high number of end customers asking for the new releases introduced during the fairs. This demand occurs immediately after the fairs. As books and other prints are often used as presents, demand rises shortly before Christmas and Easter. Regarding this part of demand, delivery before these events is extremely important as the items cannot be used as presents afterwards.

Other factors influencing demand in the printing sector are holidays and vacations. During these times, demand decreases as publishers run on low capacity and reduce activities, especially during long summer holidays. Furthermore, end customers do not require as many books and print works when they are away on holidays.

Due to these effects, the printing sector faces strong seasonal variations during the year. The available personnel and machine infrastructure determine the maximum capacity. In order to satisfy demand during seasonal peaks, working shifts are extended and machines are operated longer hours when demand increases.

The major challenge within this sector is to utilise capacities during the low seasons. As the jobs require specific training and experience, companies employ permanent staff that marks long term capacities. Temporary workers are hardly employed. The machine capacities are also provided all year round. During low seasons, personnel capacities are reduced by taking overtime that has accumulated during the peak season. Training, maintenance and repair are scheduled in the off-season.

Another way to adapt to demand variations in the printing market is to introduce new products with anti-cyclical demand. In order to improve capacity utilisation, manufacturing of these products requires similar capabilities and equipment as the current printing jobs so that the existing capacities can be employed.

### 3.5 Medical Solution

In medical technology with a focus on implants, two different seasonal influences can be observed. Emergency cases need to be treated immediately. These cases increase in winter due to accidents at icy conditions and skiing crashes so that demand for specific implants rises during this time of the year. Similar applies for vacation times when specific sports activities are carried out and the number of injuries and fractures increases.

On the contrary, there are medical treatments, e.g. on chronic diseases, that need not take place immediately and can be planned in advance. In these cases, patients prefer not to be treated during Christmas time, summer and vacation time in general. Thus, planned surgeries are scheduled in late winter, spring and autumn. Demand for the necessary medical products concentrates in the respective times of the year.

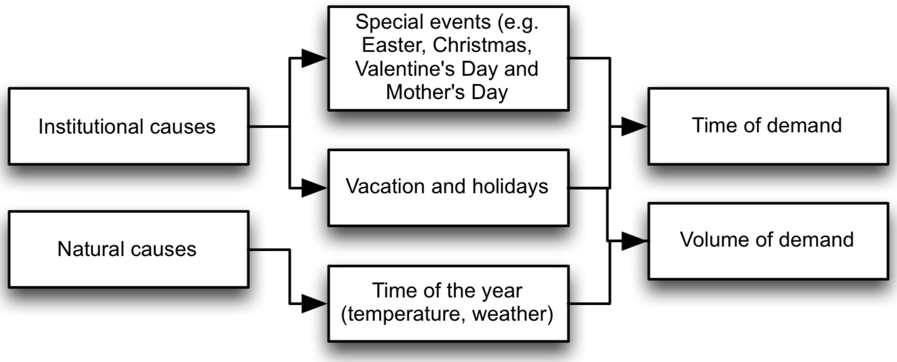


Figure 4 Relationships of seasonal factors in the luxury food sector.

A manufacturer of medical products, especially implants, needs to adapt production to the changing product mix during the year. Due to the nature of emergency surgeries, demand for implants for these cases is known on short notice. Demand for implants for planned surgeries is also placed with the manufacturer on short notice even though the purpose and date of the treatment are scheduled in advance. Therefore, production cannot be planned reliably long time in advance. Another source of delay and uncertainty of demand is that the manufacturer does not receive orders directly from the operating hospital but from an intermediary.

Production planning is further complicated by the fact that implants need to be configured to intermediaries, surgery and patient individual specifications. This leads to a great number of varieties that differ, among others, in the materials used, the sizes as well as customer-specific requirements concerning labelling and packaging. As there are strict requirements concerning steriliry of products and a hereby linked high manual effort past the point of customer individualisation, most implants are produced to order. Thus, production is hard to plan before the actual orders come in.

Legal requirements for manufacturing of medical products are another factor marking difficulties when planning production in advance. These regulations include batch purity and complete traceability of the products. In order to fulfil these requirements, manufacturing of the specific products is not planned before the orders with the configuration details come in.

The seasonal variations imply different capacity requirements during the year. One possibility to solve this is to vary shifts. Many processes take long working time but require only one set up step at the beginning of the job. Machines can be set up at the end of a shift and independently finish the installed jobs after the end of the shift.

## 4 SEASONALITIES IN PRODUCTION PLANNING

Following the observations in the seasonal sectors as described above, seasonalities can be characterised by specific factors. Critical factors are the predictability of the timing and volume of demand and supply [14]. Furthermore, capacity utilisation describes if the seasonal variations lead to capacity shortages or free capacities during different points in time. In this context the personnel and machine capacities were particularly highlighted. The on time availability of materials and components also marks a central factor. This includes cases when materials or components are produced internally or purchased externally.

Seasonalities affect production planning in different ways. Production is planned based on the necessary production steps and the available capacities. Another factor is specific time limits, e.g. earliest possible starting and latest delivery dates. In seasonal environments, there are great variations in the volume and timing of demand and supply [5]. Companies in seasonal environments face the challenge to forecast quantities and timing of supply and demand and adjust capacities to the changing conditions. In order to operate efficiently it is extremely important to utilise capacities evenly during the whole planning horizon.

As capacities are set up for at least a medium time horizon, they usually cannot be perfectly adjusted to fit varying seasonal supply and demand on short notice. If production is planned according to average demand, seasonal peaks imply running over capacity while seasonal troughs mark vacant capacities. Setting up capacities according to the seasonal peaks, vacant capacities during low seasons lead to very high costs. Efficient production in seasonal environments requires highly flexible and changeable production systems. The stronger the variations, the more complex and sophisticated are the solutions for the set up of the production processes. [15]

Based on this characterisation of seasonalities, there are different ways to react to the variations within the production process. Particularly, changeability concepts mark possibilities to ensure capacity utilisation and efficient production. There are basically two different approaches for handling seasonal variations in the business environment:ompanies can manage the variations proactively or rather react to the changes. Proactive means are promotional offers and discounts to customers to make off-season orders more attractive. This reduces the seasonality of demand. Introducing alternative products with anti-cyclical demand is another possibility to balance demand across the product portfolio and archive a more even pattern Possible reactive means are preproduction of components or the adjustment of capacities by employing temporary workers and thereby improving the seasonality of production. Additonally – if possible – a improved predictability of demand and accuracy of forecast provides a high potential. [15]

In order to identify beneficial operation schemes, the different process designs need to be simulated in the light of the seasonal influences and specific internal factors. This enables companies to optimise processes and results in the face of seasonal variations of demand or supply.

## 5 FURTHER REASEARCH ACTIVITES AND OUTLOOK

Based on the analyses of seasonalities in different sectors, a model to classify the seasonal variations is developed. This model will include all relevant factors describing seasonalities in different markets and allow for the comparison of seasonalities across different sectors.

The systematic description of seasonal variations is the basis for the evaluation of different operating patterns as reactions to the seasonalities. Patterns of changeability are of particular interest. Even though changeability and the specific patterns to react to a changing environment have already been examined, the challenges for companies in seasonal sectors have not been addressed. It is of particular interest, which changeability concepts are suitable and which means are to be preferred to increase operating performance in specific seasonal environments.

In order to adequately manage and continuously monitor performance in seasonal environments, it is furthermore necessary to adapt performance measurement to the specific conditions. This applies to performance measures and the performance measurement system as a whole. Performance measurement needs to be adjusted to the seasonal influences and to the company-specific process configuration according to the concepts of changeability

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# The Concept of Viral Engineering

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**Abstract**

The concept of viral engineering tries to tackle the coordination of independent development cells within a temporary network and so takes advantage of the dynamic market environment. The interdisciplinary connected development parties are based on their competences to support the creation of cross-functional knowledge supporting the innovation process. The connection of the participants requires a conceptual communication that is carried out within the viral description framework (VDF) enabling the product description to hold product relevant data for interdisciplinary development and agile manufacturing using semantic technologies. The VDF assimilates interdisciplinary description and knowledge for an equal understanding of the participating parties.

**Keywords:**

Engineering Management; Value Network; Innovation Management

## 1 INTRODUCTION

The backbone in our economy is situated within the small and medium enterprises (SME) and the process of creating innovation. The rapid changing economic and ecologic environment increases the difficulties to create high valued innovative products and services to withstand the change of the organisation. The agility of every single organisation is carried out by spending more and more on equipment, housing and specifically trained personnel. By this means, specialized organisations but mainly SME have to leave out ideas that might be considered promising for competitive advantage and at the end for the survival of the firm. The chances resulting of the changing environment and the increasing customer individualization can be seen in the creation and development of new ideas and valued goods. The organisation therefore can withstand the high research and development investments and the short product and production cycles by adapting rapidly to the changing environment and focussing on continuous individualization of the products designed for the customer.

Flexibility is one strategic factor of success besides quality, cost, service, product variation and time. It is defined as adaption to the change of the organisation with all its parts [1]. One way to facilitate flexibility in the product creation can be seen in rental production facilities. This allows temporarily compensation of capacities and abilities including possible cooperation between different competences and organizations for the purpose of value creation. Another way follows the concept of agile production to achieve continuous individualization and adapt rapidly to the fast changing customer needs which is seen as support of innovation [2]. Agility by this means is defined as increasing speed of reacting with certain.

As shown in section 2, supporting cross-functional competences, in the meaning of combining knowledge, competences and abilities a higher innovation potential can be achieved within the development process. In addition, a more efficient use of resources within the manufacturing can be carried out by concentrating on the competences and local available resources. To master the agility of the manufacturing process with its variety on individualized goods, the organizational requirements have to be construed. To encourage the agility in the product creation the organizational separation between product development and manufacturing is described in section 3 aiming to link competences and resources towards high innovation potential. As many agile manufacturing approaches are existent, a coordination concept of the engineering process is presented that tries to take advantage of the dynamic market environment without losing balance between stability and flexibility of the firm. This viral engineering concept, presented in section 4, tries to adapt the viral behavior to information technology supporting an agile development process. The focus hereby lies on knowledge, competences and abilities, starting from the idea to the manufacturing process. This potential seems to be important when focusing on a continuous individualization of the customer valued goods. This encourages the use of systemic methodologies towards modularity and time limitation within the context of resource efficiency.

## 2 HOW COLLABORATIVE ENGINEERING CAN SUPPORT SUSTAINABLE INNOVATION IN AN AGILE ENVIRONMENT

Especially when observing agile organizations sustainable innovation is a major success factor for long-term organizational survival. As can be seen in figure 1, the influences on innovation are highest in the beginning of the engineering process. Based on the investigations of agile organizations [3] the product-orientation will be observed in the following. The product-orientation considers innovation, product design, planning of production processes and organization of production resources as main influences on the agile organization. As a result when observing agile organizations with the focus of innovation the engineering process of products and services has to be considered.

### 2.1 Important Factors towards Innovation and Agility

The innovation is mainly influenced within the development process. The product development is characterized by bringing together different facets of ability, competence and knowledge.

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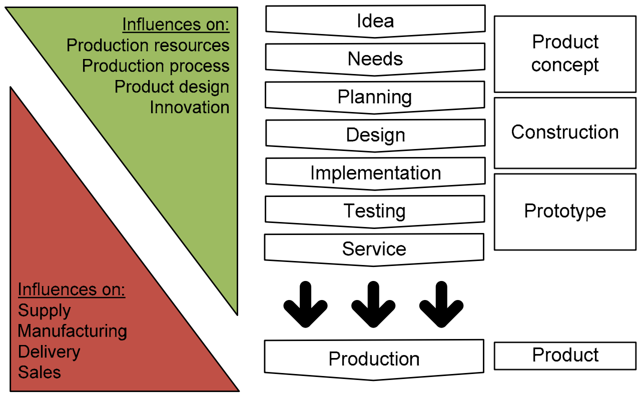


Figure 1: The influences within an engineering process on a product life cycle [3].

The main parts of knowledge can be seen in explicit and tacit knowledge. The innovation process is based on the combination and transformation of new knowledge, which according to NONAKA and TAKEUCHI usually begins with an individual [4]. Furthermore, the collective knowledge allows the core competence between system, structure and person, which all are influenced by the organizational culture [5] The individual as well as the collective knowledge can be seen as core competence of an organization [6]. Further, the innovation process depends on different factors within a geographic environment. This makes the internal mobility in this respect complicated that collaborative innovation with its goals and requirements has to be understood by every participant [7].

The agile product creation is more essential than before, in times of increasing resource efficiency. Agile systems can react fast and with marginal adaption costs [8]. A key factor is that agile systems are able to react on the individualized needs of the customer under the restrictions of using a minimal amount of resources on the change process [9]. An environment of reduced complexity promotes the speed of change [10]. One major agility factor within a rapidly changing environment, as present in job-shop productions, is the workforce [11].

### 2.2 Combination of Interdisciplinary Knowledge and Competences

Within an agile organization dynamic capabilities are understood as the firm's ability to integrate, build and reconfigure competences to deal with rapid changing environment and goals [12]. Based on the three processes competing with dynamic competences are the coordination, the learning process and the re-configuration of the organization.

The innovation is seen as a meta-functionality of core and functional competence. This aims towards the cooperation that has several advantages of bringing together knowledge, ideas and resources [13]. As the exchange of different resources within a temporary pool of organizations allows a sustainable competitive advantage cooperation can be seen as a good way to achieve new competences, abilities and knowledge throughout its combination. Furthermore, trans-disciplinary approaches promote the innovation process of the value creation [14]. The value creation is the focus of competence and value networks and a successful co-creation of development, service and products can lead to a value innovation. Due to, the investigations that cross-functional abilities and knowledge have shown that its influence on innovation is higher than specified knowledge the further investigations concentrate on interdisciplinary competences, knowledge and its combination.

### 2.3 Collaboration in the Development Process

As shown before collaboration holds the ability to create cross-functional knowledge, competence and ability which are not as easy to achieve as individual or specified knowledge. This generation of meta-functionality of core and functional and competences, knowledge and abilities is carried out for a cooperative development that has many advantages, especially when focusing on different industry sectors. In addition the sharing of knowledge, especially tacit knowledge determines the effectiveness and efficiency of a process in design, development and production [4]. Regarding collaborative development resources are used well balanced with its strength and weaknesses using the 'right' way of coordinating collaboration [15]. Typical motivating factors for collaborative product development are [16]:

- sharing of risks and reducing costs
- technology, knowledge, experience sharing
- time-to-market reduction
- product family expending and innovation
- market opportunities and competition

The collaboration throughout the connection of different disciplinary professionals improves collective learning, reduces risks and generates ideas across different professional groups and enhancing innovation performance [17]. Nowadays, the interface to cross- or multidisciplinary development shows a gap compared to single-disciplinary development. In the following, a concept is presented, which promotes the cross-functional abilities and meta-abilities based on core and functional competences to achieve a sustainable innovation [18].

## 3 COLLABORATIVE ENGINEERING IN THE CONTEXT OF VALUE CREATION

The value creation of a product typically starts with an idea, which has to be developed throughout a research and development stage. The idea is the most promising factor when it comes to the innovation process especially resulting in an advantage towards the market release. Nowadays, we often need to connect ideas with the product creation even tough collaborative engineering supports the generation of new ideas, high quality and complex product developments [3].

### 3.1 Collaboration within Networks

Due to limited resources and competences a good idea has to grow based on resource availability and allocation. The tasks are defined as information exchange, promotion of creativity, developing informal networks and coordination support [19]. Networks are suitable as a connection type between different development parties representing special knowledge, competence and ability. In general, networks are distinguished in three strategic types according to MAZZOLA et al., to be specific the efficiency, the globalization and the knowledge networks [20]. In this case all three types are used within the context of development networks (knowledge), planning network (globalization) and manufacturing network (efficiency). The separation between development, planning and manufacturing holds the advantage that an agile value chain will result that is supported by the information and communication technology (ICT).

The innovation process, value networks and all forms of collaboration require a certain amount of trust [21] based on contract, competence or goodwill. In times of rapid change and continuous market orientation the trust in information and competence allows every organization of the value chain be an elementary part [22]. Trust as a most mention critical success factor of collaborative product development [23] has to be observed within the context of the motivation of the individual participants. This success factor is hereby carried out by focusing on interdisciplinary participants and their communication. On the one hand this reduces the risk, that a single participant uses the progression for himself and his organization. On the other hand this development allows the interdisciplinary learning process and therefore shall promote the collaboration more than isolated players. The achievement of cross-functional knowledge for highest innovation is hereby in foreground.

### 3.2 Early Product-Life-Cycle Phases in Agile Value Networks

As mentioned before, the separation of development, planning and manufacturing within networks allows the networks focus on one strategy. The focusing within the networks on one strategic goal allows a lean coordination of the single networks. As an example the manufacturing networks focus on efficiency, due to the influence on innovation, design and resource allocation of the product is low. Competitive manufacturing organizations are characterized using order winning and the order qualifying criteria. The order winning criteria mainly consists of agile related priorities (i.e., high product availability, customised products, fast delivery). Meanwhile the order qualifying criteria is described by lean related priorities (i.e. cost, consistent quality, reliable and durable products) [24,25]. This criteria classification only observes the manufacturing process; meanwhile the engineering process allows certain agility for the production and the demanded goods as well.

The separation between development and manufacturing allows a complete decentralized production for the local market and uses preferably the local resources. This results in high demand volatility and a high market specification [26]. The decentralized production is exemplified with the building of agile value networks that are virulent organised. The agile value networks are built up like virtual organisations but are organized pulsatile. This allows a combination of companies based on a global network of different value network members enabling collaborative product creation [27]. The resulting virtual manufacturing organization can be evaluated using resource allocation. Also the manufacturing planning and control of a virtual factory, of individually designed products within a value network can be carried out using existing multi-agent planning and control systems [28]. Different approaches for production networks have already been investigated, e.g. the myOpenFactory process and data standard [29].

A good example is shown in the architecture and building development. The architect gives the idea and the design meanwhile the building is developed and planned by a constructional engineer the actual construction is made by construction workers, which are creative and inventive, when smoothing the mistakes of the previous out.

### 3.3 Detach the Development from the Production Using Cloud-Supported Engineering

One way to use the interdisciplinary competences of different developers and the competences and abilities of the manufacturer, which have a handful of tools for getting things done, is the organisational separation between development and production. This allows the concentration of the core-competences of each party and the achievement of new functional competences through communication, competence combination and knowledge exchange.

A good way to transfer the tacit and the explicit knowledge can be seen in networks [30]. This requires a continuous information flow over the entire value network. A good opportunity for exchanging design and control mechanism and information lies in the ICT infrastructure. The cloud as such allows a bi-directional transfer of product-relevant information and development-relevant information. To allow an information and knowledge flow over the cloud a self-description of the required developed products (i.e., material, features and design) has to be investigated. The cloud coordinates the viral value networks using defined key features of the agile factory (e.g., capacity, abilities, skills, competences) and from the description of the developed good (e.g., costs, material, quality, function, features), as shown in figure 2. The key features are compared and matched. The processing shall make use of the innovation process and the transfer of achieved knowledge and competences from the research and development to the production.

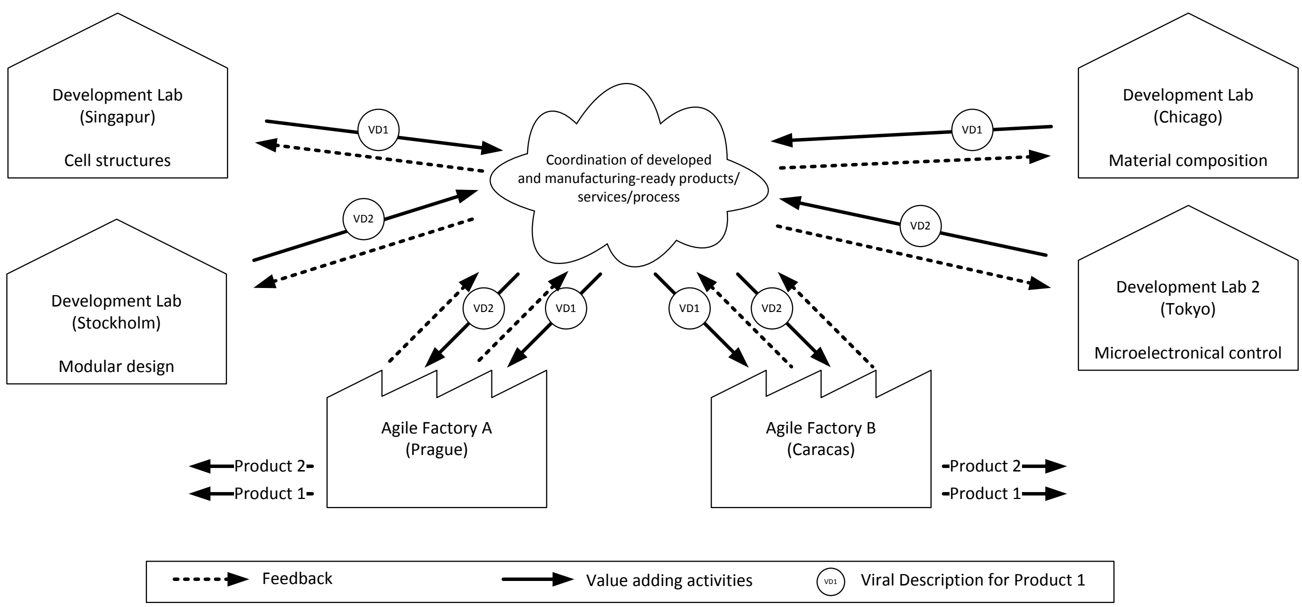


Figure 2: Cloud-supported coordination and matching of local independent product manufacturing.

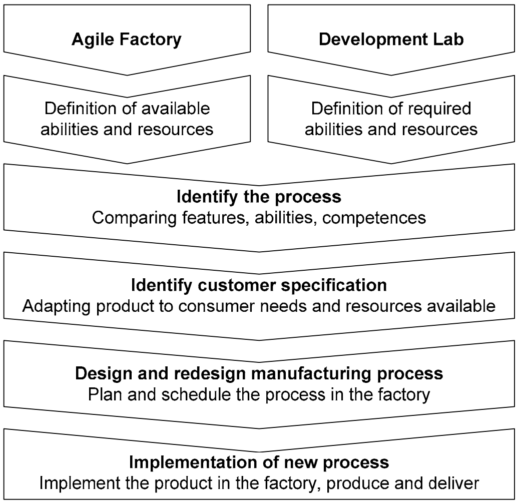


Figure 3: From developed product to the manufacturing of the good within a value network.

A description framework for product description uses semantic web methodologies [31]. In addition, the process of creating value networks and handing out the design and feature description can be simulated for different manufacturing possibilities [32]. At the end, the capability and feasibility is evaluated by the production site.

The process from development to manufacturing, as shown in figure 3, defines the required resources for the production processes that can be defined by segmenting the resources in production equipment, personnel and material. Each of those resource segments can be described by capacity, feature and competences [1].

## 4 THE CONCEPT OF VIRAL ENGINEERING

Usually the development and the production are close together due to the consistent knowledge and experience exchange as for example the automotive industry [33]. Therefore, a standard description framework is required to promote such knowledge and experience exchange within a collaborative development and transfers the manufacturing information further to the production. For this the virus as information carrier of reproduction relevant data is analysed and adapted.

### 4.1 Why a Virus Can Be a Role Model?

The agile connection between independent development laboratories and production sites is carried out by taking advantage of the present knowledge of viral behaviour. A virus emerges and evolves mainly by mutation, recombination and re-assortment. In addition, single mutations, insertions and deletions as well as acquisitions or loss of genes, rearrangement of genomes and utilization of alternate reading frames allow the continuous adaption to the environment [34]. The motivation of using a virus as a role model is seen that everyone is able to develop, modify and produce the virus, by this means the data, so long the necessary capacities, abilities and competences are available [35]. The virus evolution has its source on an ensemble of features and complex functions within a simple structure [36].

A virus by that means consists of its program code for replication but is not able to reproduce itself. For the purpose of reproduction a host cell is required. Therefore the adaption of a virus model to engineering seems well suited for a detached development and independent manufacturing of individual developed goods. The reproduction program matures in an agile development manner within several host cells. The host cell organizes the complete reproduction program within the metabolism of the host cell [37]. This allows that the production planning and the resource allocation are carried out by the factories, which have best knowledge about local resources as well as local customer needs to allow small adaptions.

### 4.2 Viral Description Framework (VDF)

The agility of production and development demands the organizational separation. The detachment of development and production networks is able to create an interdisciplinary intelligent organization. Comparing to virtual organizations the organizational intelligence for self-regulations and reactive behaviour requires informal support. This cannot be designed and has to grow and be established throughout different environmental factors [38]. Therefore, an adequate information and knowledge exchange is required [39]. The viral description framework (VDF) tries to promote the growing, establishing and shrinking of the intelligent organization with all its participants. This framework uses semantic web technologies allowing a focus on human centred workflows and improving the communication and understanding between humans and tools. This allows the transfer of preliminary defaults for further processing, the included knowledge and unique product or service characteristics. Taking for example the bionic handling assistant from Festo, researcher and developers from biology, bionics, mechanical, electrical and industrial engineering worked together for creating the handling assistant adapted from an elephant's trunk [40]. The linkage of semantic technologies hereby allows different disciplinary languages and syntaxes mixed together for each discipline by associating specific definitions and considerations.

The product description in form of a virus description (VD) holds the product information with its design, features, functionality and customer needs and the definition of the required manufacturing features. This information is essential for building, operating and reverse-linking development networks. This linkage approach is based on our understanding of the viral dissemination in networks. It spreads with its information to all 'interested' recipients but also reduces its network, when no 'need' for further reproduction is present. The adaption of the functionality of the virus to the product development and manufacturing gives a new perspective on the intelligent evolution of products within a temporary network. The evolution of a virus is in this case seen as development of a product. The product data and the attached knowledge increases over the development time, until the initial goal indicators are fulfilled. The viral reproduction is understood as manufacturing process of the readily developed. The information of the product, the bionic handling assistant, are passed to the manufacturing units by describing the single hinge and support pole as well as their connectors and controllers to fulfil the required function.

The data of material (i.e., density, weight, size) and controller specifications (i.e., power and reaction time of sensor and actuator) are distributed to the manufacturing planning department with recommended materials and technical requirements. This set of data is based on the features along the assembly to support the coordination while concentrating on the competences on the manufacturer to ensure a productive process [41].

### 4.3 Viral Engineering

The viral engineering sets a frame with its main goal to satisfy the customer under merging different disciplines for a higher innovation potential. This frame defines the restrictions from the customer within the value development, including product and service. Hereby, the major influences come from the customer and an individual or a group that makes the first steps of the idea and the conception. The other influences come from the interdisciplinary team. The following steps describe the collaborative engineering process:

1. Define the scope of development based on the customer needs
2. Rule-based competence selection of the network participants based on their core and functional competence
3. Cross-linking of the competence carrier within the product development cycle
4. Creation of the virus with its program holding data necessary for development and production
5. Reverse cross-linking of the data transfer and the development cycle
6. Maintenance of the information flow between all participants for feedback, support and adaptive developments

The idea is to collaborate during the early value creation process from the idea to the prototype and allow based on the VDF that the product can be manufactured within a range of a certain field of manufacturing competence. The focus on viral engineering lies in a concrete, systemic and rapid distribution of information by using existent information and communication technologies. The system allows multiple agents to participate and supports the communication between the engineering partners and the manufacturing partners.

The virus with its program for self-preservation allows the independent development cells to take the virus for modification, reproduction and adaption. The viral engineering is hereby only considered as interface between development parties and the transfer to the production. Hence, it can be seen as a form of “virtual (engineering) organisation”. The connection of viral networks will be carried out using temporary network structures. Compared to the virtual organization the focus lies on the process of building, operating and dissolve such value networks. It is carried out on the context of value creation by product design and development but handles data so for the implementation within an agile production environment.

### 4.4 From Viral Engineering to Agile Value Creation

The concentration only on the development process allows everybody to manufacture the good under the defined product features and so supports the systemic innovation [41]. The engineered and simulated process can be implemented within different production facilities (host cells). The batch size for the product is defined by the customers in the first place, but should be determined separately. A lower batch size supports customer-orientated manufacturing systems as well as changes in methods, materials, machines, schedules and product configurations [42].

The distribution and the brand are hereby contractual organized, as it comes within support and guarantee. This allows a product coming from an organisation that behaves as investor, developer, manufacturer, distributor as well as service provider.

The concentration on the production competences, the connection to value networks, helps promote the agility and leaves the competence and the planning decisions on scheduling and operation of the manufacturing completely within the production facility. The only requirement for the building of viral value networks is that everybody has to know the abilities and competences present. To make use of this resource allocation several frameworks have been developed that allow a responsive control of the manufacturing (PROSA) [43] as well as the co-evolution of product, processes and production systems (SPECIES) [44]. The decision if the factory operators accept or decline an order is customer and therefore profit-driven [45] and has to include the resource availability due to its great effect on the value network building.

Different methods and approaches were presented when agile manufacturing is observed. The agility of the manufacturer allows a steady resource use within a defined value network. The coordination of complex value added processes is carried out using rule-based situational instructions to allow great potential for efficient resource use within the value network. The holonic manufacturing execution systems is probably one of the best concepts that reduces the planning and increases the responsiveness as central factor within the regarded manufacturing [43,46,47]. As it can be seen the implementation of a single order can be achieved using numerous of available approaches.

## 5 SUMMARY

The concept of the viral engineering with the VDF supports the way from fixed localized organization structures towards structural detached development and production. The concentration on the available resources and competences allows single agile and intelligent development and production units to connect and increases the agility of creating individual value. This can help small and medium enterprises develop a problem-driven network of competences. The separated view on organizations along the value added life cycle gives new perspectives for combining knowledge, abilities and capabilities within the innovation process as well as for the local resource allocation.

The viral engineering concept holds a possibility how individual organizations can process the transferred data within value networks. This allows the building and operation of a network with temporary network linkage. By this means the time restricted networks prevent the value network structures from crusting and promoting individual product creation as well as the innovation process itself. The connectivity of different domain knowledge and abilities supports the innovation process and increases the chances for opening new market concepts. The interdisciplinary view on the engineering process allows a higher recognition and a new understanding of design and value. This allows the opening of new markets with low intensity of competition and assuming from agile factories using VD-developed products an individual adaption to the local consumer needs is possible. Also the use of local resources and individual production factors can bring a cost reduction as well as a higher value to the local customer.

In future observation the aspects of trust, remuneration and quality assurance have to be considered and defined over the complete viral value network. In addition, the communication and quality goals have to be encouraged between the customer, the development and the production.

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# Reconfigurable Strategic Guidelines for Successful Co-operative Value Creation

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**Abstract**

Manufacturing co-operations, innovation think tanks and technology clusters are well-known and profitable elements of a modern company's structure. The fast pace of typical product life cycles and innovation rates make it necessary to gain as much external knowledge as possible to optimise supply chain organisation. The aim of this quantitative, empirical study is to develop strategic guidelines out of the most influential success factors of manufacturing co-operations. These guidelines should be reconfigurable and easily adoptable to the situations co-operations regularly face. In order to reach these objectives the authors identified 110 success factors and analysed their cross-factorial relationships. Strategic guidelines were then formed and were evaluated by 16 senior managers of various fields, e.g. the aviation and space, transportation, strategy consulting and publishing industry. On average these managers direct 1247 employees.

**Keywords:**

Strategic Guidelines; Co-operations; Value creation

## 1 SITUATION

A study concerning innovation management points out that companies are able to operate most profitably when they are actively co-operating with suppliers and customers [1]. Research and development as well as manufacturing co-operations help to stabilise a company's situation among its competitors especially when it comes to the deployment of highly innovative products. The new focus on interactive value creation and the permeable boundaries of companies is supported by recent scientific research by [2,3,4] and by the overall megatrend towards personalisation and individualisation [5,6,7].

Researchers describe that the way customers recognise products has changed during the last two decades [7]. Customers increasingly expect to purchase not only a product but also gain access to a broad variety of product-related service benefits – the so called: product-service-bundle [8]. Without taking advantage of all available sources of know-how and experience on the open market manufacturers will be unable to generate sufficient product-service-packages.

Acknowledging that establishing business co-operations and networks are key skills [9,10,11] this still leaves the question for the right partner. Manufacturers face a highly competitive environment where the protection of intellectual property soars up to the focal task of management boards. Even medium-sized businesses have to face the world market as their key market [12]. Considering that their environment is so tough, these businesses cannot just open up their boundaries, allow their knowledge to be spread and hope for the best. However what should the leaders of companies do who want to gain the advantages of a more "open production" [3,4,5] without taking the risk of being exploited? The answer is that they need to establish strong and resilient relationships with reliable suppliers and customers.

## 2 REQUIREMENTS OF SUCCESSFUL CO-OPERATIONS

One way to realise the often proclaimed but rarely implemented mantra of vital business co-operations is to use the well structured, transparently generated and easily reconfigurable strategic guidelines presented in this contribution. These guidelines have been built to be used and are optimised for medium to large sized companies in the manufacturing industry.

The guidelines help to increase the efficiency of manufacturing co-operations in addition to strengthening their robustness in order to drive economic success [13]. For example the guidelines are able to provide support by avoiding a sudden appearance of stock-out-situations among a complex supply chain which can be critical for suppliers and OEMs. Stock-out-situations are likely to happen when the process organisation between partners is not synchronised consistently. The resulting frictional losses which are enforced by communication problems often directly lead to severe economic losses [13]. One way to avoid incidents like this is to precisely analyse which success factors influence the payoff of business co-operations in the manufacturing industry. In this contribution, the large amount of possible factors is grouped into influential fields and further into influential factors (Figure 1).

Regardless of branch or industry there are five basic principles which apply to all sorts of business co-operations. When thinking about optimising a supply chain which involves several partners these principles act as a first checklist to implement before developing specific strategic guidelines, fitted to a business model:

1. The **critical mass** needs to be reached. This means that entrepreneurs on the one hand have to quantitatively acquire enough potential partners to actually establish a co-operation network. On the other hand they will have to generate a persuasive mass of information transaction, idea spreading and lively communication between the involved partners [14].
2. All partners need to have the **intention to co-operate**. What sounds self-evident is crucial to every successful network. Exchange programs of research and development employees and a philosophy towards reconfigurable teams across companies' borders create additional reliance [15,16].
3. During a co-operation relationship the emergence of information asymmetry is inevitable. To avoid potential opportunistic behaviour from one of the partners **personal and informal relationships** need to be established early [15,16].
4. When establishing a business co-operation there has to be at least one large **focal company**. Firstly this is necessary because smaller suppliers and other members of the network


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need to align themselves with the bigger partner. Secondly a large focal partner creates a special charisma for a young and new co-operation network, which supports potential customers in their investment decisions [12,17].

5. Having reached a larger amount of people and companies involved in the co-operation it becomes useful to establish a **network management organisation**. It will optimise the process organisation and cover network marketing aspects [17].

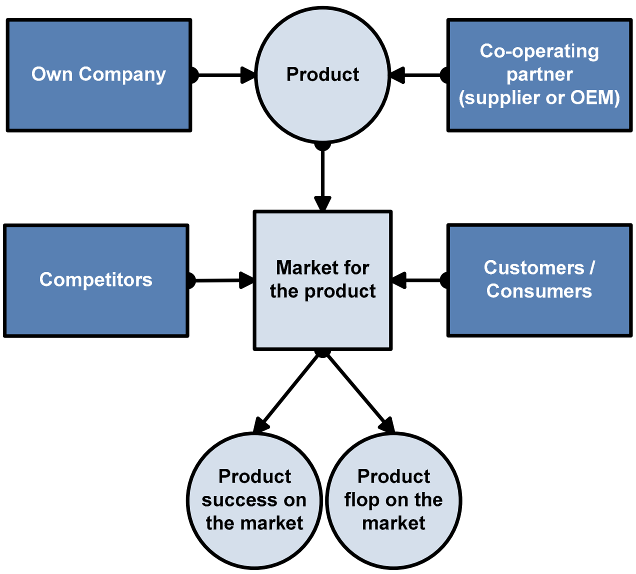


Figure 1: Four influential fields of co-operative success.

## 3 SCIENTIFIC APROACH

The aim of this study is to identify the influential factors of successful co-operative value creation and to form strategic guidelines out of them. The focus point of the study was to build strategic guidelines which are easily applicable to the manufacturing industry and at the same time develop a methodology which can be used as a tool to create newly reconfigurable guidelines for specific parts of this branch. To reach these goals a five-step methodological approach has been conducted.

### 3.1 Preliminary Study

Execution of a preliminary online-study with 72 academic respondents (B.Sc., M.Sc., Dr. Ing. and Prof. Dr.) to check and optimise the methodological steps from 2 to 5.

### 3.2 Identification

Identification of 110 influential factors of successful manufacturing co-operations by evaluating eight explorative interviews with German entrepreneurs of the aviation industry, four scientific lectures, several brainstorming sessions and scientific literature [2,4,12,13,15,16,18].

### 3.3 Selection

Filtering of the 44 most important influential factors by using the findings of the preliminary study and systematic analysis of their cross-factorial influence by using a direct influence matrix [19].

### 3.4 Development

Development of a highly reconfigurable methodology to collect, arrange and assess influential factors, before automatically merging them into strategic guidelines. Creation of 13 strategic guidelines for optimising the success of manufacturing co-operations by causally linking the 44 most important influential factors (based on their systematic analysis in the direct influence matrix).

### 3.5 Evaluation

Validation of all 13 strategic guidelines by 16 senior managers of Airbus, EADS Deutschland, Cassidian, Rockwell Collins Deutschland, Eurocopter Group, A. T. Kearney, the Aviation Cluster Hamburg Metropolitan Region, Verlagsgruppe Handelsblatt, Deutsche Bahn and several smaller companies who on average direct 1247 employees. This step was conducted via telephone and personal interviews which lasted on average 38 minutes and took place in Hamburg, Germany from May to July 2012.

## 4 RECONFIGURABLE STRATEGIC GUIDELINES FOR SUCCESSFUL CO-OPERATIVE VALUE CREATION

The scientific evaluations of this topic lead to 13 strategic guidelines for successful business co-operations in the manufacturing industry. To use these guidelines executives should pick one success factor to optimise among their own co-operation. Then they are able to check which process factors stimulate their success factors and which initial factors start the whole guideline (see 4.2 to 4.5). The result will be an initial factor, which is relatively easy to activate but which stimulates very important and resounding success factors of the whole co-operative endeavour.

### 4.1 Overview of Success Factors

The following passage gives an overview of the success factors of all 13 strategic guidelines:

1. Both partners' technical ability to cooperate in manufacturing processes
2. Partners' culture of communication
3. Efficiency of product-focused knowledge exchange
4. Ability to avoid product flops
5. Both partners' technical ability to cooperate during the research and development phase
6. Ability to split assets and liabilities among partners
7. Intensity of competition among the market sector
8. Information transaction and coordination costs
9. Both partners' social motivation to co-operate
10. Assumed benefit of a manufacturing co-operation
11. Quality of informal relations between both partners
12. Professional experience of co-operation teams
13. Incompleteness of contracts

The authors analysed how modern production co-operations can be quickly reconfigured to meet the majority of these factors. To give an impression of how the guidelines can be used the four most resounding ones will be displayed. All of the displayed factors influence each other, which is indicated by the direction of the connecting arrows. The numbers at the arrows indicate the average percentage agreement of the 16 surveyed experts of the strength of a connection between the factors

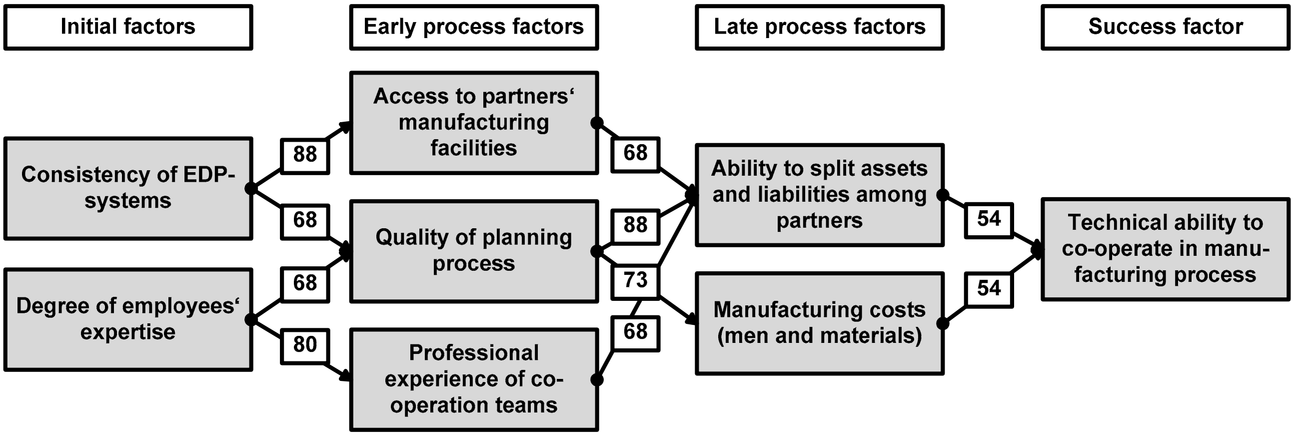


Figure 2: Guideline 1: Both partners' technical ability to cooperate in manufacturing process.

### 4.2 Guideline 1: Both Partners' Technical Ability to Cooperate in Manufacturing Process

Having identified the technical ability to cooperate as a factor which deserves optimisation managers should use this strategic guideline (Figure 2).

The guideline shows that it is possible to enhance the quality of a planning process by optimising the consistency of the EDP-systems co-operating partners use at their supply chain interface. Enforced by this increased consistency manufacturing costs can later on be reduced significantly.

Supported by insight of the partner's manufacturing facilities it is possible to increase both partners' satisfaction after splitting assets and liabilities (68 % experts' approval). This chain of causally linked incidents helps tremendously by improving both partners' technical ability to co-operate during the manufacturing process.

However one should not believe that continuous EDP-systems are a daily routine in every successful manufacturing company. Too often adequate planning software is substituted by simple charts, lists, registers or other makeshift solutions where important information is filed in an unstructured way. This forces engineers to invest time and effort into interpreting ambiguous information which often results in slips of the pen [20].

The common quality of planning processes shows that there is a lot of room for further optimisation. Consistently installed milestone planning software is a key aspect which is used too rarely [19]. A resounding 88 % of the interviewed experts agree that optimised planning processes would help to gain more out of every manufacturing co-operation. Only this planning makes it possible to handle thousands of parts, components and semi-finished products across borders of companies and countries.

Partners who are successful enough to have reached a state where their technical ability to co-operate during the manufacturing process is optimised to a satisfactory extent, should begin to concern themselves with enhancing the culture of communication which is practised between their companies.

### 4.3 Guideline 2: Partners' Culture of Communication

Entrepreneurs who want to optimise the culture of communication that is practised between them and their partners should adopt this guideline (Figure 3).

Initially one has the opportunity to increase own market reconnaissance efforts in order to raise general market transparency. Employees who are engaged in co-operation teams at a partner's company will benefit from this as higher market transparency stimulates the professional experience they are able to gain. Due to the fact that there is more information available

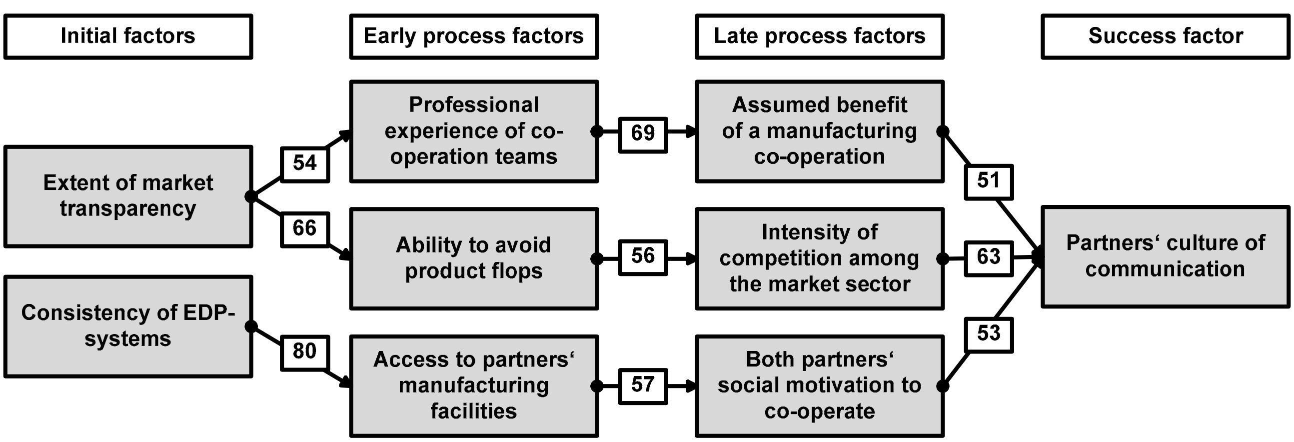


Figure 3: Guideline 2: Partners' culture of communication.

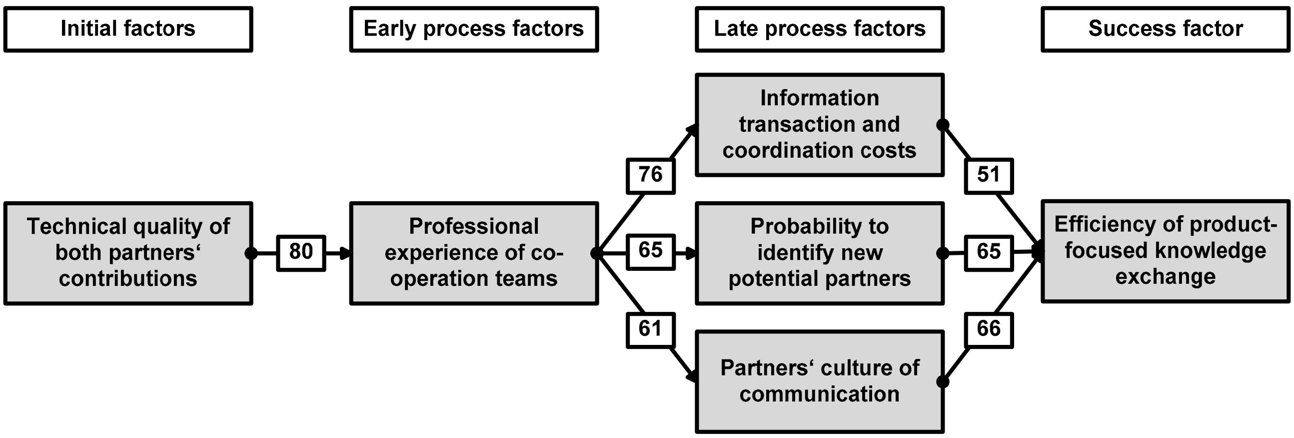


Figure 4: Guideline 3: Efficiency of product-focused knowledge exchange.

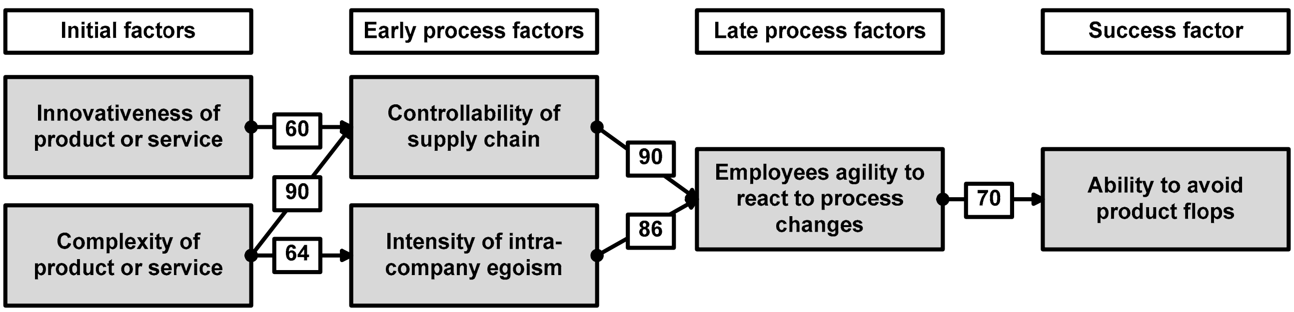


Figure 5: Guideline 4: Ability to avoid product flops.

between the co-operating companies the impression of participating in a useful endeavour increases (69 % experts' approval). This late process factor improves the culture of communication which connects both partners.

The same initial factor helps to improve the culture of communication in a second way. A healthy 66 % of the experts interviewed agree that a higher market transparency has a positive effect on the probability of whether a product becomes a flop or not. This will then ease the competitiveness within the market sector a company is in, which leads to a more lively culture of communication between co-operating partners.

The above-mentioned consistency of EDP-systems also supports this strategic guideline. However in this context of communication it furthermore boosts the motivation both partners develop for conducting co-operative endeavours (57 % experts' approval). This incident for his part tightens both partners' communicational integration (53 % experts' approval).

After partners have ensured their technical ability to co-operate (Guideline 1) and have established a healthy culture of communication it is important to make sure the product-focused information transaction is run in an efficient way.

### 4.4 Guideline 3: Efficiency of Product-Focused Knowledge Exchange

Most of the interviewed experts agree that product-specific internal knowledge is one of the most valuable goods a manufacturing company owns. They further agree that external partners should only have access to this knowledge to a certain and very controlled extent. At the same time vital business co-operations need an environment where company secrets and internal intellectual property are transferred widely unhindered in order to keep the corporate endeavour functioning (Figure 4).

One interviewee solves the dilemma in an elegant way by saying that "it is usually not necessary to unveil the company's drastic secrets." Based on with this intention one would rather scare off his partners instead of being able to trade intellectual property with them. The same interviewee further explains that it is common practise to only reveal those parts of a documentation with which partners really need to negotiate. As an example he mentions a wing of an airplane. While external data, like geometric dimensions are naturally and necessarily exchanged unhindered, entrepreneurs would tend to be a bit more nit-picking when it comes to the purpose and properties of the internal wiring.

However OEMs basically understand those peculiarities of their suppliers knowing that they distribute their products to more than one customer and that they take a certain amount of risk by partly unveiling their efforts [20]. When it comes to co-operations where a high amount of bidirectional know-how migration is crucial large non-disclosure-agreements have become a common instrument. These contracts form a reliable and unambiguous regulatory framework around the relevant parts of a company's secrets [4].

Through analysing the strategic guidelines it becomes obvious that an efficient and satisfying exchange of product-focused knowledge and company secrets is triggered by three main stimuli. While the above mentioned culture of communication within partnering companies is the strongest driver efficient product-focused knowledge exchange (66% experts' approval) two completely new factors appear here. Interestingly, according to the experts, the costs which result from communicating have a relatively small influence on the efficiency of communication (only 51 % experts' approval). One interviewee who works as senior vice president for a large aircraft manufacturer in northern Germany puts it like this: "Being in the position to ship components and semi-finished products all around the world only for final assembly, we do not really worry about costs for information transaction." Keeping this aviation-related fact in mind there is a very helpful implication in this guideline. By improving the input offered by employees in a business co-operation, the professional experience gained by all members of this co-operation is enormous (80 % experts' approval). Via two other important influential factors this will stimulate the efficiency of cross-company information transaction.

Through obeying these first three guidelines, co-operating manufacturing companies can minimize frictional losses, inspire communication and optimize the way they exchange knowledge. It now becomes necessary to also take one rather external aspect into consideration.

### 4.5 Guideline 4: Ability to Avoid Product Flops

Products often fail despite their developers and engineers conviction of having created something breathtaking. The probability of suffering a product flop or the ability to avoid it is a typical external factor in manufacturing co-operations that is driven by customers and competitors (Figure 5).

In addition the configuration of a product or good itself has large impact on its probability to fail on the market. The interviewed experts broadly agree that there is a direct connection between the complexity of a product and the controllability of its supply chain (90 % experts' approval). Furthermore this influential factor drives the degree of agility a research and development team can react with (90 % experts' approval). The strongly linked chain of cause and effect culminates in the company's ability to avoid massive product flops. Through taking these four strategic guidelines seriously entrepreneurs can cover the most vital aspects of co-operational success.

## 5 SUMMARY

For this study the authors analysed the 110 most important influential factors for the success of modern manufacturing co-operations between suppliers and original equipment manufacturers. A specific methodology was used based on the scenario technique [19]. This allowed to systematically creating 13 strategic guidelines by setting 44 influential factors in causally linked sequences. The significance of our results has been approved by 16 senior managers from several leading companies in the aviation and defence industry.

These reconfigurable strategic guidelines provide a portfolio of measures to improve and optimise business co-operations and to lead the daily gained experience into conceptual knowledge. Managers and entrepreneurs will have to choose which of them to use and which part of their supply chain they want to improve.

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# Towards Real-Time Computation of Cost of Poor Quality for Discrete Manufacturing Processes

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**Abstract**
Manufacturing enterprises are facing challenges from their internal and external environments to maintain their competitive advantage. Transparency, flexibility and adaptability are indispensable. However, the enterprises face the dilemma to monitor and control the success and effectiveness of continual improvement programs. The computation of financial and operational metrics assists to partially to measure the success of these programs. However, it would be advantageous to compute the financial metrics in real-time, similar to the computation of operational metrics. In the presented research, attempts are made to compute cost surrounding manufacturing processes in real-time, which can be aggregated to calculate different financial metrics.

**Keywords:**
Cost Inefficiency; Cost Leakage; Managerial Accounting

## 1 INTRODUCTION

Today's manufacturing enterprises are internally facing an increasing pressure to manufacture complex products with high quality, reduced lead times, low cost and low quantity, and at the same time, increase shareholders' profitability. Likewise, the enterprises' external business environment is highly competitive, volatile and driven by uncertainties. These challenges lay emphasis on the enterprises to achieve a greater degree of transparency, flexibility and adaptability in their manufacturing processes [1], which is realized through various continual improvement programs. Subsequently, performance measurement within and across an enterprise is vital to monitor and control the success and effectiveness of continual improvement programs [2].

Numerous Performance Measurement Systems (PMSs) have evolved, which stress the importance of financial and operational/non-financial metrics, and the linkage of financial and operational metrics [3]. These systems provide a comprehensive view of an enterprise to sustain competitive advantage. However, a PMS does not elaborate about the realization nor does it suggest which performance metrics should be employed. Overall, PMSs can be purely considered from a strategic viewpoint [3].

Financial metrics (e.g., return on investment) are crucial for chief executive officers, chief financial officers and accountants, which helps to identify the health of an enterprise [4]. On the contrary, the operational metrics (e.g., Overall Equipment Effectiveness (OEE)) are indispensable for operators, supervisors and managers, among others that enable them to react promptly to the situations on the shop floor [5]. Research, with support from standards and not-for-profit organizations, has been carried out extensively in isolation; this has resulted in the standardization of operational metrics.

The operational metrics are computed, mostly, in real-time [6], whereas financial metrics are calculated offline according to the enterprise's reporting cycle [7]. Thus, the financial and operational metrics can be considered as lagging and leading metrics respectively based on the current trends to calculate them [8]. The calculated financial metrics are delivered late, i.e., decision making processes are temporally delayed and will not be based on facts.

The requirements of different audiences of an enterprise are contradictory [5]. The operational metrics are communicated as an index, which represents efficient use of raw materials and resources, among others whereas the financial metrics are expressed using currency that is extremely aggregated and conceals the operational details [5]. The financial metrics are difficult to interpret by plant managers as they contain financial jargon. Likewise, accountants have challenging tasks to consolidate the real-time operational metrics to compute financial metrics.

The presented research attempts to compute the financial metrics in real-time, and link them with the operational metrics. The research is structured as follows. The methodology involves numerous concepts and technologies, which are briefly presented in Section 2. The envisaged methodology is detailed in Section 3. Next, Section 4 discusses case study and implementation details. Finally, Section 5 presents conclusion.

## 2 LITERATURE REVIEW

The envisaged methodologies use different concepts and technologies, which are elaborated in the following paragraphs.

### 2.1 Cost of Poor Quality and Problems

Quality is identified as the "degree to which an inherent characteristic fulfils requirements" [9], which has influence on revenue generated and costs incurred [10]. Likewise, the manufacturing resources are not efficiently used, which can be mainly attributed in realizing the higher quality of products [11]. Researchers and practitioners have elaborated concepts and procedures to compute the costs associated with realizing quality and lack of quality. These costs are bundled under the term Cost of Poor Quality (COPQ). COPQ is identified as "the costs that would disappear in the organization if all failures were removed from a product, service, or process" [12], which are usually expressed as a percentage of manufacturing cost, total costs and so forth [13].

Researchers stress that COPQ need to cover all the departments and management levels of an enterprise [14]. Subsequently, there exist different COPQ models. The most notably is the prevention-appraisal-failure model categorizing quality costs as prevention, appraisal, internal failure and external failure [13], as illustrated in Figure 1. The prevention and appraisal costs can be computed from the enterprise's accounting ledger [15]. The external failure costs are difficult to estimate as they might also include loss of future sales and customers. Likewise, the computation of internal failure costs is not straightforward.

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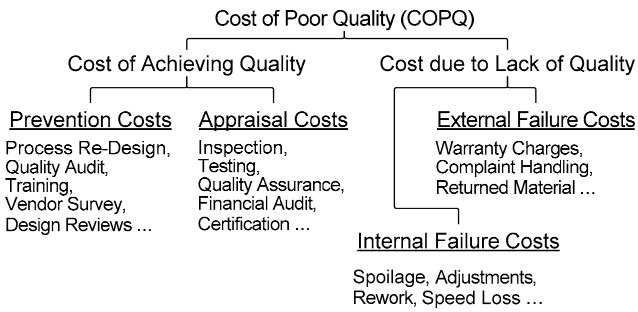


Figure 1: Cost of Poor Quality (COPQ), adapted from [13] [16].

The computation of the above mentioned costs is complicated, and is not widely employed by manufacturing enterprises due to various reasons. For instance, the process and cost data are scattered across different departments and enterprise levels, which introduces temporal integration/information gaps. Similarly, the current accounting systems lack the capabilities of accurately computing these costs [17] [16]. Hence, these costs are estimated [16], according to an enterprise's reporting cycle - monthly, quarterly, half-yearly. Additionally, the estimation is subjective based on the skills of plant managers and plant supervisors. The intensity of drawbacks associated with computation of COPQ is amplified when the manufacturing enterprise employs low volume production and high mix production schedules.

### 2.2 Managerial Accounting and Techniques

Traditional accounting techniques, especially in mass production scenario, were employed to derive financial metrics that solely concentrated on internal processes with the objective of minimizing the unit cost of a product and variance [18]. These techniques assigned direct costs and allocated aggregated indirect costs based on a pre-determined allocation rule [19]. Subsequently, these metrics had their own share of drawbacks. For instance, it was hard to distinguish between the profitable products and the ones that are incurring losses [19].

The tradition accounting techniques have evolved from pure allocation of costs to trace and assign costs based on causal relationships [19]. In this regard, the notable accounting techniques are Activity-Based Costing (ABC) and Resource Consumption Accounting (RCA). The new accounting techniques are combined under managerial accounting with the aim to provide plant managers accurate and reliable cost information about the utilization of resources that have monetary value [20]. According to Federal Accounting Standards Advisory Board (FASAB), managerial (cost) accounting is defined as "the servant of both budgetary and financial accounting and reporting because it assists those systems in providing information. Also, it provides useful information directly to management" [21].

The cost assignment, according to FASAB, employed in MA should follow certain assignment preferences [21]. Firstly, directly tracing costs to products based on the consumption of resources. Secondly, costs should be assigned to products based on cause-and-effect relationships between resources/operations, and products. Finally, allocating accumulated indirect costs proportionally to products based on a predefined cost allocation rule. Likewise, the cost should be assigned to different cost hierarchy levels - unit, batch and business sustaining [7].

The costs associated with performing an activity on every individual unit of product is termed as unit-level costs [7]. In contrast, there are activities that need to be performed at the batch-level [7]. These costs need to be assigned to batch-level costs and adhere to cause-and-effect relationships [19]. Apart from the aforementioned activities, there are activities that are performed on a wide range of enterprise entities that encompass multiple products, and customers, among others, and do not adhere to cause-and-effect relationships [7]. The costs associated with these activities need to be assigned to the business sustaining costs.

ABC concentrates mainly on activities performed in an enterprise [22]. The principle of ABC is to assign resource costs to activities depending upon the consumption of resources by the activities and reassign these activity costs to products based on cause-and-effect relationships and proportional use of activities [19]. Nonetheless, ABC has shortcomings from realization perspective. For instance, the model size tends to increase exponentially as the activity list grows [23]. Likewise, ABC considers all costs as variable, which might be useful for the long-term planning [22].

On the contrary, RCA focusses exclusively on resources and adapts the concepts of activities in a limited and disciplined fashion [24]. The costs in RCA are tagged as primary and secondary costs [22]. The primary costs originate in a resource where a certain activity is consumed. Likewise, secondary costs are assigned to a resource that originates from another resource [22]. These costs are modelled as fixed and proportional costs [23]. The fixed costs are computed based on the theoretical capacity of a resource pool and are not assigned based only on the consumption of resource outputs [22]. The fixed costs will exist as long as the resource is available [25]. Similarly, proportional costs are assigned based on the consumption of resource outputs [22]. RCA provides accurate cost information, especially with the capabilities to analyse secondary costs that deal with the decision making on outsourcing of manufacturing activities [25]. However, there are shortcomings with RCA that are comparable with drawbacks of ABC [22].

### 2.3 Events and Event Processing

Researchers and practitioners have attempted to solve complex problems using artificial intelligences techniques, which are composed of different subareas - expert systems, and neural networks, among others [26]. The Rule-Based System (RBS) is a type of expert system [26]. Nonetheless, RBSs do not have the capability to handle temporal reasoning [27], which is a significant hurdle in realizing real-time monitoring and control of manufacturing processes. Thus, the concepts of events and event processing need to be exploited to overcome the limitations of RBS.

Events are ubiquitous, which encompasses three aspects [28]: event form indicates the data associated with an event; event significance denotes an activity/operation; and event relativity describes the relationships with other events. Events can be classified as simple-, derived- and complex-events, which is based on the abstraction levels [28]. Event abstraction denotes amount of information available for decision making. Subsequently, simple events have less information in comparison to derived- and complex-events. Further, the aforementioned events are triggered randomly, which necessitates establishing relationships between events. Researchers have identified different types of relationships between events based on time, causality and aggregation [28].

The aforementioned relationships are used to create events with higher abstraction and overcome temporal reasoning. In this regard, event patterns are necessary to create events with higher abstraction levels [29]. The event patterns are defined using Event Processing Language (EPL) and from the computer science perspective, these patterns are encoded as Event Processing Agents (EPAs). The EPAs can be organized into networks and communicate with each other to form Event Processing Networks (EPNs) [30]. The EPNs can be nested and recursive to represent the complex manufacturing processes [30].

The aforementioned events, EPAs and EPNs are interpreted by the Complex Event Processing (CEP) engine [28]. The event processing engine triggers predefine reactions whenever a predefined situation is detected as defined in event pattern [31]. These reactions are defined in event pattern rules [28], which mostly create new events with higher abstraction levels and/or invoke predefined methods.

Event processing has been extensively adapted by financial trading, telecommunication, and other related industries in comparison to manufacturing [32]. Nevertheless, research articles can be found employing event processing in manufacturing [33] [34]. Likewise, Manufacturing Execution Systems (MES) software vendors mention usage of event processing on their website [35] [36] [37].

## 3 METHODOLOGY

An attempt is made in the presented research to compute internal failure costs in manufacturing enterprises, which can be used to compute different financial metrics. Further, discrete manufacturing with high mix production and low volume production schedules is considered. The following paragraphs elaborate envisaged methodology to compute different costs that will form the foundation to compute numerous financial metrics.

### 3.1 Enterprise Entities and Identification

Monitoring and controlling of manufacturing processes is indispensable for sustaining a competitive advantage. However, the manufacturing processes, from a monitoring and control view, are imprecise and intangible as they are viewed and executed differently by enterprise members. Thus, it is crucial to monitor and control the underlying tangible enterprise entities of manufacturing processes. Resources, manufacturing operations, production orders, production schedules, raw materials, and products, among others are a few of the enterprise entities that can be actually monitored and controlled.

Subsequently, it is indispensable that these enterprise entities are uniquely identifiable, which can be done physically or virtually. In this regard, there exist a number of standards and guidelines to tag/label enterprise entities. For instance, Unique Identification (UID) as a barcode label can be physically glued onto a product that can be read using the barcode reader attached to the operators' consoles. Likewise, a machine can assign a UID to enterprise entities, especially products and raw materials, which can be communicated with other machines.

### 3.2 Costs – Manufacturing, Leakage and Inefficiency

A manufacturing enterprise might employ a cost advantage strategy or differentiation advantage strategy to sustain its competitive advantage [38]. In either strategy, it is essential to reduce the costs incurred during manufacturing, and increase the profit. This is highly critical for suppliers, who have minimal influence on the product design and supply products according to the quoted price. An enterprise has opportunities to enhance its manufacturing processes, only if different costs are made available to the plant managers and plant supervisors along with the operational metrics within an appropriate timeframe, preferably in real-time.

*Manufacturing Cost*

The manufacturing cost contributes considerably to the overall product cost and influences the profit [39]. Nevertheless, the managers are not in a position to determine the manufacturing cost accurately and especially, in real-time. A manufacturing activity consumes different types of inputs that are defined in manufacturing bill of materials or recipes, as depicted in Figure 2. Some of the activity inputs can be directly traced to products based on the actual consumption. Additionally, some of the activity inputs can be assigned to the product based on the causal relationships after the actual consumption. This will maximize the use of cost tracing and cost assignments to enhance the accuracy of the manufacturing cost. The manufacturing cost can also consist of indirect costs (e.g., rent), which can be allocated based on a predefined rule. However, the indirect costs are not considered in the presented research.

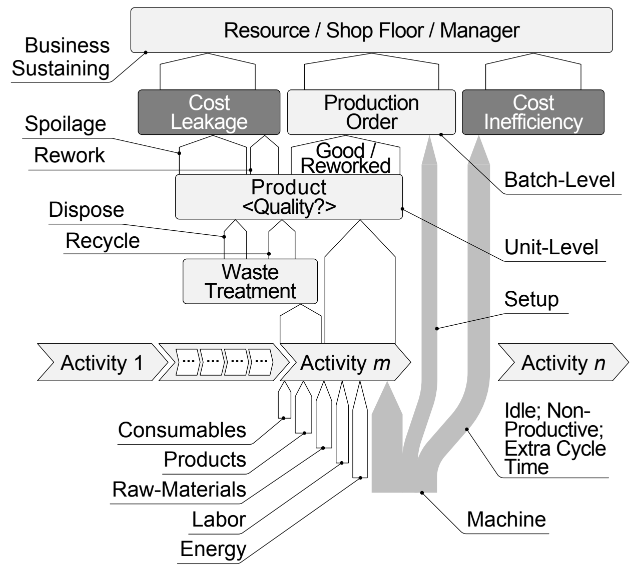


Figure 2: Cost assignments and their flow for an activity.

Figure 2 illustrates the computation of manufacturing cost of a product at a process activity. Here, it is critical that the products as well as other enterprise entities are uniquely identifiable. However, in reality, a product is manufactured by routing the product through different manufacturing process activities as defined in its process plan. Thus, it is necessary that the manufacturing costs are accumulated across the process plan of a product using UID. On a similar line, the outcome of a manufacturing activity can also constitute scrap, which can be identified as "residual material that results from manufacturing a product" [40]. This scrap needs to be further processed for various reasons. The processing of scrap/waste and the associated costs can be suitably assigned to products. Nonetheless, this is a tricky issue as it depends upon the underlying recycling/disposal processes employed by the manufacturing enterprise. In addition, there will be issues associated with quantifying the scrap. In many instances, the scrap is accumulated over a period and later processed/sold, which is reflected in the accounting ledger [40]. Thus, predefined rules need to be employed to determine the costs to be allocated to products based upon a combination of activity inputs and scrap generated.

The aforementioned situation will result in the computation of manufacturing cost of products at the unit level. These costs need to be aggregated to their corresponding production order at the batch level, as depicted in Figure 2. The production orders should also be uniquely identifiable. In addition, there are certain activities, like setup, that cannot be assigned to individual products but rather to a production order. Researchers consider assigning time and cost of setup to non-productive [19]. Because of advances in manufacturing design and technology, the setup activities can be performed quickly or offline. In any case, the resource executing a setup activity can signal start and stop, and these timestamps can be considered to compute the setup cost and assign the costs to production order.

*Cost Leakage*

Products are, sometimes, manufactured with a lack of quality, which might result in rework and spoilage. Quality inspections are crucial to identify rework and spoilage. Rework is identified as “units of production that do not meet the specifications required by customers but which are subsequently repaired and sold as good finished units” [40]. Likewise, spoilage is recognized as “units of production-whether fully or partially completed-that do not meet the specifications required by the customer for good units and that are discarded or sold at reduced price” [40].

The rework and spoilages costs are treated differently from a financial accounting perspective; sometime the costs are evenly distributed to good products or recorded into the accounting ledger as losses [40]. In addition, financial accounting does not differentiate between the quality issues occurring at the first, intermediate and last process step. Likewise, the rework and spoilage have been associated with the non-productive of resources [19]. Overall, the rework and spoilage costs are difficult to compute accurately, and further impossible to trace and assign these costs to products and production orders.

According to Merriam-Webster dictionary, a leak is defined as “to enter or escape through an opening usually by a fault or mistake.” The rework and spoilage do not add any value; rather the costs associated with the time and efforts invested to produce poor quality products are leaked. Thus, the rework and spoilage costs can be included under cost leakage that can be further aggregated to the business sustaining level, as depicted in Figure 2.

Quality inspections are necessary to identify good products, rework products, and spoilage. These inspections are constrained by the product specifications and manufacturing processes. In some instances, quality inspection is performed after execution of every process activity, and in other instances, quality inspection is carried out after execution of certain process activities. In the presented research, it is assumed that quality inspection is performed for all products at different stages of manufacturing processes.

The spoilage can occur at different stages in manufacturing processes. Subsequently, only the manufacturing cost of the current process activity and previous successfully executed, if any, process activities of a product need to be assigned to the cost leakage. Thus, it is necessary that the products have UIDs to realize the reallocation of already computed manufacturing costs to cost leakage. Likewise, quality inspections can reveal flaws in products that can be rectified by reworking with additional process activities. Nevertheless, calculating the rework costs is a complicated issue that depends upon the activities employed for rectifying the flaws. The rework costs can be accurately calculated after rectifying the flaws, which might hinder performance analysis and decision making. Subsequently, the different types of flaws must be properly identified and classified. Moreover, each flaw must be defined with attributes (e.g., severity) that assist in performing offline analysis and instantiating suitable continual improvement programs. In addition, financial related information, such as resource details, time required and cost that would be incurred to rectify a flaw, has to be defined in a process database.

There exist different accounting techniques to compute and assign costs. Cost leakage can be computed by employing ABC or RCA. Further, the financial information can be accessed from Enterprise Resource Planning (ERP) System and/or process database.

*Cost Inefficiency*

There are certain costs that are incurred during execution of processes both internal and external to a manufacturing enterprise. These costs can be represented by the inefficient utilization of stated resource capacity, lousy material handling, and deficient delivery of services [13], and so forth. Due to inadequate entry in the accounting ledger [41], researchers have termed these costs as hidden costs, intangible costs and invisible costs [17]. The presented research attempts to compute these costs with exclusive focus on (internal) manufacturing processes and corresponding inefficient use of resources. These costs can be collectively termed as cost inefficiency.

Enormous amounts of research have been carried out surrounding OEE. Further, OEE has been extensively adapted by manufacturing enterprises and is a standard module provided by many MES software vendors. The underlying fundamentals of OEE can be exploited to determine the cost inefficiency. OEE is composed of availability, performance rate and quality elements [42]. Additionally, six big losses have been identified associated with these elements - breakdowns, setup and adjustments, small stops, reduced speed, start-up rejects and manufacturing rejects [43].

The first four big losses are related to time that denote non-productive time of a resource. In the presented research, setups are considered as part of productive time for reasons stated previously whereas breakdowns, adjustments, small stops and reduced speed are considered as non-productive, which can be taken into account for deriving the cost inefficiency. Breakdowns, adjustments and small stops can be traced manually by operators or automatically. In contrast, the reduced speed can be determined by comparing the actual cycle time with the planned cycle time.

The aforementioned different non-productive time can be used to compute cost inefficiency. ABC considers all costs incurred during manufacturing as variable costs [22]. Hence, it is at disadvantage to compute cost inefficiency. On the contrary, RCA is a promising accounting technique that employs fixed and proportional cost to compute and assign different types of costs. Subsequently, RCA needs to be used to compute cost inefficiency. The necessary total cost consisting of fixed and primary costs is assigned to products as a manufacturing cost based on causal relationships. The remaining non-productive time is converted to cost inefficiency by considering only fixed cost. The necessary financial information can be obtained from a predefined location - ERP System and/or process database.

The calculated cost inefficiency is crucial from the perspective of resource and can be aggregated to business sustaining level. The cost can be used mainly to initiate continual improvement program. In addition, the computed values assist in make or buy decisions.

## 4 CASE STUDY

The previously elaborated in methodology in Section 3 is put into practice in a foundry. The foundry has a state-of-the-art production line supported with automated machines. The castings composed of different aluminium alloys can range from 500 grams to 60 kg with the mould box size 700 mm x 630 mm. Further, the foundry has a maximum capacity to handle 10000 ton/year of molten metal and employs 22 employees per shift. Finally, the foundry is capable of adjusting its manufacturing environment to facilitate different lot sizes. Consequently, it is crucial for the plant managers and plant supervisors to identify different costs accurately and subsequently, if necessary, initiate suitable continual improvement program.

Figure 3 illustrates schematically the computation of financial and operational metrics, especially the source of input data. The automated machines on the shop floor have been integrated and the real-time process data is made available [44] [45]. The sub-set of real-time process data is used to create tracking objects, which encompasses the three aspects of events. The tracking objects are of type product, production order and resource. Likewise, different EPAs along with necessary EPLs are created that implement the logic of cost tracing and cost assignment. Further, EPNs are created by connecting EPAs to compute manufacturing cost, cost leakage and cost inefficiency. These EPAs and EPNs are loaded into the NEsper CEP engine, which processes the incoming tracking objects and returns suitable cost information.

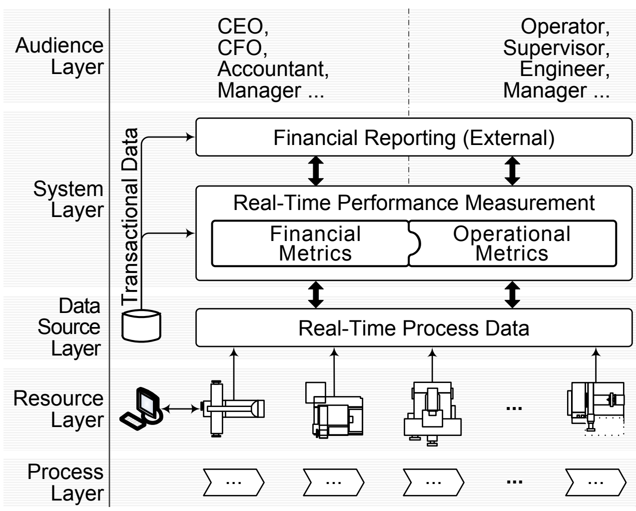


Figure 3 : Computation of financial and operational metrics.

The aforementioned information is presented along with the operational metrics to the plant managers and management using graphical elements - charts and gauges. Furthermore, the information can be aggregated over a day, week and so forth, which can be analysed to measure the success of continual improvement programs. Enterprise members need to initiate corrective action, if necessary, when the manufacturing processes deviate from the planned objectives as indicated by the metrics, which is not addressed in the presented research.

## 5 CONCLUSION

Manufacturing require information to monitor and control the success of initiated continual improvement programs. In the presented research, a methodology is presented to compute the manufacturing cost. In addition, the computation of cost associated with lack of quality, termed as cost leakage, and cost associated with the inefficient use of resource, labelled as cost inefficiency, has been elaborated. These costs can be aggregated to compute financial metrics and link them with the operational metrics. The computation of aforementioned costs is demonstrated in an industrial scenario by employing the state-of-the-art CEP engine. Thus, the costs can be computed in real-time using the real-time process data from shop floor and necessary financial information from ERP System and/or process database.

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# Tool for Life Cycle Costing of Electric Motors during the Early Design Phases

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**Abstract**

In order to obtain even more competitive and efficient electric motors, it is necessary to take into, during the account design phase, not only the electromagnetic performances, but also the environmental impact and Life Cycle Cost (LCC). The paper presents a methodology and a software tool for the evaluation of the LCC of electric motors (particular attention is reserved to the manufacturing and use costs), yet during the early design phases. The integration of the proposed tool in a larger platform, to consider also the environmental impacts and motor performances, is also presented. The cost estimation tool has been tested for small sized asynchronous single-phase electric motors for household appliances.

**Keywords:**

Life Cycle Cost; Electric Motors; Manufacturing

## 1 INTRODUCTION AND RELATED WORKS

The electric motor is one of the most common electric and electronic products in all industrialized countries. In order to obtain optimized electric motors, it is necessary to overcome the traditional design processes, taking into account not only the electromagnetic performances of the new products, but also other aspects such as efficiency, environmental impact or costs. In particular, while the manufacturing costs are usually calculated at the end of the development process, before the beginning of the production phase, the Life Cycle Cost (LCC) is often neglected. The calculation of the LCC allows designers to develop electric motors for specific applications, thanks to the possibility to evaluate the use cost during the use phase. In particular, the possibility to estimate the production costs during the early phases of the design process permits designers to immediately reject unfeasible solutions, avoiding expensive modifications in the successive phases of the product development process. While the manufacturing cost is extremely important for those electric motors manufactured in large scale (where even a small cost reduction is important for a competitive product), the use phase cost represents the most important cost item, if compared with the other items of the product life cycle.

Cost estimation is a well-known research topic, as proven by the number of approaches and methods available in literature [1]. Concerning the manufacturing cost estimation method, one of the meaningful classifications has been proposed by Duverlie and Castelain [2], who propose the following classes: intuitive, analogical, parametric and analytical. Since these parametric and analytical methods consist of the formalization of the tacit manufacturing, they can be considered knowledge-based [3]. Niazi et al. [4] present a detailed survey of the state of the art in product cost estimation covering qualitative and quantitative techniques and methodologies. A recent review concerning the cost estimation approaches and software systems is reported in [5] [6]. According to the classification proposed in [2], the analytical cost estimation methods are the most suitable for a detailed analysis because they consist of evaluating the product cost from decomposing the work required into elementary tasks. An example of this costing approach is presented in [7].

The development of a new analytical cost estimation method, applied to electric motor costing, starts by defining a standard manufacturing process. A detailed description of an electric motor, in terms of its design and manufacturing processes, is proposed by [8], but this does not describe how to estimate the manufacturing costs. On the other hand, an analysis of the manufacturing costs is presented in [9], but the author does not propose any general method to estimate the cost. It is possible to conclude that no methods exist to deal with estimating the manufacturing costs for electric motors. The literature presents approaches for the cost calculation of a single and specific manufacturing operation (sheet metal forming, plastic injection, aluminum die-casting, turning and assembling), but these are not integrated into a single approach dedicated to the entire motor [10] [11].

The estimation of the use phase cost strictly depends by the field of application of the electric motors. The literature propones specific studies aiming at measuring the Life Cycle Cost of electric motors used for electric/hybrid vehicles [12] [13] or other products, as a pump in chemical industry [14]. Despite the quality of the results, none of the above works present a method to estimate electric motor cost during the manufacturing and use phases, combined to calculate the Life Cycle Cost.

The integration of software tools which supports the design phase has been recognized as essential to achieve a high quality product in a short time to market [15]. The most innovative tools are conceived to support the design phase from the performance point of view [16] [17], neglecting other aspects such as environmental and economic sustainability. The environmental impact of an electric motor has been evaluated in [18], but, in this case, the cost and performance aspects have been neglected. Motor-Master+ [19] is a free online search engine to select and manage the electric motors, allowing a quick and accurate cost comparison of motors with different efficiencies. However, it does not provide tools to calculate performance and cost. This literature overview highlights the lack of a platform of integrated tools to support the design phase of electric motors. Hence, the paper aims to overcome the limitations of the approaches presented in literature through the:

- definition of a method and tool for the Life Cycle Cost estimation of electric motors during the early design phases;
- definition of a platform of tools to allow the integrated design of electric motors, considering product cost, performance and environmental aspects.

The paper is structured in four sections. Section N° 2 presets the methodology used to estimate the LCC of the electric motors, Section N° 3 illustrates the tool related to the proposed methodology and it presents the relationships with other design software tools. Section N° 4 presents the results of real test cases, whereas the Section N° 5 concludes the paper and it traces out future works.

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## 2 METHODOLOGY

In this section the approach to evaluate the life cycle cost of a medium-small sized electric motor, including manufacturing and use costs, over a defined period of time, is explained. Only these phases have been considered because they are the most important of the entire lifecycle. In particular the knowing of the manufacturing costs is essential for motor manufacturers to calculate the selling price, while the use phase cost is the most relevant for energy using products and cannot be neglected.

In details, the manufacturing cost concerns the raw material cost, the standard components cost, the direct manufacturing cost due to labor and machine tools, and also includes a part of indirect cost related to the machine tools setup and the scheduled maintenance in production phase. That part of indirect cost are considered as a percentile addition for each machine tool cost per hour. The proposed approach was applied in a typical manufacturer of electric motors. This company provided know how about motor manufacturing and also data regarding bills of material and parameters of costs.

Instead, the use phase cost, related to product using (energy consumption and efficiency over time), is a future cost expressed in present day value by applying an average discount rate. More explanation about it in the next sections.

The Figure 1 shows the methodological flow behind the cost estimation tool, implemented in this research work to support the engineer during design; in next section the software architecture is described with each applicative module.

The life cycle cost assessment focuses on the motor technical configuration. So, the input data concerns the identification of product family. This early phase is useful to define the expected product components and the related assembling procedures. The component list is composed by standard items, sub-assemblies and simple components. The standard items are commercial parts, like screws or bearings, that are sized by the geometrical and technical motor details, and then directly acquired on the market. The proposed method provides a knowledge, based on tables and schematic workflow, as a repository of parameters to select and classify products and to attribute features costing. Then each resultant configuration individuates a specific bill of material and an assembling processes flow.

The methodology is based on the analysis of a virtual 3D model, that contains attributes and information about motor type, geometrical parameters, and materials. Considering a 3D assembly model, each component (part or sub-assembly) includes data and parameters useful for costing. The manufacturing cost is basically related to the geometrical parameters such as the shaft diameter and length, the wires length for windings and coils, and size of laminated sheets. Therefore, to evaluate production costing and timing, it is necessary to consider also the material data that are attributed to each 3D part model. All the above parameters are the input data to define: raw materials, manufacturing process times, and required labor hours for costing the electric motor features on manufacturing and operating phase. The studied method is able to attribute different manufacturing flows for each motor type, and to calculate the final production cost considering each machining process.

The analysis to define the raw materials and manufacturing time is related to a knowledge based repository which provides the parameter conditions and formulas for the calculation. In the meanwhile, a database collects the machine tool parameters, the commercial items and the specific costs for each production process. The knowledge was formalized in parameter sets mainly in tables, thus an eliciting phase has been required involving a technical team of experts from company.

While both analysis regarding product structure and production operations are useful for manufacturing cost, the electromagnetic simulation tool, based on Finite Element Method Analysis (FEA), is necessary to evaluate the motor energy consumption and efficiency for use phase cost evaluation. In particular, the simulation tool is a separated application integrated in the proposed platform. The related calculation outputs are the motor efficiency curves, the energy consumption, and data on power and torque. The LCC assessment needs a reliable consumption assessment to calculate a correct cost during motor operating phase. Another aspect for the operating phase evaluation is the actualization of future energy cost, using a discount rate which depends by the economic inflation. The LCC approach supports the designer to assess the discounted payback, and gives a measure unit to compare money savings in different product configurations.

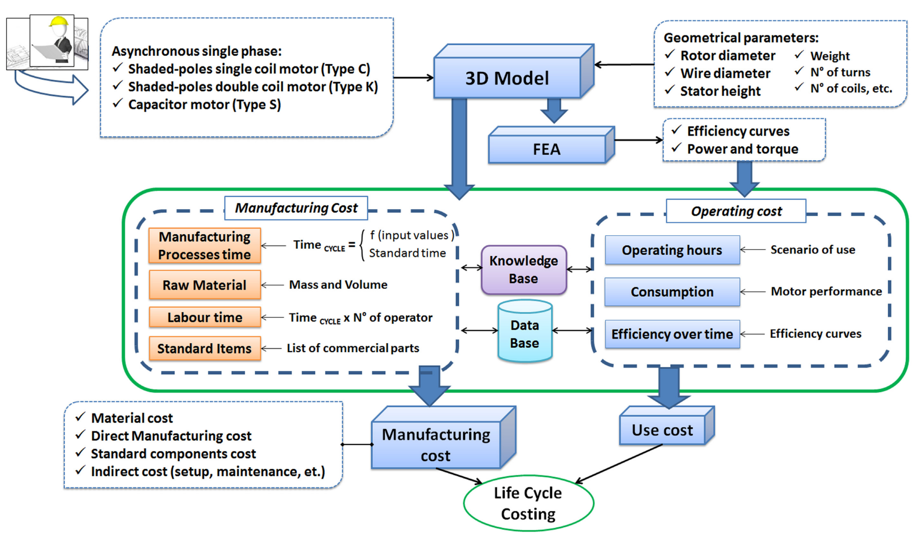


Figure 1: The methodological approach for motor costing.

### 2.1 Knowledge Domains

The elicited knowledge, concerning the standard know-how procedures for motor costing, has been formalized in analytical functions. The required knowledge has been classified in five levels: geometrical, technical, material, manufacturing, and operating.

The geometrical domain concerns the dimension parameters and their variations; the technical domain mainly interests the procedures to recognize the manufacturing features from an electric motor configuration; the material domain is composed of a database that includes the key to attribute cutting parameters in the calculation of manufacturing processes; the manufacturing domain collects the functions for feature costing; finally the operating domain includes the knowledge regarding different scenarios of use, the cost of electricity, and the energy consumption for different kind of electric motors.

### 2.2 The Manufacturing Phase Modeling

The manufacturing cost model has been conceived to consider the costs related to the each manufacturing process and the costs of the raw material used during the relative process.

The research focuses the analysis of three types of asynchronous single-phase electric motors: the shaded-poles single coil motor (type C), shaded-poles with double coil motor (type K) and capacitor motor (type S). Therefore, the proposed approach remains valid for all types of small-medium size electric motors. In fact, the manufacturing flows, that are analyzed for these three types of motors, are based on a modular object-oriented structure. Thus, different kind of motors could be implemented in the proposed platform with the same approach.

Particularly, Figure 2 shows the basically manufacturing flows for shaded poles motor and capacitor motor types. Considering the manufacturing flow for shaded poles motors (types C and K in Figure 2 a), the shearing machining provides semi-finished components (rotor, stator and core), shaped by a rapid pressing tool that induces shear stress on a sheet metal pack. This step is common to all types of asynchronous motors (including S capacitor type in Figure 2 b). The processes such as die casting and turning complete the rotor manufacturing, and are similar for the three kind of analyzed motors. In the production of shaded poles motors, the stator is finished by the insertion of shading coils. Instead, capacitor motors are finished with the manufacturing of a stator winding. Finally, the assembling phases more depends on the electric motor architecture and weight. Furthermore, this process also concerns some pre-assembling processes, such as welding and cementing, where the items are prepared for the final mounting.

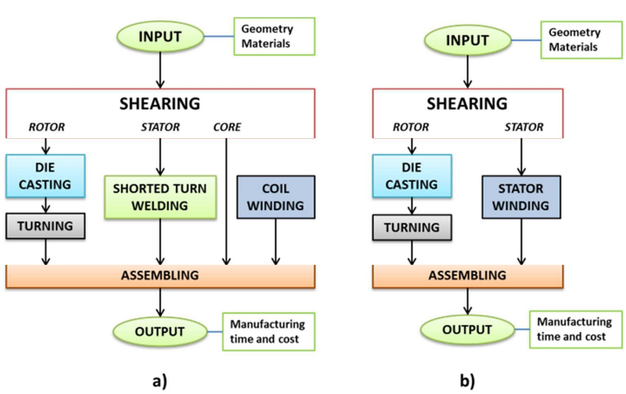


Figure 2: The main manufacturing processes for asynchronous electric motors: a) C and K shaded poles type, b) S capacitor type.

Generally, each proposed feature encloses a formalized knowledge which concerns geometrical and manufacturing parameters useful to calculate the cycle time due to machine tools and labor. The shaded poles motor C and K present a similar flow of manufacturing processes, whereas the type S (capacitor motor) has some differences mainly due to the absence of shorted turns.

As an example, the approach for shearing process analysis is described. Equation 1 shows the timing calculation for the shearing. The equation parameters mainly depend by the geometrical dimensions, such as the stator height (sheet metal pack) or the sheet width, and by the sheet metal material that directly influences the pressing velocity.

$$\mathrm{T_{cycle}} = \frac{\mathrm{T_{op}}}{\frac{\left(\mathrm{n_{press}} \cdot \mathrm{n_{figs}}\right)}{\mathrm{n_{sheets}}}} \qquad (1)$$

Analyzing equation (1), the $T_{cycle}$ indicates the time to realize the shaped sheet metal (shearing) for each product. The time of the labor working shift per day ($T_{op}$) can be assumed as 8 hours constant. The parameter $n_{press}$ defines the number of cuttings per working shift in a machining tool. This value, stored into the main database, depends by the selected material, the sheet metal width and the shape size. Indirectly, the last parameters also influence the selection of the machining tool and the relative cost per working hour used to calculate the process cost. The term $n_{figs}$ identifies the number of laminations cut from a sheet for each shearing cycle. It depends by the geometrical dimensions of the rotor and stator lamination shapes and by the sheet width. Finally, $n_{sheets}$ is the number of sheet metals necessary to obtain the designed stator and rotor packs, and is directly correlated with the motor height. This approach is valid for shearing processes in medium-small sized electric motor, but the same approach can be extended to each manufacturing processes defined in Figure 2. The calculated time is then multiplied for the cost of the equipment/machine used, in order to obtain the manufacturing cost for each process.

### 2.3 The Use Phase Modeling

Concerning Energy using Product (EuP) or Energy related Product (ErP) categories, which electric motors belong to, the use phase is certainly the most critical stage of the entire life cycle. Most of the energy is consumed during this phase and, as a consequence, a large amount of cost is determined during this phase. It is possible to suppose that a percentage of about 80-85% of the life cycle cost of an electric motor is due to the use phase. This underlines the need to accurately estimate the energy consumption and to carefully model the use scenario.

Usually, the use phase energy consumption is estimated considering the power consumption of the electric motor at the maximum speed and the number of hours in which it is used. This kind of approach can lead to relevant errors, because frequently electric motors are designed to be used in several work points (variable speed motors are very common thanks to the introduction of electronic control boards). For example, a cooker hood has three or four different speeds, but generally the estimation of the energy consumption is performed assuming that the motor is switched on one hour per day at maximum speed. Another example are the washing machines which have at least two different work points: low speed during the washing phase and high speed during the spin dryer phase with different power consumptions. Therefore, an accurate model of the use phase is essential to obtain a life cycle cost estimation with an acceptable accuracy.

In the proposed approach, the use phase has been modeled considering more than one work point. Furthermore, for each power rate, a different use profile has to be specified inserting the working time per year. Starting from these data, the energy consumption of the electric motor under analysis is calculated using the following equation (2):

$$E_{use} = \sum_{n=1}^{N} \left( \mathrm{P}_{wp1} \cdot \mathrm{WT}_{wp1} \cdot d_{\varepsilon}(n,1) + \cdots + \mathrm{P}_{wpI} \cdot \mathrm{WT}_{wpI} \cdot d_{\varepsilon}(n,I) \right)_n \quad (2)$$

where $E_{use}$ is the total energy consumption, $P_{wpi}$ and $WT_{wpi}$ are respectively the power absorption (in kW) and the working time (in hours per year) of the electric motor at the i-th working point, $N$ is the life cycle time (in years), $I$ is the number of working points considered in the analysis and $d_{\varepsilon}(n,i)$ is a function dependent on the n-th year and the i-th working point which take into account the decay of efficiency (dimensionless).

The electric motor curves (the efficiency and power consumption curves), which are essential to estimate the energy consumption, are calculated by the use of a FEA simulator integrated in the developed software platform (see the next Section 3). The user has only to input the duration of life and a use profile on the basis of the company know-how about its own products and the applications in which they will be used. Furthermore, the approach allows to consider a decay of the efficiency during the use phase. A correction factor can be introduced in the calculation of the energy consumption in order to take into account the inefficiencies which are unavoidable during the product life cycle. The user can freely sets this parameter to choose an estimated deterioration of performances to apply after a chosen year.

When the energy consumption has been accurately estimated, the cost related to the use phase can be calculated considering the unitary cost of electrical energy. A discounting back procedure is applied to calculate the present value of future costs. Finally, the equation (3) is used to assess the electric motor life cycle cost:

$$\mathrm{LCC} = \mathrm{C}_m + \sum_{n=1}^{N} \frac{C_{energy} \cdot E_{use,n}}{(1+r)^n} \quad (3)$$

where $LCC$ is the life cycle cost (in €), $C_{energy}$ is the unitary cost of electrical energy (in €/kWh) retrieved from a database, $E_{use,n}$ is the total energy consumption at year $n$ (in kWh) calculated by the equation (1), $N$ is the life cycle time (in years), $r$ is the discount rate (dimensionless) and $\mathrm{C}_m$ is the manufacturing cost (in €).

The proposed approach does not consider the maintenance costs. Considering that the focus of the present research is on small sized electric motors, in particular for application in household appliances, the maintenance has been ignored because, usually, for this kind of applications, the life time of the entire product is shorter than the working time of the electric motor. Furthermore, these small electric motors have a low initial cost and, for this reason, when they get out of order the most common maintenance service is the substitution with new ones. Anyway, the approach is general and the equation (3) can be easily updated adding a cost item for the maintenance, in order to extend the validity to larger motor for which maintenance is quite important.

## 3 COST ESTIMATION TOOL

The costing methodology described in the previous section is implemented in a software tool which is a part of a complex web-based platform called EROD. It is composed of several software tools which help designers in the configuration and simulation of electric motors. The whole system, developed using the ASP.NET technology (Active Server Pages on .NET Framework), can be hosted in a company server and can be used as a simple website, where all the functionalities are controlled by an univocal interface. This is an essential characteristic, because in this way the designer can simultaneously verify the impact of design decision-making in terms of performance, efficiency, eco-sustainability and life cycle cost. The main modules of the platform are:

- The Knowledge-based (KB) system, which is the core of the entire platform and aims to standardize the design process to define and optimize electric motors using the company know-how stored in different databases (Rules DB and Motors DB);
- The DFEE module, which supports designers in the proper modifications of the solution in order to increase energy efficiency and performance and to reduce losses in the new product;
- The LCA module, which allows the environmental load of the configured electric motor to be calculated;
- The Cost Estimation module (Figure 3) for the rapid calculation of the life cycle cost. This tool is described below in further detail.

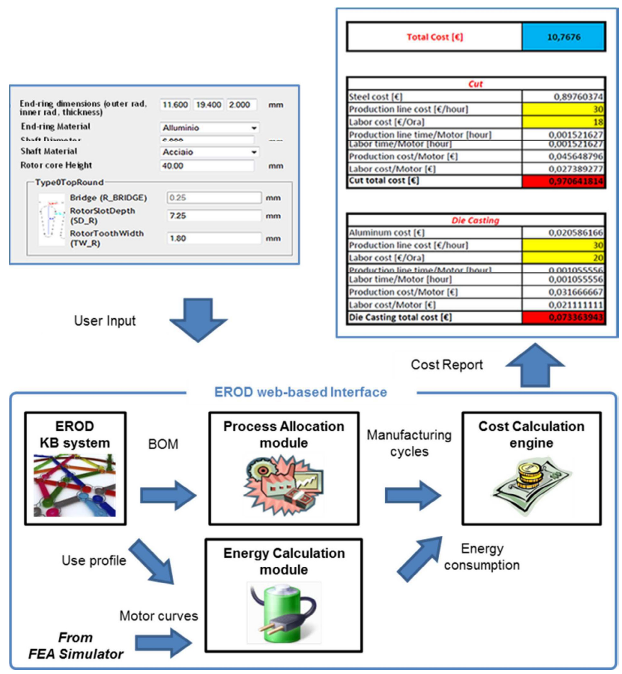


Figure 3: Cost Estimation module.

Through the use of a common web browser, designers can access the univocal GUI (Graphical User Interface) of the EROD platform to configure the solution. The KB system guides the end-users step by step in the configuration, selection of materials, sizing of all the components and modeling of the use scenario. The output of the KB system is a sort of BOM which contains all the required data about components (geometrical dimensions, materials, etc.) to calculate the manufacturing costs, as well as the use profile in the different work points.

The electric motor model, built by the designer and shared between all the platform modules, is used by the Process Allocation module which is able to assign one or more manufacturing processes to each component. Using the information of the BOM, the Process Allocation module is also able to estimate the quantities of materials required for the production to calculate the related costs.

As regards the use phase, the Energy Calculation module estimates the energy consumption of the entire life cycle for the electric motor under analysis. This module communicates with the FEA simulator, integrated in the platform, to obtain the motor curves and thanks to the use scenario modeled by the user can calculate the electrical energy consumption.

At this stage the Cost Calculation engine has all the necessary data to assess the life cycle cost, considering the information stored in the platform databases regarding the unitary costs of materials, the costs of company production lines, the labor cost and the unitary cost of energy. A discounting back procedure is applied to finally calculate the life cycle cost. This module builds a report in which costs related to each life cycle phase, as well as, the total life cycle cost are reported. Furthermore, concerning manufacturing costs, for each electric motor component, the report shows costs of each required material and manufacturing process.

## 4 CASE STUDIES AND RESULT DISCUSSION

The Life Cycle Cost estimation tool has been tested within a Large Enterprise (millions motors each year), which mainly designs and manufactures small sized asynchronous single-phase electric motors for household appliances. The energy consumed by the household appliances electric motors represents a very important part of the global energy consumed by the electric motor. This is the reason why the authors have selected this kind of motors as case study.

The test cases have involved the technical department (five designers) and the production department (two technicians) with the aims to evaluate the reliability of the proposed cost estimation tool and the LCC of an electric motor for household appliances. During this phase, also the suppliers of external components were involved to study the manufacturing processes and the relative manufacturing costs. The designers were responsible in using the cost estimation software tool, whereas, the production technicians have supported the validation phase providing updated values for the manufacturing processes. The validation phase was focused on the assessment of both the cost estimation approach and the improvements given by the proposed framework during the design process.

During the experimentation, three kinds of asynchronous single-phase electric motors have been considered. They mainly differ in the number of coils, lamination shape and size (Figure 4). While the manufacturing cost has been evaluated for each motor, the LCC analysis has been carried out only for the motor K.

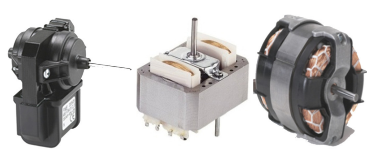


Figure 4: Examples of asynchronous single-phase electric motors designed during the test phase

The Figure 5 summarizes the results of the experimentation phase, in terms of manufacturing cost, reporting for each phase of the manufacturing process its impact on the overall manufacturing cost and the relative error committed by the cost estimation tool. In terms of cost uncertainty, the deviation between the estimated and the actual costs ranges between 2% up to 11%; the second value is relative to the more complex motors. The actual costs have been calculated by the company using their own traditional methods, which; for confidential and brevity reasons they are not discussed here. The most important deviations between the actual and the estimated costs are represented by the cost of the commercial components and the assembling process. The first difference is due to the deviation between the standard BOM of an asynchronous single-phase electric motor taken as reference and the real BOM of the engineered motor, which changes according to the customization required by the customer. This kind of error directly impacts the second type of deviation since the assembling cost depends on the number and types of components.

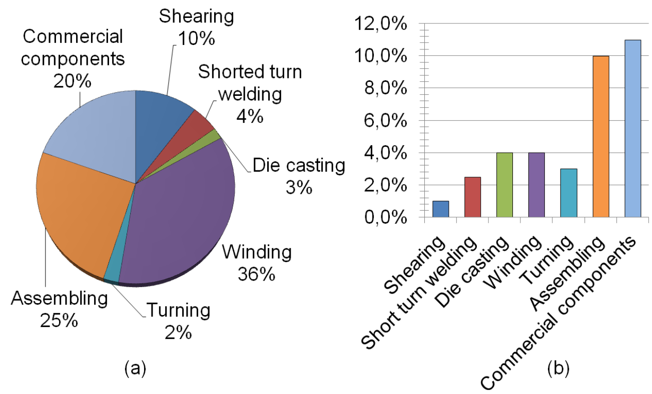


Figure 5: (a) Average manufacturing costs of an electric motor, (b) Average deviation between the estimated and the actual costs.

The cost of an electric motor during the use phase has been calculated considering to apply this motor to a cooker hood. The selected motor has four rotational speeds, called Working Points (WPs), one with a relative electric power. To calculate the cost during the use phase, the designers involved during the test have estimated the following general parameters, related to the Italian market:

- Energy cost: 0,1913 €/kWh
- Life: 8 Years
- Discount rate: 6 %
- Manufacturing cost: confidential
- Total working time per year: 365 hours/year

and the following Working Points:

- WP1: 20% of the time @ 52W;
- WP2: 40% of the time @ 88W;
- WP3: 30% of the time @ 123W;
- WP4: 10% of the time @ 149W;

The results illustrated in Figure 6 highlights that, while the manufacturing cost is essential for the motor manufacturer point of view to develop even more competitive motors, for the end users, the use phase cost is the most important one.

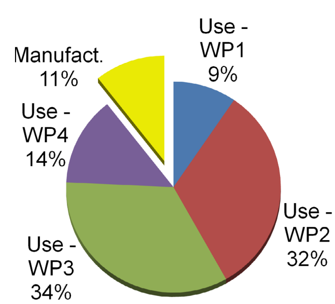


Figure 6: LCC of an electric motor, relative to the manufacturing and use phase (one cost for each Working Point, WP).

The integration of the cost estimation tool within a design platform has allowed the company to increase its responsiveness to the customer's request for a quotation of a new motor. Starting from the motor requirements (power, torque, speed, etc.), the designer is able, at the same time, to design the motor and assess the manufacturing costs. The tool for the streamlined-LCA allows the designer to also asses the environmental impact during all the life cycle phases.

## 5 CONCLUSIONS

This paper presents a costing methodology which allows the Life Cycle Cost of electric motors to be assessed. The electric motor manufacturing processes and use scenarios have been analyzed in order to formalize the rules for the LCC evaluation. The approach has been implemented in a software tool, which is a module of a more complex platform developed to support engineers in designing more efficient, economic and eco-sustainable electric motors.

In particular, the possibility to assess the manufacturing costs during the configuration phase allows solutions which are unfeasible from an economic point of view to be discarded immediately, avoiding modifications of the new product during the production phase. Furthermore, the integration of the Cost Estimation tool in the EROD configuration platform enables the design of electric motors which are optimized in terms of costs and eco-sustainability. As a result the development time and, consequentially, the time to market as well as the final product costs will certainly decrease. The results obtained during the experimentation phase confirmed the validity and the robustness of the approach and of the developed software tool.

Future developments have to be focused on the improvement of the costing algorithms to calculate the cost during the manufacturing and use phase. Firstly, specific operations (i.e. assembling) have to deepen detailed, and, secondly, other use phase cost items (i.e. maintenance) have to be analyzed in order to reduce the uncertainty of the cost estimation. There is also the necessity to extend the cost estimation module in order to cover other common electric motor types, such as asynchronous three-phase or brushless PM motors. Since the proposed cost estimation tool is specific for electric motors, an integration with a general purpose cost estimation tool could be implemented. In this scenario, the tool presented in this paper will represent a module of a wider LCC tool estimator.

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# Design of Production Systems for Large Maritime Structures

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**Abstract**

The following article presents a methodology for factory design projects in the maritime industry. Therefore the special requirements for the planning of maritime production facilities are introduced regarding the different planning steps in factory design. Based on that, an integrated methodology is presented to fulfill these special requirements and ensure valuable planning results. Approaches of the methodology are the application of type representatives, material flow simulation and layout planning algorithms. Finally the methodology is implemented in a software tool which supports the planner in factory design projects in the maritime industry.

**Keywords:**

Factory Design; Maritime Industry; Material Flow Simulation

## 1 INTRODUCTION

The maritime industry produces large structures which are deployed in or on the global oceans and inland waters. Examples are ships, drilling platforms or converter platforms and groundings for offshore wind energy plants. The fundamental production process for these structures is quite similar and often takes place on shipyards with launching facilities. The structures consist of a high amount of steel plates and stiffeners. In a certain number of cutting, bending and welding steps the steel structure is erected. It is then outfitted with equipment, which affords the structure its functionality, e.g. engines for ships or transformers for converter platforms. This article focuses on the planning of production facilities for these structures.

The goal of the factory design for facilities to produce large maritime structures is to realize efficient production systems to persist on the highly competitive maritime market. One key problem of maritime manufacturers is the fluctuating demand of the different products. Due to this variation the shipyards are forced to keep their production as flexible as possible. Combined with the high cost pressure the manufacturers face two competitive objectives, what makes the strategic planning of production resources difficult.

Figure 1 shows exemplarily the progression of worldwide new orders for three different ship types (data from [1]). As the ship number does not show the real working effort and the added value of the ships, the so called CGT (Compensated Gross Tons) is shown too. The CGT is a measure which considers the dimensions and the complexity of a ship and is an indicator for the needed workload to produce a ship. The CGT is also used to compare the productivity of different shipyards. In [2] the OECD gives a detailed description of the CGT-measure.

It is obvious that in long term a shipyard needs to be flexible and should not focus only on one ship type to be able to deal with fluctuating demand. In some cases, e.g. in cruise liner production, specialization can be a successful strategy. But in long term shipyards will focus on more than one ship type or have to change the production program frequently. An example for flexibility is the Nordic Yards Company in Warnemünde and Wismar on the Baltic Sea. They produced container ships as well as cruise vessels and now switched their portfolio to offshore converter platforms. To be able to deal with these changes in the production program a flexible structure of the facilities as well as personnel are necessary. These circumstances have to be considered already in the factory design process. As investments are carried out based on the factory design results, the quality of the results should be as high as possible. Consequently a planning tool is required, which supports the planner in each planning step of the factory design and ensures the high planning quality.

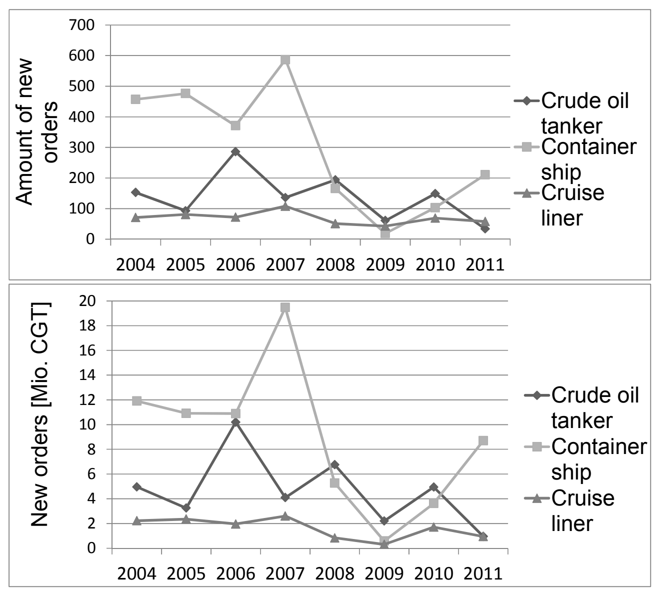


Figure 1: Demand progression for certain ship types [1].

The available planning methodologies and tools for factory planning are predominantly developed and adapted for other industries with basic conditions differing from the maritime industry e.g. automotive industry. Basic conditions differ for example in the availability and quality of data or the production process itself with industry-specific dependencies. The here proposed research has the objective to provide a planning tool, which fits the special requirements of the maritime industry. Therefore the requirements for maritime manufacturers are worked out. Afterwards a planning approach is introduced which is then implemented in a planning tool to support the planner during the factory design process.

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## 2 REQUIREMENTS IN FACTORY DESIGN FOR MARITIME MANUFACTURERS

The production process for maritime structures is divided into the construction of the steel structure, the so called hull, and the outfitting process. As shipyards try to increase the pre-outfitting of the steel hull already in the pre-assembly in order to reduce the occupancy time of the final assembly, the hull assembly and the outfitting processes are getting more and more integrated.

To perform the processes for the steel structure specialized cutting, bending and welding resources are necessary [3]. These resources have to be defined in quality and quantity for a certain production program during the factory design process. Additional to these resources transport facilities and personnel have to be determined.

Beside the definition of the resources another key task is the determination of the factory layout, which means the spatial arrangement of the calculated resources.

According to the factory design process in [4] and [5] this paper focusses on the following planning steps:

1. Preparation of production program
2. Definition of function and dimensioning
3. Structuring and design of factory layout

In practice, these steps are not processed sequentially [6]. Changes in planning goals, assessment criteria or input information lead to planning loops between these planning steps. These changes are relevant especially in the maritime industry because of the uncertain input information and the instable market demand. This leads to special requirements for the design process for maritime production systems, which are defined in the following.

### 2.1 Preparation of Production Program

Maritime manufacturers face particular problems when they start the factory planning process. The first problem is the lack of information on the production program for the next years. This concerns the qualitative data (ship type) as well as the quantitative data (number of new orders per year). The next problem is the incompleteness of product data to estimate efforts for the different production processes. In the maritime industry it is common that the production process starts before the design of the ship is completed [7]. The product information is often incomplete and the determination of capacity demand is consequently difficult.

Thus a solution is necessary, that enables to generate data for production programs without the detailed product information. Another requirement is the necessity to generate different production program scenarios without large effort, to deal with the uncertainty of future demand. The generated production programs should embody the capacity demand, which are used for the dimensioning of the production resources.

### 2.2 Definition of Function and Dimensioning

In this planning step the planner determines the function and the resources of the factory based on the production program. The vertical ranges of manufacture of shipyards are, apart from certain production process like bending of steel plates, very similar today. So the decisions on the function of the shipyard are made by common make or buy calculations. Hence the key problem in this planning step is the dimensioning of the resources. For each production stage the resources have to be defined in quality (manufacturing technology and degree of automation) and in quantity (number of machines and working places). The resources include machinery, personnel and transport facilities.

Due to the complex production process with a lot of dependencies between the production stages, a static planning approach would not meet the requirements of a sufficient resource planning for maritime production facilities. Beside the production machinery the transport systems play a key role in the maritime production process. They are used for transport of parts as well as retain function during assembly processes of heavy parts. This overlap has to be considered too in the capacity and throughput planning. Therefore a dynamic planning approach is necessary which considers the dependencies and enables to determine throughput times in a dynamic manner.

### 2.3 Structuring and Design of Factory Layout

In the structuring and design step the determined resources are structured and the layout of the factory is designed. Nowadays the layouts are developed based on the experience of the planner. Due to the complexity of the production process the planner should be supported in the development of factory layouts. Hereby the competitive objectives of a flexible layout on the one hand and an efficient layout on the other hand should be taken into account.

As the production process consists of different assembly steps, the size of the parts increases rapidly with every additional assembly stage. The dimensions go for example from smaller parts like profiles with dimensions of 150 mm height, 1000 mm length and 9 mm width to the final ship with 250 m length, 30 m width and 8 m draught (example: cruise ship). Thus the required area for one additional resource can have major influence on the layout design of the factory.

As in factory planning it is common to develop different scenarios with changes in the resources, planning loops between the dimensioning and the layout design occur frequently. In practice different software tools for the planning steps are applied. The interfaces between these tools are in most cases not standardized and the frequent changes of planning tools lead to unnecessary planning effort. Thus an integrated approach is desirable to prevent this inefficient workflow.

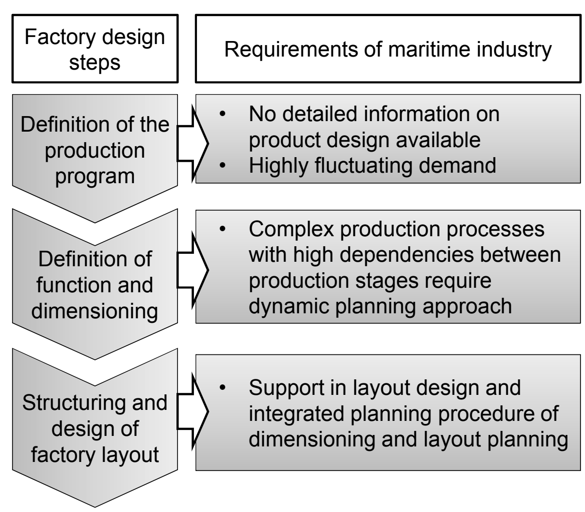


Figure 2: Particular requirements of maritime industry on factory design process.

The requirements are summarized in figure 2. To fulfill these specific requirements a new, integrated planning methodology is introduced. The methodology combines different approaches, which deal with the specific circumstances of the maritime industry. After the conception of the methodology, it is implemented in a planning tool. This tool supports the factory planner during the factory design process for maritime structures.

## 3 PLANNING APPROACH FOR MARITIME MANUFACTURERS

### 3.1 Type Representatives for Production Program Definition

To overcome the problem of the missing information of products, which are still in development, the application of the type representative approach is proposed [8]. A type representative is a part, which represents a group of parts by uniting features such as geometry, mass and volume. To determine a type representative the following steps have to be examined. First, groups of parts have to be defined which are technologically similar. For each group one type representative has to be declared with the corresponding capacity demands for the parts. Selection criteria for the type representative are the required working time, price/ cost, geometry, in-house activity, mass and volume [4].

In the maritime industry the objective is to generate type representatives for each ship type to analyze different production program scenarios in the strategic factory planning. Thus the ship type is the first differentiator. Each ship structure can be roughly segmented in a bow-ship-, mid-ship-, stern-ship- and deckhouse-area. Each area has different structural characteristics, which lead to different efforts and sequences in the production processes. In the mid-ship area are a lot of flat plates and profiles with regular welding seams. The amount of bended parts is low. The same pertains for the deckhouse, but the thickness of plates in this area is lower compared with the mid-ship. In contrast to the mid-ship and deckhouse-area the bow-ship consists of a high amount of bended plates and a high part density with irregular welding seams. The manual effort for welding in these parts is much higher than in the mid-ship, because the welding takes place in a narrower environment and is more difficult to automate. Thus for each ship area type representatives are defined.

To be able to calculate capacity demands for each production stage, type representatives are defined for the different production stages. Figure 3 shows the product structure and the corresponding production processes. In case that a process is planned to be done in-house, for these processes the capacity demand has to be defined based on the type representatives. Only if the capacity demand is known for each production stage, resources can be chosen in the next planning step.

The determination of type representatives is introduced exemplarily on the sub assembly process. Figure 4 shows results of an analysis of the capacity demand for sub assembly parts on a panel assembly line. In this process so called flat panels are assembled from steel plates and profiles. On station one of the panel assembly line the plates are welded by a one-side submerged-arc welding gantry. The array of plates has to be cut to the final shape including cut outs by a thermal cutting gantry. This step as well as the removal of steel primer for the next process is performed on station two. On station three the profiles are tack-welded on the plate array, which are finally welded completely on station four.

Different panels were analyzed based on their structure and capacity demand on the panel assembly line for each ship area of a certain ship type. It is obvious that the capacity demand differs depending on the ship area, which the panel belongs to. The variations result from the different geometry of the parts.

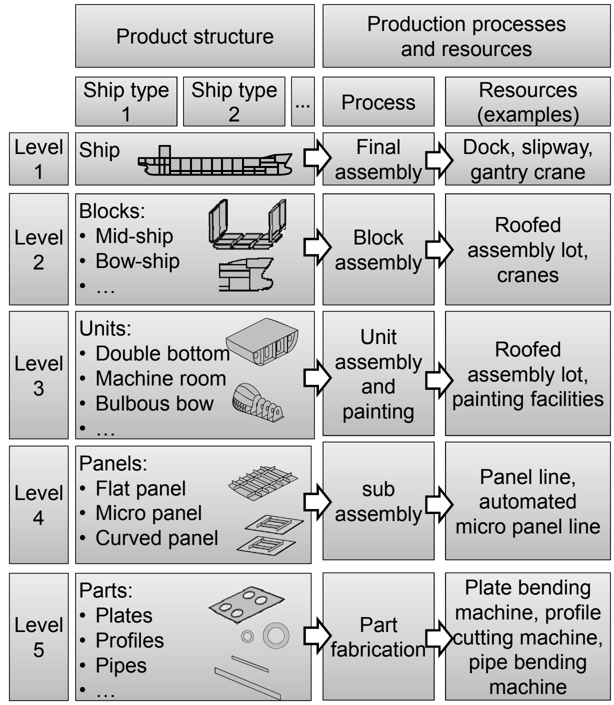


Figure 3: Product and process structure of maritime steel structures.

Based on this analysis the panels for the ship areas are grouped. In the next step the type representatives for the groups were chosen regarding the criteria in [4].

As the required working effort for the type representative is known, they embody the input of the production system and are the basis for the resource planning. Each one has a certain work schedule with a defined working time.

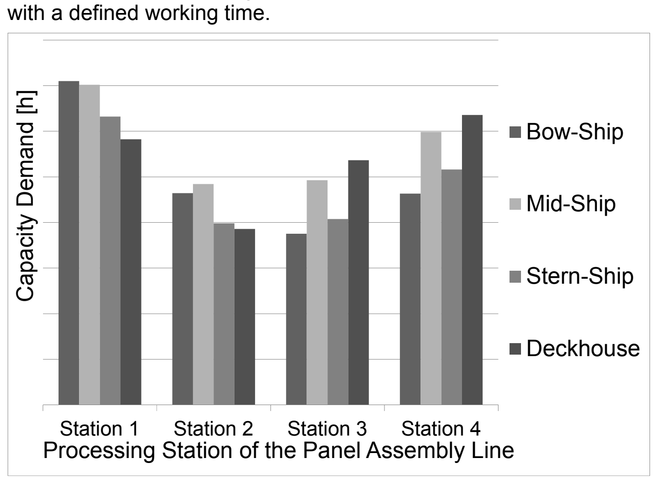


Figure 4: Capacity demands of different panels on a panel assembly line.

The analysis and type representative definition has to be examined for each production stage and each ship type. Then it is possible to built new production program scenarios without detailed information on the future ship. The production program is generated by combining the type representatives to a notional ship and calculating the related capacity demand for each production stage.

If a long container ship should be produced, a certain amount of the mid-ship blocks, units, panels and parts are chosen from the type representatives. In case of a shorter container ship, the amount of the type representatives is lower in order to reduce the capacity demand.

### 3.2 Dynamic Resource Planning

Due to the complexity and the dependencies in the maritime production processes a dynamic resource dimensioning is required. To enable a dynamic capacity planning material flow simulation is applied. Material flow simulation is one element of the digital factory approach and is currently applied for factory design projects in different industries [9].

In the maritime industry material flow simulation is also a core topic in the production planning for innovative shipyards [10], [11], [12], [13]. Most of the applications concentrate on the production planning with operative planning problems like resource utilization and scheduling optimization [14]. As this paper focuses on the factory design, the considered time horizon as well as the planning objective is different. First approaches for the simulation-based factory design are described in [15]. But in this approaches only part of the maritime production processes are regarded (e.g. Block assembly). There is a lack of approaches that enables to simulate different scenarios of a complete maritime production system. However, in factory design it is necessary to consider each production process and their dependencies.

To utilize material flow simulation for the entire production processes of a shipyard all production resources have to be modeled in a simulation environment. Due to the different degrees of automation and forms of spatial organization in the maritime industry specialized resource modules are necessary. In the panel assembly for example an assembly line is deployed. As described in 3.1 a panel is assembled usually on four stations following the principles of a flow production line without a fixed cycle time. In contrast to the panel assembly line the block and unit assembly is organized as a job shop system. Each assembly lot has almost the same functionality and they can be considered as homogeneous. In the pipe fabrication the group principle prevails. All resources to produce pipes and pipe pre-assemblies from cutting, bending, welding and conservation are pooled in one production area. The final assembly in the maritime industry is typical for the jobsite assembly.

These different forms of organization have to be implemented in the material flow simulation to enable the arbitrary combination of different variants of production systems.

Additional to the forms of spatial organization the operational procedure differs. This concerns especially the assembly processes. While in the final assembly the process already starts when the first two parts have arrived, the process in the sub-assembly does not start until all assembly parts are delivered to the assembly line. Therefore the resource modules of the simulation provide options for operational strategies of the material flow. Hereby constraints in assembly sequences of the different parts can be considered in the simulation.

The basic forms of spatial organizations and operational procedures constitute the static resource fundament of the modular simulation environment. With these modules the specific resources can be modeled. Each resource is assigned with a form of spatial organization and an operational procedure. Then the resource can be inserted into a simulation model. That enables the planer to reconfigure a new production scenario in a simple manner. This is important, as in a planning project different resource scenarios are simulated. This concerns the quantity of the resources, e.g. the number of assembly lots in the unit assembly, as well as the qualitative determination of resource, e.g. different welding technologies or degrees of automation in the panel assembly.

The key to a dynamic production analysis is the logistics, which is responsible for the transports between the static production resources. Therefore the transport systems and the logistics processes have to be modeled regarding the special requirements of maritime processes.

Due to the varying mass and volume of the parts the transport lot sizes vary and the transport systems go from small sizes like a forklift to huge gantry cranes with a payload of more than 500 tons. Each transport system is modeled with their technical features (e.g. speed, payload) and accessibility of the production resources. To realize a dynamic behavior each transport system can only be used when it is available and the payload of the system is not exceeded by the transported part. To organize the transports a transport control is developed. When a part is processed on a production stage it registers itself for transport with the destination of the next production stage. The transport control pools all transport requests and observes the activities of all transport systems of the shipyard. As soon as a transport system is available with the desired requirements of a registered part (geometry, weight, accessibility from source to sink) the transport takes place in the simulation. So the realistic, dynamic behavior of the maritime production is modeled in a simulation environment. Bottlenecks can be analyzed in the machinery as well as in the transport capacity.

### 3.3 Layout Planning

Subsequent to the resource dimensioning, the resources have to be arranged on the factory layout. But in the maritime industry an integrated approach is required, to prevent frequent system changes due to planning loops.

To realize an integrated dimensioning and layout design in one software system the so called matrix of distances is the enabler. The matrix delivers the distances between all resources in a current layout scenario. This can be linked to the logistics feature of the simulation, where the transport time is calculated based on the distance of the transport source and sink. A relocation of a resource in the model leads to a change of the distances for this resource in the matrix. During the simulation run different transport times are calculated and so the effects of the relocation can be evaluated directly in the next simulation run.

In addition to that, the system should supply the planner by providing useful layout solution. Although a lot of different algorithms exist to automate the arrangement of resources, none of these algorithms are applied in the commonly used simulation systems [16]. Consequently a research gap for the factory design can be revealed.

The layout algorithms can be distinguished in analytical approaches and heuristics. While analytical approaches provide an optimal solution, they can only be utilized for very simple arrangement problems. As a result heuristics are more established in the layout planning [17]. Another distinctive feature of layout planning algorithms is the consideration of different areas required for the resources. Some approaches simplify by assuming that each resource has the same area requirements. This is not applicable regarding the large differences in the production areas in the maritime production stages. To provide the planner with useful solutions an algorithm needs to be implemented regarding different space areas. Two common approaches which fulfill these requirements are the CORELAP and the MODULAP algorithms. Both determine an initial layout derived from the transportation matrix and the area requirement for each resource. They calculate the arrangement sequence based on the intensity of the transport relation for the resources. Then for each resource the favored and collision-free location is determined. [18] shows a detailed description of the algorithms. While MODULAP considers a fixed length-width-ratio the CORELAP approach calculates based on a fix raster without this fixed relation. Thus the CORELAP can lead to unreal facility arrangements due to different length-width-ratios. In this case a combined algorithm was chosen, because of the easier implementation of the CORELAP arrangement cycle in a software and the possibility to consider fixed length-width-ratio in MODULAP.

As the layout algorithms are currently not able to consider general conditions they only provide an ideal layout which is optimized for an efficient material flow. Flexibility concerns are often not included in these algorithms. Thus the tool provides the planner a pick an place functionality to manually adapt the generated layout. Thereby it is possible to regard for example flexibility or safety concerns in the layout.

## 4 PLANNING TOOL FOR MARITIME PRODUCTION FACILITIES

To implement the approach in a planning tool the first step is to realize a database with all type representatives for different maritime structures. This database has to be filled once and should be extended and updated constantly. The database provides type representatives with the information on required process steps, work times for each process, weight and their dimensions. Thereof the capacity demand is calculated for the resources as well as the transport systems. Figure 5 shows the procedure to build production scenarios and calculate capacity demands based on the type representative database.

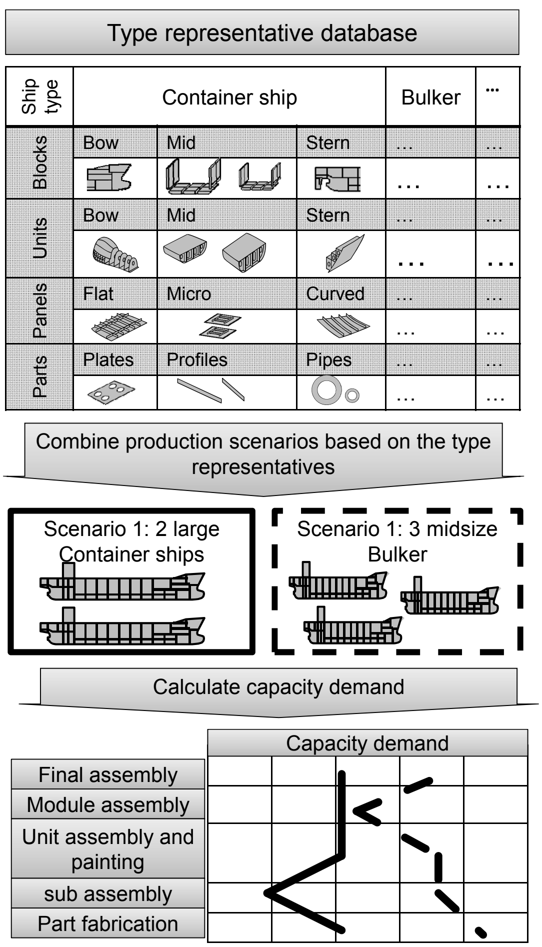


Figure 5: Procedure to generate production scenarios based on a type representative database.

The next step is to implement the resource modules for maritime production resources in a simulation environment. In this case the material flow simulation software plant simulation (Siemens) was chosen. With the application programming interface (API) it facilitates to program own resource modules for special maritime needs. Each resource has its own shift system and assigned personnel. By dialogue the planner chooses the operational strategy and the form of spatial organization for the workshops. This dialogue provides also the possibility to add new, change or delete existing resources, if the planner wants to start a new simulation scenario.

To reduce the effort of the planner to build a simulation model for different scenarios an automated model generator is implemented too. The standardized module structure of the maritime production resources enables a simple algorithm which only requires a table of the resources and their coordinates on the factory site. The model generator allocates the resources and displays the layout in 2D and 3D. For the 3D view every resource is linked to a VRML-file in the resource data table.

The logistics function is implemented in the logistics feature which includes the transport systems as well as the transport control. Transport systems are modeled by tables with information on reachable resources, the maximum payload and the velocity for every system. Another table gives information on transport lot sizes for each part type. Before a transport takes place in the simulation a suitable transport system has to be found. Four criteria have to be fulfilled:

- source and sink are reachable for the transport system
- transport lot size is reached in the buffer of the source
- volume and mass of the transported parts do not exceed the payload and dimensions of the transport system
- the transport system is available

If a transport system is chosen, the transport time has to be calculated. Therefore the matrix of the distances (distance between source and sink) and the velocity characteristics of the transport system are utilized. The matrix of distances is compiled based on the current resources and their location in the simulation model.

The last step is the implementation of the layout algorithms. The algorithms are integrated by the API of plant simulation in the layout algorithms feature. The feature calculates the matrix of transport intensity based on the process information and the transport lot sizes. By dialog the planner starts the layout algorithm. A collision free layout is displayed in 2D and 3D. As the implemented algorithm does not consider constrains as exit paths or pillars in a factory building the planner has to convert the proposed ideal layout to a realistic layout. By starting a simulation run the planner can directly assess the improvements or deteriorations of the relocation of the resources. Differences between ideal and real layout are visualized. The simulation results are visualized by Gantt-charts, Sankey-diagrams and workload curves for each production stage. Figure 6 shows the structure of the integrated planning tool for the factory design for maritime structures.

## 5 CONCLUSION

The introduced planning methodology provides a solution to support factory design for maritime production facilities. The methodology concerns the specific requirements of factory planning projects in the maritime industry. To fulfill these requirements a combination of different approaches is introduced based on the type representative approach, material flow simulation and layout planning algorithms. The methodology is implemented into an integrated planning tool to support the planner during the factory design process. The following advantages are achieved by the application of the planning tool.

- Simplified compilation of production program scenarios without detailed product information in early planning phases by the application of a type representative database
- Straightforward generation of production system scenarios and dynamic analysis by the development of maritime modules in a material simulation environment
- Objective generation of efficient factory layouts by application of layout planning algorithms
- Reduction of planning administration by integration of dynamic capacity planning and layout planning in one software-environment
- Reduction of the degree of abstraction in early planning stage by application of interactive 3D layout planning

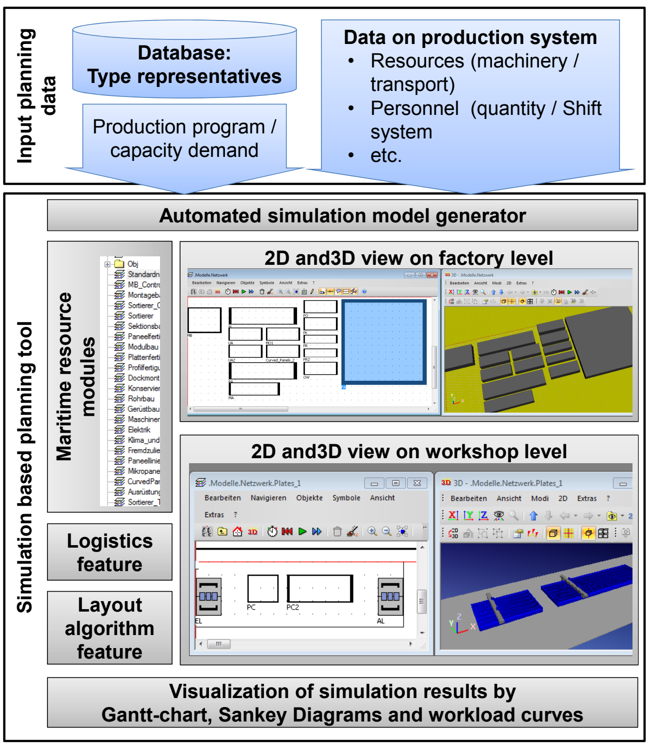


Figure 6: Overview on the integrated planning tool based on a material flow simulation system.

The application of the planning tool leads to a higher planning quality in the strategic factory design. The integrated tool also reduces planning time because it prevents frequent system changes.

The planning tool was developed and applied in factory design projects for maritime production facilities all over the world. The following research concentrates on the integration of additional layout algorithms. Here algorithms which take the flexibility into account will be focused. Future research also includes the integration of stereoscopic visualization in a virtual reality environment to further reduce the degree of abstraction in the layout planning. Another research topic is the diversification of the resource modules to fulfill the requirements of other industries.

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# Development of Lightweight Designs for the Production of Wind Turbine Towers

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**Abstract**

The usable wind energy increases exponentially by increasing the height of wind turbine generators. The material requirements and the tower weight increases disproportionately high by growing tower height. In current designs, the height of towers is limited. The application of lightweight design concepts in the production of wind turbine tower sections can lead to a reduction in the weight with the same tower stiffness. Therefore lightweight designs have great potential to increase wind turbine efficiency. In this paper, the results of the research for lightweight concepts and their implementation on towers and a guiding systematic approach are presented. As part of the research, design concepts have been developed. These design concepts allow the mass reduction, with constant stiffness, for the wind turbine towers on land (onshore). Several investigation loops of these lightweight designs were run. Different concepts of bionics, aviation, aerospace and automotive have been investigated for their suitability in wind turbine towers. A suitable concept was identified based on trapezoidal sheets. Using these sheets, the weight of towers can be reduced by 20 %.

**Keywords:**

Wind Turbine; Tower; Lightweight Design; FEA

## 1 INTRODUCTION

The next generations of wind turbines shall be built higher and higher. In higher layers of atmosphere, turbulences caused by ground roughness are substantially reduced, wind force increases and the wind blows more steadily. Energy efficiency grows exponentially with increasing height of the tower and a better energy yield is guaranteed. However, as soon as the mass of the construction reaches a critical weight, the towers of wind turbines are affected by buckling. As the tower mass increases quadratically with its height, the towers need to be disproportionately strengthened. Thus, the tower is the largest and heaviest part of a wind turbine and to a large extent responsible for the transportation and installation costs. The costs of the tower take up 15 % to 25 % of the total costs of a wind turbine project. These costs grow exponentially with increasing tower height.

The towers of wind turbines are currently manufactured in lattice mast, concrete, hybrid or tubular steel construction method [1, 2, 3]. Rarely used and only applied for small wind turbines are steel tubes with braced cables [4]. For the installation of steel lattice mast towers in comparison to other tower construction, more labour force is needed, which means, in conjunction with the high labour costs in Germany high installation costs. In addition, the design of steel lattice mast towers is currently controversial [4]. The pre-stressed concrete towers are glued on site from prefabricated segments with concrete resin mixture. In the manufacture of pre-stressed concrete towers all building materials are transported to the site and mixed at the building site. This concrete structure is dependent on environmental conditions and ultimately the accuracy of the design is limited [4]. The hybrid tower is referred to the combination of two different constructions [5]. Due to the low installation times steel towers are the most common tower design for commercial wind turbines [6]. Furthermore, there are alternative design approaches, which are still subject of research, however, they are still not produced or initially just built as test plants. On the one hand, a sandwich concept for wind turbine towers has been developed, which provides a tower structure with an outer and an inner tube. The core is filled with different materials, elastomer has shown itself as a suitable filler material between two alloy steels (e.g. S460) [7]. On the other hand TimberTower GmbH aims to build towers out of wood. With a timber frame and glued wood plates, heights of up to 200 m can be achieved. Previously only a 100 m high test tower was built [8].

Within the research project "Light weight construction of large-scale products using the example of weight-optimized tower segments" (LeiTu) at IPH – Institut für Integrierte Produktion Hannover, concepts how the towers of wind turbines can be built lighter and therefore higher are examined to gain the most possible energy output. The objective of this research was to reduce the mass of the towers without decreasing the tower's rigidity and to keep production and transportation costs in mind. The development of lightweight designs for the construction and layout of the towers was the most important aim of the project.

## 2 THE INVESTIGATION OF LIGHTWEIGHT CONSTRUCTION

With lightweight construction, special requirements must be observed. Security is one of the key represents, including loads, approval and construction regulations. With respect to the design of the lightweight constructions, there are other requirements in terms of materials and production technologies. These claims must adhere to certain criteria, such as mass, forces, material selection, etc. The basis for the design of lightweight construction is created by boundary conditions such as society, politics, law or markets. The principle of lightweight construction can be achieved using different strategies: Concept lightweight design, lightweight fabric, lightweight design and lightweight manufacturing supply. For the final research project concept, lightweight design was applied. The concept lightweight design examines a total or a partial system where suitable structural parts, components and modules are selected and adapted to the whole or the subsystem. Hereby the weight of the overall system is minimized. In the research project, the tower is considered as a subsystem of a wind turbine. The tower as a whole system includes, for example, components and modules, such as the front door, power transmission cable, lifts etc. For the research project, the main component of the tubular steel tower, the tubular

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element was selected. Up to now, lightweight construction of towers has not been fully investigated. However, in other industries, lightweight construction is already available, such as in automotive, aviation, aerospace and shipbuilding, where it is already the state of the art, and ideas and inspirations can be transferred to the wind industry.

Since the development of a lightweight design is in general a multistep process, several loops of conceptualization have been passed through. This means different approaches from bionics, aviation and aerospace as well as the automotive sector were researched and tested for their suitability to the wind turbine towers. All important factors such as forming behaviour, mechanical properties, weight reduction as well as advantages and disadvantages of the lightweight approaches have been documented. Various criteria in the lightweight concept design were explored which were created and developed with the CAD program Creo Parametric. The mass criteria (weight loss) and production (manufacturability) of the lightweight construction gave the final arguments for selecting the favoured lightweight structures. In the following different design approaches are described.

### 2.1 Bionical Design Approach

Bionics deals with the implementation of living natural principles into technology. The assumption implies that in nature (relatively) optimized structures where created through evolutionary processes. Practice shows repeatedly that intelligent designs are created based on natural principles [9]. Constructions from bionics, like shape and topology, enable optimization of components and structures. For this reason, forms following nature were examined in the research project. The result is the first favoured design approach: The artificial "Banana stalk". Based on the structure of a banana plant petiole, a technical structure was developed at the Fraunhofer Institute [10]. In practice this turns out to be stable and light at the same time (figure 1) [10]. The design approach "Banana stalk tower" is based on this structure. The main structural elements of this lightweight tower are the circular elements which are joined together by webs or ridges (figure 1). The idea was to achieve a stiffening effect in the tower by several interconnected related elements. Structural reinforcements are targeted through localized anisotropies, which help to increase the rigidity of a lightweight construction. The outside wall thickness corresponded to 8 mm and the inside wall thickness 5 mm. The outside-diameter of the tower was 5 m and the inside-diameter 4.4 m.

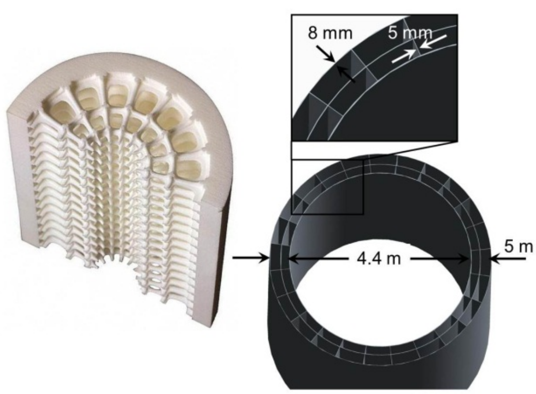



Figure 1: Left: Banana stalk (source: Fraunhofer Institut). Right: CAD-model banana stalk tower.

In order to achieve an optimum stiffening geometry, several models with different tower stiffening opportunities were created. Figure 2 shows some designed banana stalk variants. The idea of a combination of the banana stalk tower with a V-shaped stiffening originates from the metacarpal of a bearded vulture. Using tubular stiffeners, the largest possible moment of inertia or moment of resistance shall be achieved so to reduce the weight while maintaining stiffness. With hollow profiles, higher moments of inertia can be achieved than with solid cross sections. Each of the tower variants consists of about 16 segments, which, when combined, become a cylindrical tower. This provides the advantage of abolishing the limitation of the tower diameter due to transportation problems. Another advantage of a such constructed tower would be a smaller effort in the workshop production which has to be quantified in the future. However, the effort necessary at the construction site would rise. The idea was derived to form individual elements which are produced by wire extrusion in a manufacturing facility and then can be assembled to a tower at the construction site. The wire extrusion is a pressure forming process with pure compressive forces in all three directions of stress and is used for the production of solid and hollow wires, such as rods or tubes [11]. The materials that can be processed by wire extrusion are aluminium, magnesium, titanium alloys as well as hot stamping steels.

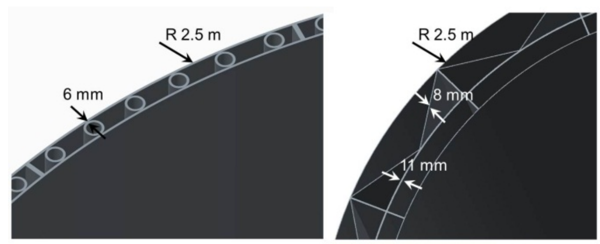



Figure 2: CAD-model banana stalk variants with a tubular (left) and a V-shaped stiffening (right).

Currently, in Germany, steel sections in the range of up to approximately 150 mm in diameter are produced. The minimum wall thickness is 3.5 mm [12]. The production of the profiles with steel is not possible since the constructed profiles have a diameter of about 600 mm. Due to the stated limits, the production of the profiles as shown in the extrusion process is only possible with great difficulty.

### 2.2 Design Approach from the Aviation and Aerospace Industry

Thin sheets can only maintain low resistance against deformations or instabilities. Analogue to the construction of an aircraft fuselage, constructive stiffeners like stringers and frames were examined during the research project. Stringers are longitudinal stiffeners which increase stiffness of large area components and prevent the bulging of these components. In aviation and aerospace technology, they form the supporting structure together with the frames (figure 3). The wall thickness of the stringer corresponded to 10 mm and the wall thickness of the outside sheet 5 mm. The outside-diameter of the tower was 5 m. The fuselage stringer construction is currently mainly applied in the automotive industry, but also in aerospace technology, and architecture, especially in the construction of large buildings.

The idea of structural stiffeners was transferred to the tower. The basic idea was to achieve stiffness of the steel sheets by installing stringers. Using stringers would minimize the thickness of the material. As a result, the total weight of the tower would be reduced, but the same rigidity maintained.

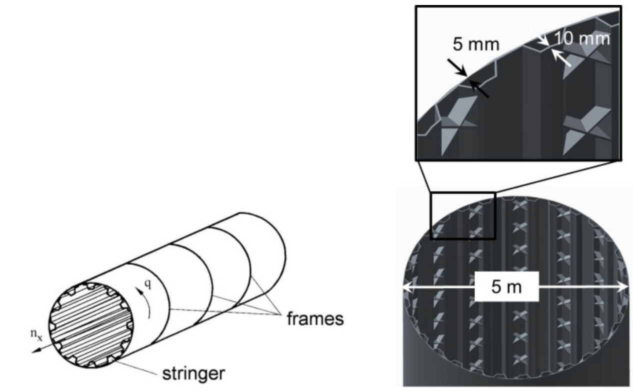



Figure 3: Left: Schematic representation of an aircraft fuselage [9]. Right: CAD-model stringer tower with stringers and a cross-shaped frames variant.

The stiffening effect essentially depends on the depth of the stiffening elements, whereby the following effects occur [9]:

- The line of gravity moves from the mid-plane of the sheet metal
- The moment of inertia increases disproportionately because of the dominant Steiner'schen part

As an example for the stiffening effect, the buckling resistance of metal strips is shown in figure 4. As shown in figure 4 KLEIN found significant deviations between theory and practice. This is due to the fact that, in the use of the theoretical estimate neither the sheet thickness nor the partial thinning of the feeder side of the metal strip has been considered. The buckling resistance of sheet metal can be expressed by the critical stress of the first eigenmode:

$$\sigma_{Bkrit} = k \frac{\pi^2 * E * J}{(1-\vartheta^2) * b^2 * t} \quad (1)$$

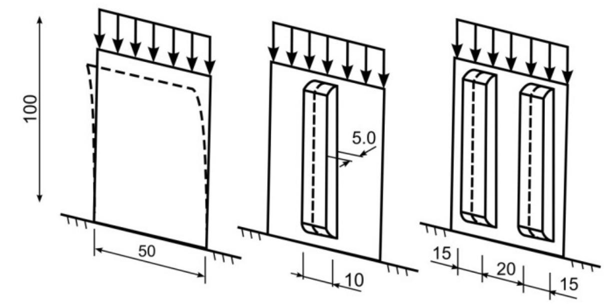
with: k = buckling value; E = elasticity modulus; J = moment of inertia; $\vartheta$ = Poisson; b = width; t = thickness

The equation shows that the moment of inertia J, along with other variables, has a decisive influence on the buckling behaviour.

Comparing an unstiffened metal strip and a stiffened metal strip, the influence of the stiffening elements are depicted in figure 4. As can be seen, there is a rise in the buckling resistance compared to the unstiffened sheet. For the development of a stringer, lightweight tower stiffeners (stringers) were created and brought together as the tower's geometry. Due to the complexity of implementing the straight elements, the tower was constructed with a constant diameter (cylindrical). The created CAD model is shown in figure 3. Since this tower has a higher mass than a conventional tower, it was optimized in terms of its weight and structure.

To ensure the manufacturability of the tower, material research was conducted. The goal was to find materials which ensure a later manufacturability of the stringer lightweight tower.

On the market, so-called trapezoidal sheets are available. These sheets were supposed to fulfil the function of the stiffeners and replace the stringer elements. The material used by the manufacturer is hot galvanized sheet steel grade S 320 GD + Z with a yield strength of 320 N/mm$^2$. The profiles are manufactured as standard with a thickness up to 1.5 mm; by special order, sheet metal thicknesses of up to 5 mm can be produced.




| | | | |
|---|---|---|---|
| theoretical | $\hat{\sigma}_{B_{krit}}$ | $\bar{\sigma}_{B_{krit}} = 5.3 \cdot \hat{\sigma}_{B_{krit}}$ | $\bar{\bar{\sigma}}_{B_{krit}} = 7.9 \cdot \hat{\sigma}_{B_{krit}}$ |
| in practice | - | $\bar{\sigma}_{B_{krit}} = 3.0 \cdot \hat{\sigma}_{B_{krit}}$ | $\bar{\bar{\sigma}}_{B_{krit}} = 4.0 \cdot \hat{\sigma}_{B_{krit}}$ |

Figure 4: Influence of the stiffening elements of the critical buckling stress [9].

In the research project, two different profiles of one manufacturer were examined for their suitability for the tower construction. The construction is based on the geometric data of the trapezoidal sheets. This geometry is transferred to the radius of the light tower, figure 5. Thus, the tower has been constructed with a diameter of 5 m and a wall thickness of 20 mm. The sheet thickness of the trapezoidal sheet was 5.5 mm.

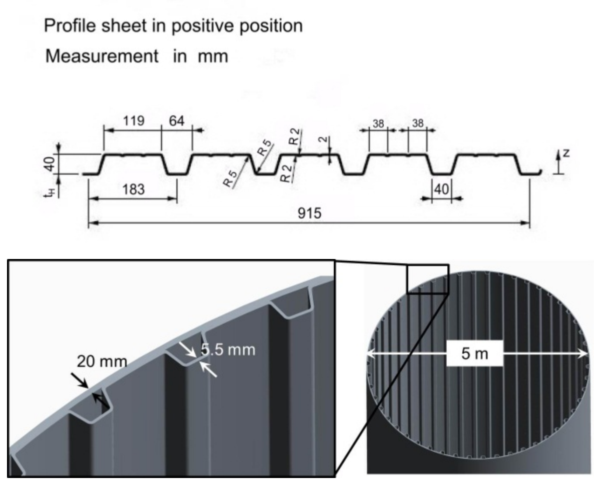



Figure 5: Top: Trapezoidal sheet T40.1 [13]. Bottom: CAD-model trapezoidal tower.

## 3 FEA-MODEL AND RESULTS FOR REFERENCE PLANTS

To evaluate the developed tower concepts, the REpower 5M was chosen as reference plant. This plant was the highest tubular steel tower with a hub height 120 m at the time of the investigations.

In the project a model was developed that describes the stiffness of the tower, in correspondence with the attacking load profile based on the load collective of the reference plant. To determine the strain on the tower segments adequately, the simulation software ANSYS, that is based on the finite element method, was used.

The model has been simplified for the finite element analysis and the plant was divided into the three main components: rotor

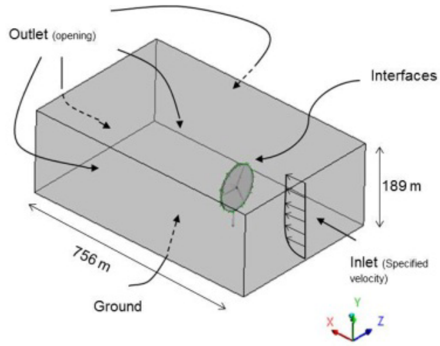



Figure 6: CFX model with boundary conditions.

including hub, nacelle and tower. From this, an FE-model was created. The IEC61400-1 provided the basis for determining the wind forces in the fluid simulations.

In figure 6, the flow mechanics in the ANSYS CFX-model are shown, including the boundary conditions: inlet and outlet area of the fluid, open areas of the model, boundary condition of the model and the interface between the two flow fields blades and environment.

In ANSYS CFX, the relevant wind models obtained from the IEC standard were used on the investigated reference system as input data for the simulation, simulated with fluid mechanics and from there the wind forces on the tower were calculated.

For observing the wind height profile of the plant, the normal wind profile model (NWP) was selected according to IEC 61400-1 as an input to the simulation as follows:

$$V(z) = V_{hub} * (\frac{z}{z_{hub}})^{\alpha} \quad (2)$$

For the simulation of turbulent extreme wind speeds, the model extreme wind speed (EWM) was selected:

$$V_{e50}(z) = 1{,}4 * V_{ref} * (\frac{z}{z_{hub}})^{0{,}11} \quad (3)$$

$V_{e50}$ describes the expected extreme wind speed within 50 years. $\alpha$ is the height exponent for the logarithmic wind profile, $z_{hub}$ corresponds to the hub height and $V_{hub}$ to the corresponding wind speed. The reference wind speed is marked as $V_{ref}$. For the design of the towers, the IEC standard requires, the use of so-called security classes. The partial safety factors for these classes are agreed between manufacturer and customer. To calculate the actual loads of the wind turbines, the flow simulations were performed without regard for the safety classes.

To calculate the total load of the tower, the results from the fluid simulation were imported into the structural mechanics simulation and with this, the loads caused by the wind were transferred to the structure model. For the structural mechanics simulation, the weight of the entire system (rotor, nacelle and tower) was added. The calculation of the deformation and the stress of the tower resulted in the total load on the tower. The results of the calculation for the first reference tower show that the maximum stresses occur at the base of the tower with 86 MPa. The maximum deformation is observed at the top of the tower and is 531 mm.

To validate the developed lightweight construction, a second reference plant was selected. The industrial partners provided real wind loads on the turbine with a hub height of 90 m as well as the technical data of the plant, such as the diameter of the tower, the tower shell thickness and the weight of the main components (second reference tower). The model for the simulation of the second reference system was created on the basis of the available design data which was imported into ANSYS with appropriate boundary conditions (loads, supports, etc.). Since for this plant the wind loads and weight loads at the tower head were already known, only structural analyses were carried out. The second reference tower with a 90 m hub height weighs 220 tons and had a maximum stress of 141 MPa. The maximum deformation is 556 mm.

### 3.1 Accomplishment and Results of FEA

The three presented design approaches have been implemented in the Creo Parametric CAD software and optimized by iterative simulation loops, varying the design parameters based on the evaluation criteria weight reduction and appropriate load.

Each design approach was tested structural-mechanically. To speed up the simulation time, only a 10 m high tower segment was investigated. The used load was the wind load determined from the CFX calculation. Here it was assumed that the tower experiences extreme wind loads (worst case); these are the maximum loads that the tower must withstand. The three design approaches were finally assessed in regard to the stresses and deformations as well as the reduction in weight. Then the most suitable design was selected.

The simulation of the banana stalk tower showed a total weight of 404 tons, a deformation of 6 mm and a maximum stress of 173 MPa. The results of the stringer tower showed a maximum deformation of 12 mm with a maximum stress of about 140 MPa. This tower has also a total weight of 404 tons. The simulation of the trapezoidal tower showed a maximum deformation of 9.5 mm. The maximum stress reached a value of 111 MPa, which is a multiple of the reference tower. A total weight of 400 tons was achieved.

In Table 1, the simulation results of the three presented lightweight construction and the first reference plant, the REpower 5M (120 m hub height), are summarized. The stress values of the banana stalk tower do not exceed any critical factor in the design of the towers, but are higher than the stress levels of the reference tower. This approach has, in addition, a higher deformation. Therefore, this approach was not followed further. The simulation results of the stringer tower show a higher overall deformation of the tower compared to the trapezoidal tower. The trapezoidal tower does have higher stress levels, but the weight reduction potential of this approach is much better, compared to the other two lightweight concepts.

| Designation | Max. Stress at 120 m [MPa] | Max. Deformation at 10 m [mm] | Weight at 120 m [t] |
|---|---|---|---|
| Reference tower | 86 | 5 | 540 |
| Banana stalk tower | 173 | 6 | 404 |
| Stringer tower | 140 | 12 | 404 |
| Trapezoidal tower | 111 | 9.5 | 400 |

Table 1: Comparison of the results of the first reference tower with the presented lightweight designs.

Next, this lightweight concept was calculated as a whole tower with a hub height of 90 m after consulting our industry partners. For validation, the selected concept (trapezoidal tower) was created as an entire tower with 90 m hub height using the Creo Parametric CAD program. Then, a finite element model of the trapezoidal tower was created, based on the stresses of the second reference system and evaluated with structural mechanics. This tower variant has a weight of 176 tons. The maximum stress is 105 MPa and the deformation is 666 mm. The trapezoidal tower has a stress that is below the permissible stress of construction steel and is also somewhat lower in comparison with the second reference plant. As shown, we have developed a tower concept which shows a weight reduction while maintaining rigidity. The developed lightweight concept can reach up to 20 % material savings compared to conventional produced towers.

## 4 PRACTICAL IMPLEMENTATION POSSIBILITIES OF A LIGHTWEIGHT CONCEPT

For the production of a lightweight trapezoidal tower, different structural elements (external leaf and trapezoidal sheet) are required. Because of this, the connection technology is of great importance and should be investigated in further research projects. Here we have only listed the theoretical possibilities of the joining technology of the lightweight trapezoidal tower, and mechanical strength, the parameter limits and the long term behaviour of the compound are of interest. For the production of the trapezoidal tower, the trapezoidal sheets need to be connected to the external skin sheet. The trapezoidal sheets should reduce the bending of the lightweight tower or increase the load bearing capacity. The installation of the trapezoidal sheets on the steel tube could be done by gluing, welding, riveting and mechanical joining operations. However, the question arises whether to join the sheets before or after the round rolling of the tower. With metal gluing only low temperatures are necessary, so that thin sheets can be connected without tension and contortion. With welding or soldering, in contrast, significantly higher temperatures are required, which lead to structural changes. A relatively high static and dynamic load capacity can be expected with an adhesive connection, as the stress can be distributed on the entire surface. Despite the aforementioned advantages of the adhesive joint, it is always necessary to analyse the specific compound ratios, because the quality of the connection is determined by many factors [9]. Other option of joining operation could be hole- and tapping screws. Both techniques allow a force and form-fit connection without work-intensive component preparation. The connection could be produced with one-sided accessibility. A calculation of a suitable connection technique has to be consider in future research projects.

## 5 SUMMARY / OUTLOOK

In wind energy harvesting, higher energy yields can be achieved with greater hub heights. With increasing tower height the material requirements and the tower weight increases disproportionately. The towers are limited due to their current construction in height. The application of lightweight design principles in the production of the tower sections of wind turbines can lead to a reduction of the weight with the same stiffness of the towers. Therefore, lightweight designs have great potential to increase wind turbine efficiency.

As part of the research project design concepts have been developed. These design concepts allow the mass reduction, with constant stiffness, for the wind turbine towers on land (onshore). Different concepts from bionics, aviation and aerospace as well as the automotive industry have been researched and tested for their suitability to the wind turbine towers.

From bionics a banana stalk structure was transferred to the tower. From aerospace technology, a concept originated with stringers of an aircraft fuselage, which were selected as structural stiffeners and transferred to the tower. As optimization of the second approach, trapezoidal tower as lightweight concept was developed. Here, trapezoidal sheets were used as a constructive reinforcement to the tower. The developed tower constructions were analysed concerning the highest stress value and the largest deformation of the tower.

To evaluate the lightweight concepts two reference plants were selected and simulated by finite element analysis.

For each of the loads of the first reference plant (120 m hub height) the structural mechanics of the design concepts were investigated. To accelerate the time of simulation the structural mechanic of a 10 m high tower segment was investigated, instead of a complete plant. The calculated wind load from ANSYS CFX was here used for mechanical analysis.

To validate the developed lightweight concept, a FE-model was created and the trapezoidal tower investigated based on the real wind loads of the second reference plant (90 m hub height).

The simulation results showed that a 90 m tower can endure the loads with the developed lightweight concept. With the trapezoidal tower a weight reduction of up to 20 % can be achieved compared to a 90 m tubular steel tower. In further research activities, the developed lightweight trapezoidal tower should be developed further and optimized with respect to sheet thickness, sheet profile and use of other steels, such as high-strength steels.

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# Method for Planning a Changeable Press Plant

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**Abstract**

Today producing companies are facing an unpredictable and unstable market situation. Because of the strong customer orientation in the consumer goods industry, the Miele & Cie. KG is also affected by these incidents. The results are an increasing number of variants and a shortening of model life cycles. To ensure the long-term competitiveness, adapted strategies must be developed. A major challenge arises, particularly for press shops, because of the distinct difference between the constant long life of press systems and the decreasing model life cycle of the manufactured products. As a basis for the planning of a new press system, only the data of the current production and the next generation are available, which covers a time period of about ten years. The subsequent type of use of the press and the related requirements for the following 20 – 30 years cannot be planned. To ensure the sustainable planning of press shops, a holistic methodology is developed which involves the aspects of changeability. This includes the selection of the press system with appropriate press drive, tool change, transfer, etc. Further aspects like choice of site, assembly and material flow are considered.

**Keywords:**

Press Shop Design; Changeability; Production System

## 1 INTRODUCTION

Today the companies in the home appliance industry in Germany are facing an incalculable and unstable market situation. In addition to unpredictable influences, like the financial and economic crisis, the ongoing globalization, limitations of resources and increasing customer requirements have an effect to the business. Due to its strong customer focus the Miele & Cie. KG notices these repercussions. Therefore, methods must be developed to ensure the long-term competitiveness.

The Miele & Cie. KG is one of ten partners in the research project WamoPro* – “Changeability by a modular design of production systems” (duration 2010 to 2013). The objective of the research project WamoPro is an instrument for the planning of a changeable production system. The production systems of the different companies are structured, modularized into specific modules of the dimensions technology, organization and personnel and finally synchronized. In this way, the changeability of the distinct divisions ought to be strengthened in order to achieve a fast and cost-efficient solution for the current market situation.

## 2 IMPACT ON THE PRESS SHOP

To maintain the efficiency of a press shop, the running costs have to be minimized. This refers to both the production as well as the investment costs for the production of the current and future products. For this reason the adaptable oriented selection of press systems for the production of future product-generations is crucial in the sheet metal industry. As durable used goods, presses represent a particularly high investment. While the life cycles of the models are getting shorter and shorter for every product generation, the useful life of press systems remain constant. A press system for housing components of washing machines produces 30 until 40 years (Figure 1).

As a basis for the planning of a new press system, only the data of the current and the following product generation are available whereby a maximum time horizon of ten years is covered. The subsequent type of use and the associated requirements in the following years cannot be planned. Therefore, the dimensioning of the system presents a challenge to the selection of a new press system. If the planning of the plants is designed only on the basis of currently known requirements, the optimal use throughout the working life is unlikely. This leads to restrictions of the product development in terms of the component geometry.

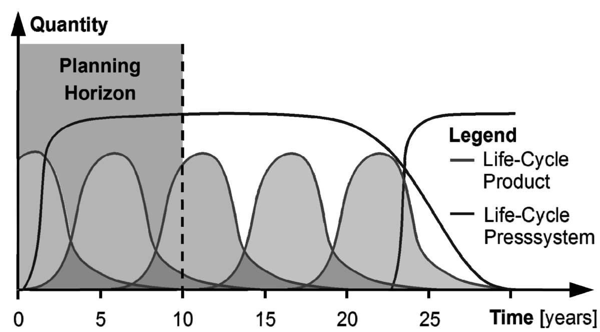


Figure 1: Comparison of the life cycles of products and press systems.

For this reason it is absolutely necessary to create changeable press systems. The changeability in this case is defined as the ability of the system to adapt to the requirements of a turbulent environment that are not necessarily foreseeable. The potential of the changeability is composed of flexibility and the responsiveness of the system [1].

## 3 STATE OF THE ART

The planning of press plants must be done with a holistic approach, combining and synchronizing the organizational and personnel structures as well as the adaptable utilization of the technology. Today, there is no integrated planning method for the press shop design, which includes the aspect of changeability. The “Process-oriented planning-cascades in the field structure of a press shop” described by Baur provides a holistic planning approach. The three cascades strategic/concept phase, project management and weakpoint/efficiency analysis are passed for the replanning or

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restructuring of a press shop [2]. In this way, the production planner will be assisted with the application of the planning process, but the changeable orientation for the production of future product generations is ignored. Gloßner makes another contribution with an integrated methodology for the replanning of press plants in the automotive industry. The aim of this method is to determine technical feasibility and the costs of parts for the planned products consistently in an early phase of the vehicle development. A consideration of strategic and long-term planning in terms of adaptability does not take place [3].

A scientific discussion of the described discrepancy of the product and equipment life cycles provides the analysis of technology, production structure and plants in the SFB 768 “Managing Cycles in Innovation Processes”. The focus in the development of solutions to counter this problem is the increase of the innovation capability of manufacturing equipment [4] [5].

So far the described approach to increase the changeability in press shops refer exclusively to the technical aspect to extend the production range of the several working stations. In this context the use of modular and standardized tools or the exploit of the potential of the servo press technology is prioritized [6].

## 4 PRESS SHOP DESIGN

To create the procedure model for the press shop design in terms of changeability the essential approach of the joint project of WamoPro is used. Here the studied production system is divided into company-specific modules of the dimensions Technology (T), Organization (O) and Personnel (P). Afterwards follows the synchronization and reconfiguration that is required by the current situation with a functional production system as a result.

As a superior structure, the phase model of the factory planning process described in the VDI guideline 5200 [7] was selected, as shown in Figure 2. This process is organized into seven phases, covering the entire process from the definition of the objectives through to the initial support of the production unit. For the individual phases the press shop specific objectives, contents, planning tools as well as the input and output data were defined. As a major sector of influence for the observance of changeability the first three phases were identified. The next steps deal with the detailing and the implementation. The degree of changeability is already set at this point.

In the following the three major planning phases are briefly outlined with their respective input and output data and subsequently the planning of the concept is examined in more detail.

### 4.1 Setting of Objectives for the Press Shop Creation

Following the approach of WamoPro the planning process is always initiated by a change trigger, see Figure 3. This corresponds to a pulse on the observed production system and is caused by external influences, such as sudden fluctuations in orders, or internal factors, such as a new strategic direction of the company. Strategic issues can be the production of new parts, modernization or the overall increase of changeability. Based on the particular pulse it is necessary to derive the associated targets for the press shop.

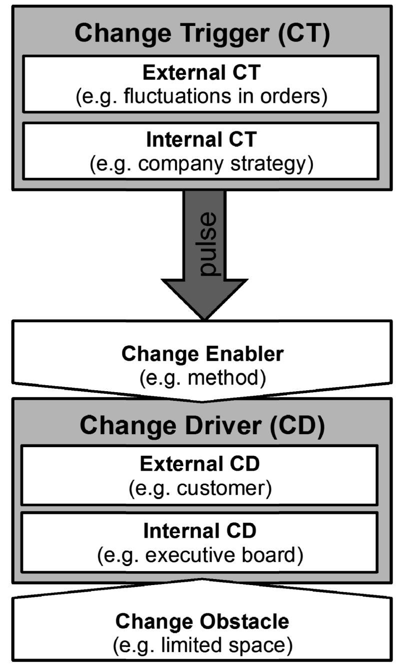


Figure 3: Factors of changebility.

The objectives of the current factory planning were defined by Wiendahl in the different target areas of economy, flexibility, changeability and attractiveness [8]. For the planning of internal press shops, the economics are particularly emphasized because the large investments over a long period have to pay off compared to external service providers. The flexibility is understood in relation to the press shop as the ability to adapt to the known short to medium term changes of the product spectrum, for example fluctuation in sales or pre-planned variants. The scheduling of the changeability of the system goes beyond these requirements and pursues the integrative approach to consider the future challenges of the press shop at an early stage. The optimal degree of changeability must be defined and thus leads to an awareness of the planner for the future-oriented design of the project objectives. The result of the phase is the detailed formulation of the project objectives with respect to the operation fields T-O-P including the budgets and schedules as well as the degree of changeability.

### 4.2 Establishment of the Project Basis

The formulated project objectives are used as input for the establishment of the project basis to identify the current situation. According to the objectives, an analysis of the affected system sectors is estimated. Depending whether the project implies a

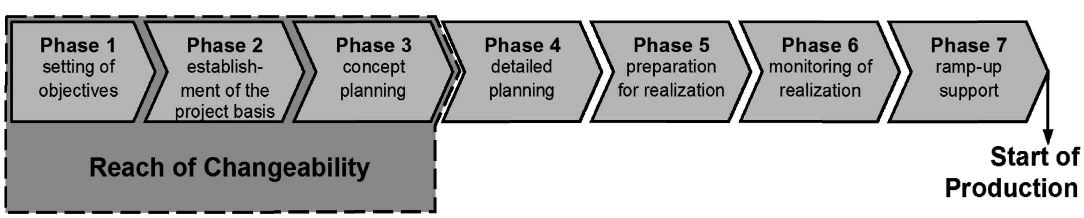


Figure 2: Phase Model of the factory planning process.

replanning or an optimization the results of the different forms of analysis are weighed. The four basic analyses are the feasibility-, the operational-, the market- and the changeability analysis [9] [10].

The **feasibility analysis** can be performed in different ways based on the elaborated objectives. If, for example, the target is to test the production of a new part or a variant, a rough method plan for the tools is created. Based on this data, a capacity check and a cost evaluation for the integration of the new part in the existing production system can be made additionally. If the integration is not possible the target must be achieved by replanning or reconstruction.

The **operational analysis** is also highly dependent on the selection of the targets. In particular, the actual status of the dimensions organization and personnel is required in this case. Statements about the current production program, production sequence, material flow, personnel structures and the available plants provide information on the implementation effort to achieve the desired objectives. Tools and instruments for the analysis of facilities, employees as well as product and process data are provided by Aggeteleky, Pawellek and Schenk [9] [11] [12].

The **market analysis** includes the study of available technologies in the sector of press plants. It will take into account the developments of the individual components of presses, and new organizational approaches. Consultation with suppliers and service providers as well as continuous monitoring of the market by means of periodicals or trade fairs provide the necessary input.

A changeability analysis must take place particularly for the reconstruction. In this way, a balance between the changeability targets and the current status of changeability of the existing system can be estimated. The detected difference is an indicator of the degree of changeability that the developed concepts should provide. The evaluation is based on Hernandez Morales [13].

As a result of the phase, a report that contains all the relevant framework conditions according to the defined objectives emerges. On this basis, the project effort can be estimated. Furthermore, a specification for the transfer to potential suppliers can be derived.

### 4.3 Conception of Press Shops

The conception is divided into six steps (Figure 4). After establishing the requirements the planning section has to be defined, which determines the level of abstraction of the project.

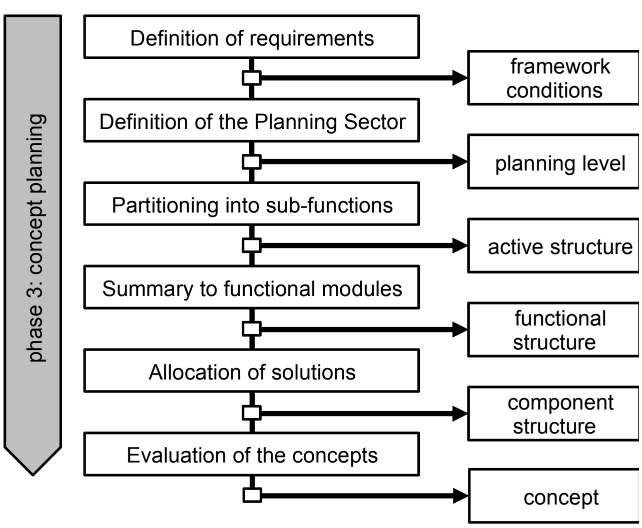


Figure 4: Concept planning.

In the next step, the respective production process is subdivided into its sub-functions. By systematizing the press shop components into functional modules, partial solutions can be assigned that in combination result in holistic concepts. A final evaluation of these concepts leads to a decision.

**Step 1: Definition of requirements based on the objectives and framework conditions**

As criteria for the selection of forming equipment, Doege quotes three main categories: product requirements, market needs and legal claims [14]. For the changeable design of the concepts future-oriented aspects must be supplemented (Figure 5).

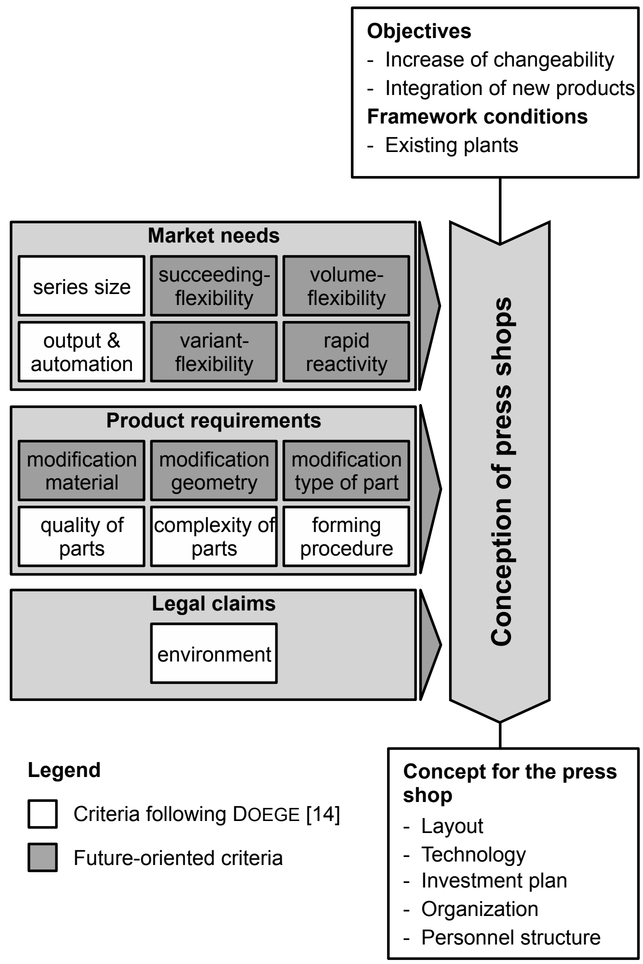


Figure 5: Requirements for the conception of changeable press plants.

Thus, in addition to the product requirements of the current generation, the possibilities for modifications of the material, the geometry and the type of product are directly considered. The appropriate limits of these adjustments need to be worked out with the product development. The market needs go beyond the current planning for the size of the series and the output and have to provide additionally a volume and variant flexibility in combination with rapid reactivity. Furthermore succeeding flexibility that describes integrative capacity of the production process to adapt to future product requirements is required.

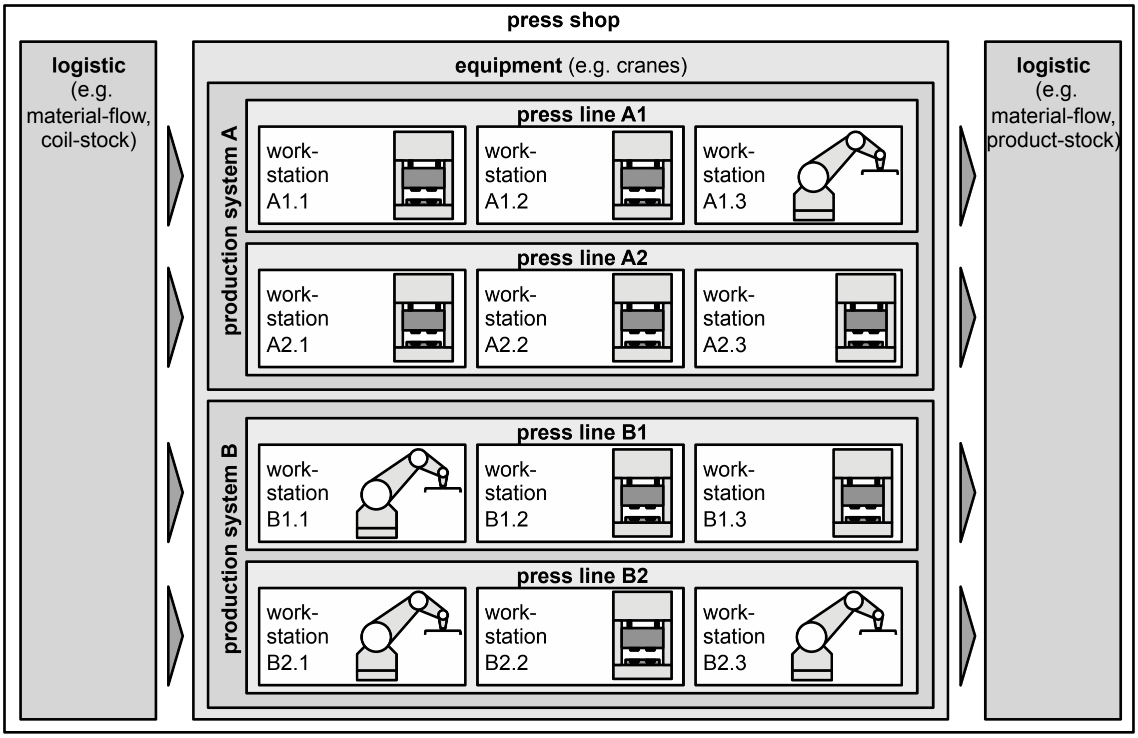


Figure 6: Phase Model of the factory planning process

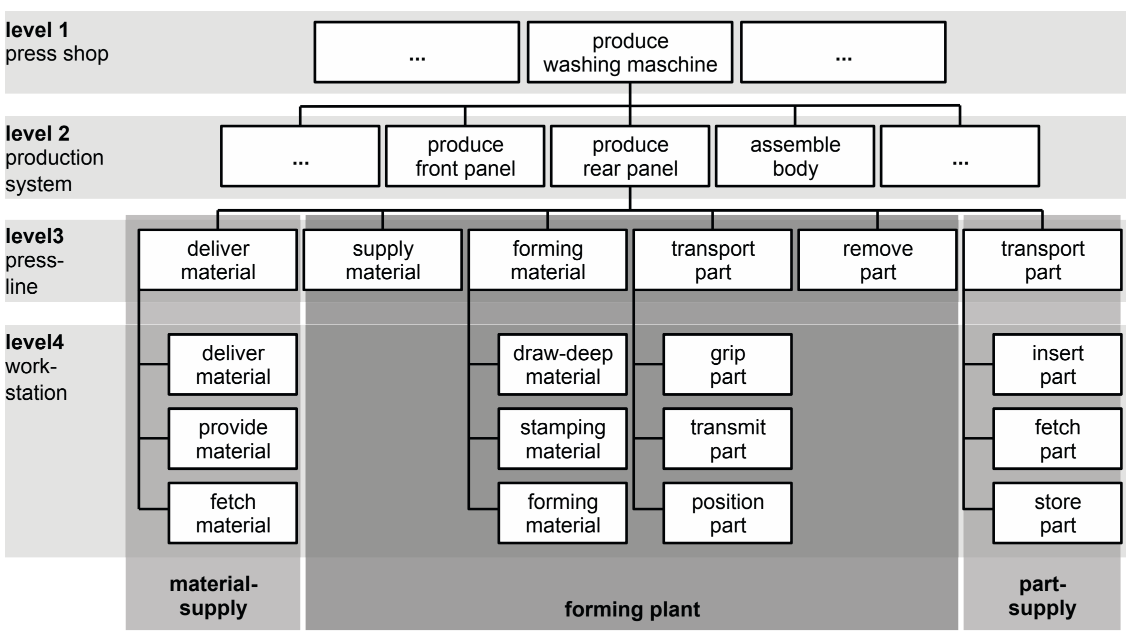


Figure 7: Structure of a production system into sub-functions using the example of the rear panal production for a washing maschine

**Step 2 : Definiton of the Planning sector**

The identification of the planning sector is determined by the structure of the press shop (Figure 6). A press shop consists of different production systems, which are composed of single press lines with workstations, such as individual presses or transfer systems. Also a combination with special purpose plants, like bending maschines as workstations is possible. The equipment, such as cranes or forklifts, is comprehensively associated to the production system. Furthermore the logistic divisions are connected to the production system to control the flow of material from the raw materials (coils or blanks) to the plants and the transporation of the finished parts to the subsequent areas. Modelled after Schenk, this structure can be transferred into a hierarchical level model (Figure 7) [12].

**Step 3 : Partitioning into sub-functions**

The production process is divded into sub-functions according to the level classification, which in their entirety depict the production procedure. Figure 7 shows a simplified example of a rear panel production for a washing maschine. At level 3 of the press line, the sub-functions are listed in solution-neutral manner along the material flow. From the delivery of the material, via the supply and transport within the plants, by the different forming stages up to the removal and the transportation of the finished parts, the sub-functions are identified. At level 4 of the workstations a further detailing is performed.

**Step 4 : Summary of the sub-functions to functional modules**

Subsequently follows a allocation of the sub-functions at the various levels to the functional modules. These functional modules describe the summary of sub-functions to holistic production units, as in the example of the rear panel prouction the forming line. Further functional modules in this case are the material and part supply. The functional modules can be further decomposed depending on the application [15].

**Step 5: Allocation of solutions to the function modules**

To proceed to the next step to assign solutions to the identified functional modules, it is necessary to further subdivide them. For the example of the forming plant a systematization of the press components is performed. In accordance with the sub-functions at level 3, the corresponding components are assigned. As shown in Figure 8 a press line basically consists of four main components: feeder (material in), press (material forming), transfer (part transport) and output device (part out). The change of perspective from the functional to the plant site allows a further disassembly of the components. In this way the press system can be further divided into its subsystems like press drive, tool changer, press frame, etc.

Due to the systematic partitioning of the production units into its individual components, an assignment of partial solutions is made possible. As simplified in Figure 9, the solutions can be listed in a morphological box. Apart from the technological, organizational and personnel modules can also be added to this morphology. The solutions are on file in a library, which is kept current by a continuous operating knowledge management. The creation of the different concepts is done by selection of the individual partial solutions that have been previously examined for consistency.

This example shows the creation of two different concepts. The choice of a hydraulic press line which is connected via a rod transfer with vacuum spiders and which has no additional interfaces results in a very rigid design. This configuration leads to a concept with which only products can be produced that require six tool stages and can be transported with the given vacuum spiders. This concept, however, is cost-effective and space-saving. Concept two is more changeable. With the help of servo-drives, various force profiles can be utilized and the robots with interchangeable vacuum spiders can transport a wider range of portable part geometries with a small transfer period. Because of the two additional interfaces as a result of the U-installation of the presses, the presses can be used in a flow path with six stages or parallel as two individual presses and a line of four. In this manner, the press plant can be used for small as well as for large or complex parts.

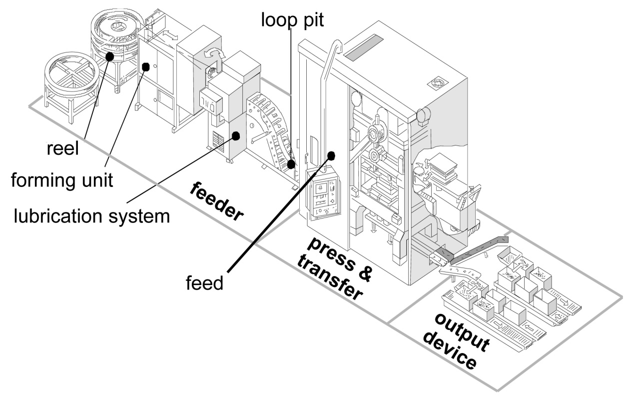


Figure 8: Systematization of press components following [15].

**Step 6 : Evaluation of the concepts regarding the rquirements**

To determine these differences and the fulfillment of the objective criteria the concepts are analyzed in accordance with the requirements and evaluated by a efficiency analysis. The nominal/actual comparison in terms of changeability is based on the evaluation scheme of Hernandez Morales and will be integrated into the efficiency analysis [13].

## 5 SUMMARY

As a part of the joint project WamoPro, guidelines were developed which allow a structured approach for the planning of a press shop in terms of changeability. The objectives and framework conditions for each project are identified and subsequently conduce as input data for the conception. By systematizing the press shop into functional modules, partial solutions can be assigned, which in their combination lead to different concepts.

To increase the efficiency of this approach, the existing partial solutions will be cataloged and evaluated with regard to their ability to change. Furthermore, an evaluation methodology has to be developed that describes the degree of changeability and thus permits a nominal/actual comparison.

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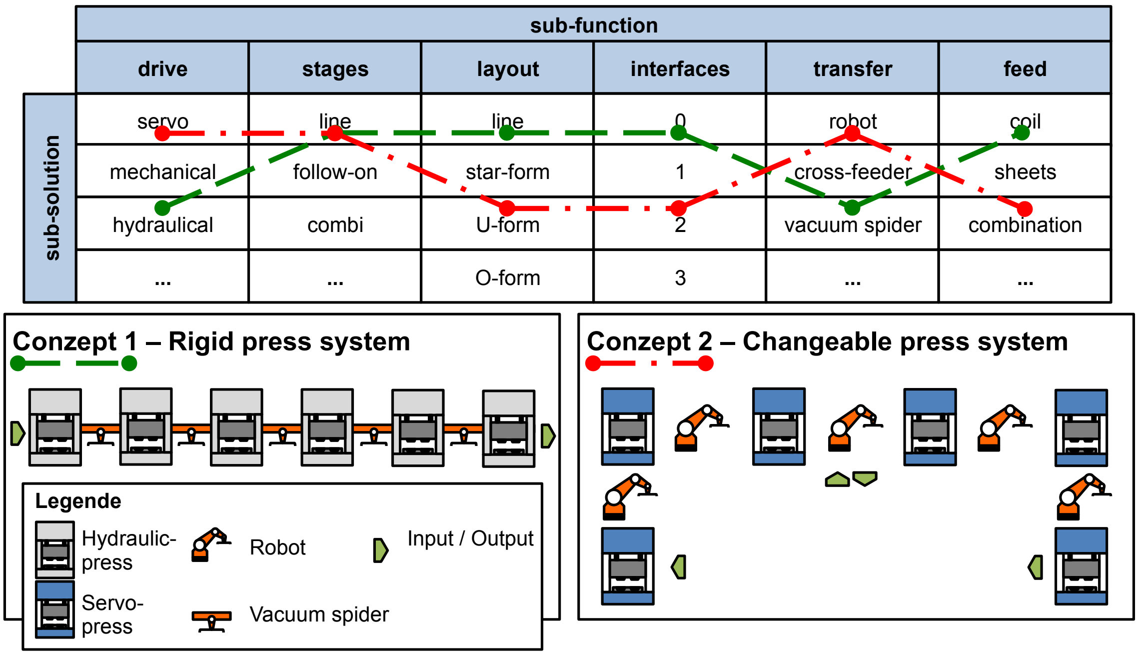


Figure 9: Simplified representation of the concept development by the morphology

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# Reconfigurable Manufacturing System Design and Implementation – An Industrial Application at a Manufacturer of Consumer Goods

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**Abstract**

Reconfigurable Manufacturing Systems (RMS) have been an increasing area of interest in the research arena. However, it seems that current literature is lacking application and implementation cases where RMS are simulated, tested, and evaluated as a feasible manufacturing concept. A Manufacturer of Consumer Goods identified the potential of the RMS concept and decided to investigate the concept in a real production installation. The result of this development is a proof of concept of a changeable and reconfigurable assembly and decoration system based on the principles of RMS. This proof of concept is meant primarily to show the physical feasibility of the system and provide a first-look into a real production application of the RMS ideas. The purpose of this paper is to present the design of the manufacturer's RMS proof of concept, its implementation, and evaluation results.

**Keywords:**

Reconfigurable Manufacturing Systems; Assembly Systems; Proof of Concept

## 1 INTRODUCTION

As a direct result of global competition and turbulence in the market, manufacturers face several future challenges such as: 1) unpredictability and frequent market changes, 2) varied product demands and accelerated product introduction, and 3) a greater push for more highly customized products etc. These challenges are consequences of strong global competition, higher demands from customers, and hastened changes in both product and process technology [1]. In order to have competitive advantage, manufacturers must meet market changes with fast responses as well as continue to deliver high-quality products cheaply. However, because of their lack of flexibility and throughput, traditional manufacturing systems such as dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS) are unable to manage rapidly changing situations in a cost effective fashion. In order to accommodate rapid and various changes cost-effectively and productively, a new manufacturing approach is required [2] [3].

Koren et al. (1999) defines a reconfigurable manufacturing system (RMS) as a system which is "designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements." Simply, the objective of RMS is to provide exact capacity and functionality at the exact time it is needed [2].

Having recognised the potential of the RMS concept, A Manufacturer of Consumer Goods (MCG), chose to investigate the concept within a real production setting. Though several examples of the RMS concept do exist, none of them were designed and tested in an industrial application. The result of the investigation is a proof of concept of a changeable and reconfigurable assembly and decoration system based on the principles of RMS. The primary role of the proof of concept was to illustrate the *physical* viability of the system and provide a glimpse into applied RMS ideas within production. In addition, a simulation model was developed to simulate the logicalness of the proof of concept including material flow and productivity. Using the simulation as a base, several scenarios were developed and simulated to further validate the proof of concept.

The drive of this paper is to present MCG's RMS design of the proof of concept including its implementation, and further thoughts on evaluation and results. The paper will present a first-time production application of RMS, several design repercussions, challenges, and developmental potential in order to achieve physical feasibility of RMS manufacturing concept and consequently creating a preferred method for future manufacturing and manufacturers.

Due to its large scale of production, constant need of adaptation, complexity of supply chain, volume and high need for customisation within production and products, MCG is a valid and strong case study within the field of RMS.

## 2 RMS DESIGN

There are three phases within the design and operation of a reconfigurable system. First, the system is constructed of standard modules with specific functions. Each module has particular physical and information interfaces, which provide opportunities for combinations with additional modules or control via external resources. Second, the system subsists in a particular configuration and the variables of configurability and assembly selections are determined wherefore a system configuration is constructed with the selected modules. Third, configuration of the system is commenced. In order for the system to exhibit the required behaviour and accomplish the desired tasks, control variables are manipulated of the adjustable components until the desired function is displayed. Once tasks are complete, the system is able to be dismantled and the modules are equipped to be reassembled and reused for upcoming tasks [4].

Three important design issues of RMS include: architecture design, configuration design, and control design. *Architecture* design defines both the components and interactions of the system which begins in the system design phase. System components refer to the encapsulated modules whereas the interactions are the modules' assembly options. To ensure the system can handle change and uncertainties cost-effectively, the design of the system architecture should include as many system variants as possible. These variants are defined by both the system components and their subsequent interactions. *Configuration* design dictates the configuration of the system within the system architecture for the particular task, and it is implemented during the system application phase. A configuration is the assembly of selected modules to optimize completion of given tasks. *Control* design helps to define the necessary and appropriate

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process variables in order to enable configurations to be operated successfully to accomplish tasks and is involved in the system operation phase [4].

An applied scenario of an RMS was illustrated by Bi et al., 2007 in Figure 1, in which both a reconfigurable hardware system and a reconfigurable software system are involved in the system. The hardware system includes reconfigurable machining, fixturing, assembly, inspection or calibration, and material-handling systems. The reconfigurability in these systems is at the machine or cell level, though some systems embody reconfigurability at the factory floor or the manufacturing level. The objective is to supply variable products, thus the various system components and interactions are determined in the architecture design to support the primary aim. Constraints of the architecture design must also be taken into account, which derive from applications of operating RMS. The subsequent design complexity relies on system level, change requirements and uncertainties [4].

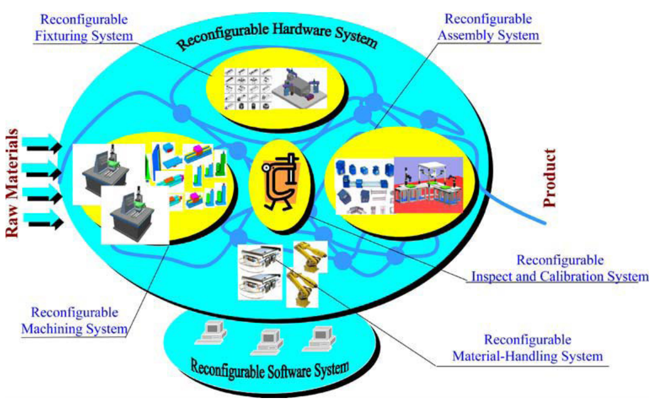


Figure 1: An application scenario of an RMS [4].

### 2.1 Changeability in Assembly Systems

Wiendahl et. al. (2007) discuss changeability and flexibility's classes, objectives, and enablers in order to elaborate on the terms changeability, flexibility and reconfigurability, and further discuss these affects on assembly systems [5].

*Changeability Objectives for Assembly*

There are five types of flexibility in assembly systems: routing, operational, changeover, conversion, and failure. These types of flexibility can be grouped by three characteristics: Date-oriented flexibility: relates to events that occur in the system quite often. This flexibility requires flexible routing, in order to change the material handling structure of a line, and flexible operations in order to fit specific operations to the required product with a short changeover time. Period-oriented flexibility refers to a characteristic that is needed on a longer time horizon. This flexibility referrers to the changeability and reconfigurability of the system (changeover flexibility) for rapid changes, and require conversion flexibility when whole lines or stations have to be changed. Incident-oriented flexibility is an ad-hoc characteristic and relates mostly to failures in the system, hence failure flexibility is needed to minimize downtime and idle time [5].

*Changeability Enablers for Assembly*

In addition to the enablers of RMS, two changeability enablers can be added when discussing assembly, namely mobility and flexibility in automation. Mobility refers to the ease of transporting modules and elements of the system or even moving the entire system, and is a crucial part in the reduction of changeover time. Flexibility in automation enables the operators and planners to determine the right level of automation needed in the system in order to perform a certain action. Automation can be upgraded (an increase in automation) or downgraded (a decrease in automation) in order to fit a product or a location of production [5].

### 2.2 Design of Reconfigurable Assembly Systems

According to Koren and Shpitalni (2010) there are two main steps in product manufacturing: 1) fabrication of components (e.g. injection moulding), and 2) assembly. By fixing a part and mobilising it through the system, operations are being performed and a finish product is produced. The modular structure of a reconfigurable assembly system enables a rearrangement of the handling of parts and opens the possibility for serial and parallel structures which, in turn, can allow scaling up and down in capacity to better supply unpredictable market demands. Additionally, the authors recognize 3 basic types of assembly systems:

1. Fully automated assembly: suitable for mass produced parts with high quality.
2. Hybrid systems: combine automation and manual work
3. Manual assembly: a very reconfigurable system as humans are very adaptable though often provides low productivity and quality [6].

## 3 MCG'S PROOF OF CONCEPT

### 3.1 MCG's Challenges

MCG first became interested in the RMS concept as a part of an investigation of future production concepts. As a part of that investigation, several new and exciting manufacturing and supply chain concepts were discussed, such as: Rapid Manufacturing (or Additive Manufacturing) – the prospect of using 3D printing technologies in order to produce mass scale consumer goods, Glocalized Manufacturing – a supply chain concept that presents the future supply chain as a global network of local independent, self-sufficient supply chains, and Smart Factories – factories that are change-ready, intelligent, and are able to produce a wide range of products in an economies of scale fashion [7].

A future perspective for MCG is the ability to be responsive and switch from push manufacturing to pull based manufacturing. At the moment, MCG relies mainly on forecasting, a fact that puts tremendous pressure on its supply chain and manufacturing capabilities. Most of MCG products are supplied with high economies of scale due to the sheer volume of its production. However, a growing number of unique elements are being manufactured in small batches, according to customers' demand. In addition, most of MCG's current manufacturing systems are dedicated to the elements it is presently producing. These dedicated systems are capable of manufacturing a high volume of elements to a very low price, but when flexibility is needed, they are unable to accommodate.

In addition to the above, MCG is facing general Western manufacturer's challenges such as: challenges with the global structure and fragmentation of production, an increasing trend of individualisation both of consumers and retailers, an increasing harsh effect of demand fluctuation and seasonality, etc. [7] [8] Considering these facts, a system that can be rapidly changed but still produce high volume was needed thus the RMS concept was chosen to be tested.

In order to illustrate that the RMS concept can deliver to MCG satisfaction and be implemented in the production area as a manufacturing platform of the future, MCG chose to construct a proof of concept. This proof of concept is not a fully operating prototype but rather a first example of the RMS design in an industrial application. As such, the design of the proof of concept had several compromises that a fully operational manufacturing system will not have. These will be specified later in this paper.

### 3.2 Focus Area

The proof of concept has 4 main objectives to validate:

1. Reduction in changeover time

a. Changeability in system level – the changeover time between modules should not exceed 10 minutes while the target time is 5 minutes. These targets were set after comparing the productivity of current manufacturing systems at MCG combined with the desired outcome for productivity in the RMS. The changeover in the system occurs when a scale up/down occurs or when a higher/lower number of tools is required than that is available in the current setup. Additionally, changeover in system level can occur if a higher/lower number of inputs/outputs is necessary as shown in the Figure 2.

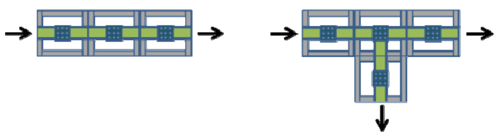

Figure 2: Adding an additional module for a system changeover.

b. Changeability in module level – the changeover in each individual module. Changeover in module level should not exceed 5 minutes while the target time is 3 minutes. Similarly to system changeability, these targets were set by comparison to existing manufacturing systems at MCG. Changeover in module level occurs when the module has changed a location; hence changed physical appearance (the structure of the conveyors on the module - more about this in the design section) or when more/less/different tools are necessary on the module, as illustrated in Figure 3.

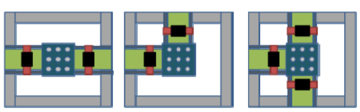

Figure 3: Changing the location of conveyors and tools for module changeover.

2. Customized flexibility

Customized flexibility is the ability to integrate into the system either: a dedicated tool, a flexible robot, or a manual operator according to demand and the action needed, as shown in Figure 4:

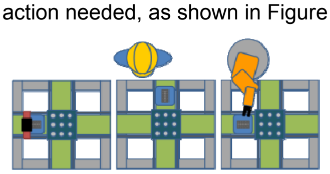

Figure 4: Adding different levels of automation customized flexibility.

3. Scale up/down

Scaling up occurs by adding additional modules/tools with the same functionality as the ones already implemented in the system, as shown, for example, in the image below. Scaling up should increase production capacity by at least 50% depending on cycle times of modules and tools in the configuration. This target was set after an analysis of material handling in the system and as minimum acceptance criteria for a new manufacturing platform in MCG. Correspondently, scaling down can reduce the output of the system in case capacity needs to be lower, illustrated in Figure 5:

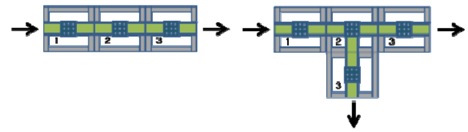

Figure 5: Adding another module "3" will increase capacity.

4. Changes in functionality

Changes in functionality refer to the change in the functionality of modules and the sequence of production. This proof of concept will aspire to integrate a date marking digital printer to illustrate the decoration process. By doing that, we can show that the sequence of production (assembly to decoration, decoration to assembly) can be changed, as well as the functionality of the module itself (from assembly module to a decoration module) as shown in Figure 6. A change in functionality will aspire to reach the same changeover times of regular module (max. 10 minutes).

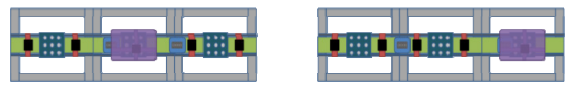

Figure 6: Changing the sequence of production allows flexibility in process planning.

### 3.3 Test Objects

In order to test the RMS assembly proof of concept, a part family was chosen. This part family has some similar geometries but the main characteristic of choice was that the family has common assembly. In other words, there are two types of assemblies that repeat in the entire family.

Another reason for this choice was that these assemblies are not common in MCG's portfolio, meaning these parts are not sold as often as others. This contributed to the fact that in order to make economies of scale, MCG has to produce large number of parts and store them in inventory.

In addition to this part family, which was chosen to test changeover within the family, an objective of the system is the possibility of changeover to new parts or to parts outside of the family. This experiment will examine prolongation of the system life time as new tools can be added to fit new product and by that increasing the value of the RMS system as a worth-while investment for industrial companies.

## 4 PROOF OF CONCEPT DESIGN

The proof of concept's main objective is to show the physical feasibility of RMS as a manufacturing concept at MCG. To complement this physical set, a computer simulation is being contracted. This simulation will be able to examine countless possibilities and to determine the productivity, flexibility, and return on investment of the RMS concept while benchmarking it to some of the existing platforms available today. The simulation models are not in this paper's scope.

The proof of concept is constructed of 5 main parts: the Base Unit (BU), conveyors, the centre piece, the jigs, and tools, as seen in figure 7. Similar to other RMS designs (the iFactory in Stuttgart and Windsor, the Transfer Factory manufactured by Festo, and the Agil@prod at the Institut Français de Mécanique Avancée (IFMA)); the MCG's proof of concept is based on the main principals of RMS, namely: modularity, Integrability, Customization, Convertibility, and Diagnosability [2]. However, some crucial design decisions made for the MCG proof of concept, differentiates it from the other systems. These design choices will be specified in this section.

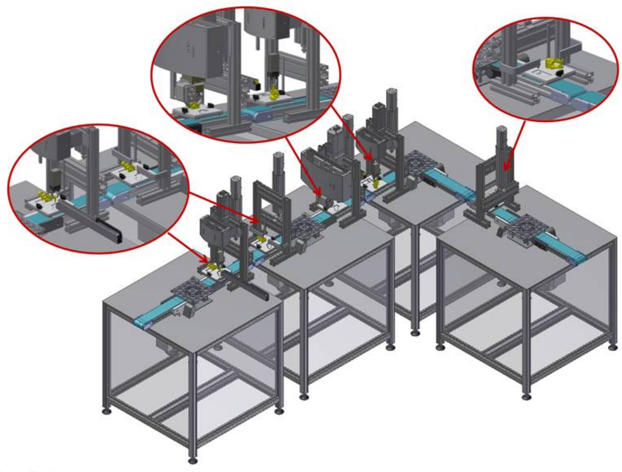

Figure 7: MCG's RMS proof of concept design.

### 4.1 The Base Unit (BU) Design

Unlike other examples for RMS systems, MCG's proof of concept's BU is a square. The reason for this choice was to allow the system to grow in more than one direction without having to dedicate a special diversion module. This way, all modules are capable of directing the jigs in both x and y directions. The modular structure of the system fulfils the first principal of RMS: modularity.

All BUs are completely identical. This will allow all BUs to be implemented in all locations in the system. BUs are stripped of all conveyors and tools in the initial state but are equipped with all the necessary control modules and electronics to enable "plug & play" integration of conveyors and tools (it may be important to state that at this stage, tool and conveyor control and electronics are implemented on the tools themselves and it is not a part of the BU control design). The change-readiness ("plug & play") of the system both on the system level (mechanical and control connectivity to other BUs) and on the module level (mechanical and control connectivity to conveyors and tools), illustrates the Integrability of the system. The only component that is attached to the BU is the centre piece, which will be further introduced in the following section. The dimensions of the BU were specified to match MCG's strict requirements for ergonomics and are fitted for manual labour as well, as illustrated in Figure 8.

The BU connects to other BUs in the system using a "4 female 1 male" connectivity cables, as illustrated in Figure 9. This connectivity design was chosen in order to avoid redundancy in the system while still covering all possible connections available for a BU.

Other than control and electronics connectivity, each BU is equipped with mechanical interlocking mechanisms that will be connected to the relevant BUs. Additionally, a system of retracting wheels was designed, in order to allow the mobility of a BU without the need of a manual forklift or an AGV.

For the purpose of this proof of concept, only 4 BUs will initially be manufactured. This amount will allow testing of several complex configurations that will be sufficient to determine the feasibility of the concept as a manufacturing concept in MCG.

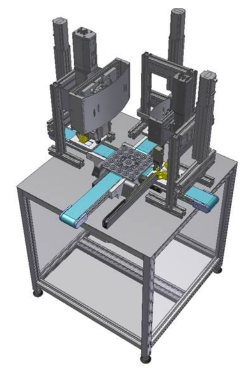

Figure 8: A BU with tools and conveyors, centre piece is constant.

Figure 9: A BU connectivity illustration – "4 females 1 male".

### 4.2 The Centre Piece Design

Since a bidirectional structure was chosen for the proof of concept, a central diverting piece had to be implemented in the centre of the BU. This piece had to be capable of 90 degree on-spot rotation in order to keep the jig with the same relative direction to the conveyors and tools. Several concepts have been evaluated, including smart conveyors and turn tables. However, since most of these concept are either incapable of 90 degrees turns or are too slow, a new design had to be developed.

Inspired by advances in robotics and several military applications, a solution based on Omni-wheels was developed, that is capable of 90 degrees, on-spot turning and does not jeopardize cycle time and accuracy, as can be seen in Figure 10. The Omni-wheel solution showed promising results in the conceptual testing and was chosen to be implemented in the final design.

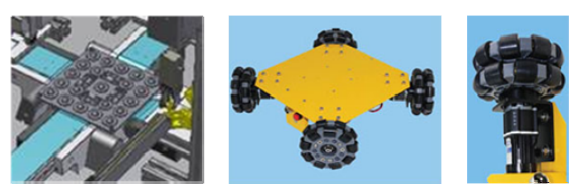

Figure 10: The Omni-wheel centre piece solution [9].

### 4.3 The Tool Design

This proof of concept consists of 5 dedicated tools: 2 puncher tools (assembling the screw to the elements), 2 pick and place tools (capable of handling both screws), and a flip tool (to flip the crane base 90 degrees between the assemblies of the different screws). All tools in the system have an identical interface to the BU, both in terms of mechanical and control connectivity. The fact that tools can be easily and rapidly changed on the BU will contribute to a better utilization of the BU and for not dedicating BU to a particular function or tool. The tools in the system must be able to handle the entire part family with minimal changes during changeovers. An illustration of the different tools is provided in Figure 11.

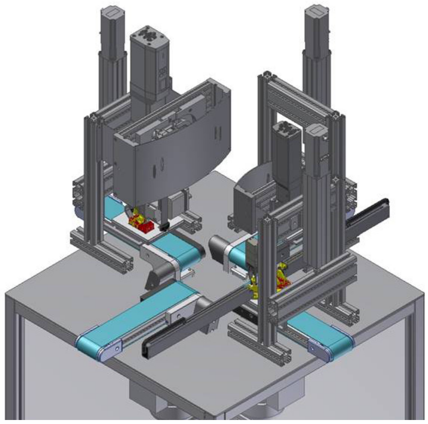

Figure 11: All three tools implemented on a BU, from the left: flip tool, puncher, and pick & place.

As mentioned before, the control units of the tools are a part of the tools themselves. This will reduce the amount of control and intelligence necessary in the BU which will not be utilized if the respective tool is not installed.

A consideration that had to be taken in the design of the tools is their weight. Since the tools, as well as other components of the system, have to be change-ready and "plug & play", their design had to ensure that an operator can perform a changeover without the use of a crane or other machinery that would slow the process. In the design phase, a decision to implement only electro-mechanical tools was made. In recent years, MCG has researched the energy consumption of pneumatic and as this proof of concept was an investigation of a future manufacturing platform, it has been decided to investigate the potential tools of the future. However, since electro-mechanical tools often have heavy motors and controls, weight became an issue and had to be taken into consideration. Another consideration in this regard is the low number of suppliers that offer electro-mechanical industrial production tools. We do, however, expect more and more suppliers to deliver these tools to the industry.

In addition to the dedicated tools of the proof of concept, two intelligent tools are implemented as well: a 6 axis robot and a Digital Printer (DP) both mechanically and control. The 6 axis robot will be used to illustrate different levels of automation in the system and the DP will be used to simulate the decoration process in which elements have a picture imprinted on them.

### 4.4 The Conveyors Design

The conveyors, like the tools, are equipped with their own control on board to reduce the amount of electronics in the BU and hasten the changeover. As mentioned above, the BU will be mounted with conveyors only in the directions they are necessary. This will reduce the overall number of conveyors needed in the system, while still providing the modularity and flexibility of the material handling in the system. The conveyors in this proof of concept are bidirectional which will reduce the need for changeover if a conveyor is needed in the opposite direction. See an example for a layout with only the necessary conveyors mounted, in Figure 12.

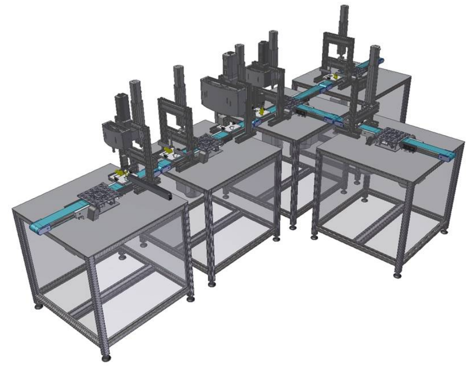

Figure 12: The system with tools and only the relevant conveyors.

### 4.5 The Fixture Design

Similar to all other aspects of the system, the fixture is also modular and reconfigurable. The fixture is constructed of two parts. The lower part, a generic part that is suitable for transportation on the conveyors, and the upper part, which is part specific. The upper and the lower part are connected with a quick release mechanism to ensure that the changeover is fast as well, as can be seen in Figure 13. In the future, the fixtures could contain RFID tags or other identification methods in order to provide information about the element they are carrying. This will allow the system to start producing an element while still running a different element in the pipeline.

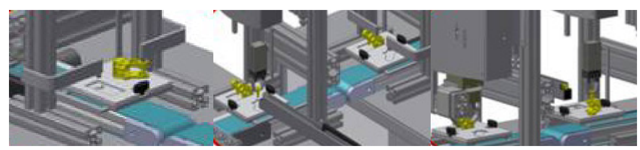

Figure 13: The jig.

### 4.6 The Control Design

As previously mentioned, all tools and conveyors have embedded intelligence. Their connectivity to the BU is done via a standardised digital I/O interface. The fact that only digital signals are being transmitted between the tools (and the conveyors) and the main PLC in the BU, eases the requirements of the interfaces and allows the intelligent tools to use the same standardised interfaces. Each BU will receive a unique ID through a PLC, which will be recognised when connected to other BUs and to the Graphical User Interface (GUI). In doing so, the system will be able to recognise how many BUs are connected and in which configuration they are connected to each other. Additionally, this structure will enable BU to BU diagnosability in order to check that all BUs are well connected before manufacturing.

### 4.7 The GUI Design

In addition to the normal user interface that will allow users to interact with the system, specify which element is to be assembled and the quantity, perform a diagnostics of connectivity and system readiness, and general system safety, the GUI provides two other interesting aspects that are to be tested in this proof of concept. The first is an automatic detection of system configuration. The system will be able to automatically recognize how modules are connected to each other, where conveyors are mounted and to which direction they are moving, and which tools are implemented. This will minimize the user interaction necessary with the system and will allow the operator to simply configure the desired configuration, a fact which will reduce changeover time. The user will also have the opportunity to specify which assembly is about to be carried out and receive a recommendation from the GUI regarding which configurations will perform best, depending on scale, tools, number of BUs, etc. The recommendation for best configuration will be based on a simulation that will take into account all the above factors and will produce a visual representation of the preferred layout.

Another aspect that is tested in the proof of concept is a drag & drop advance mode menu in the GUI (see Figure 14). This drag & drop platform will eliminate the systems dependency in predefined scenarios and configuration and will enable the operator to create new configurations in case a new element was introduced to the system or if situation requires. In the future, the drag & drop layout will be combined with the simulation to allow the operator to virtually test the configuration before actually implementing it.

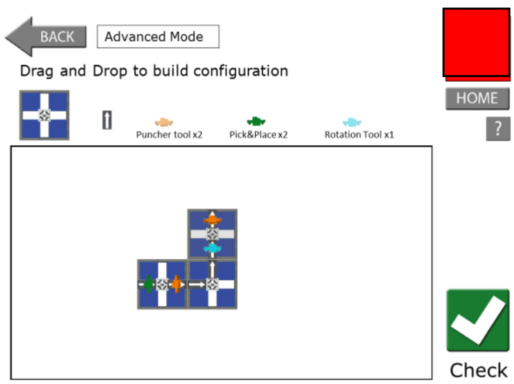


Figure 14: The drag & drop menu in the GUI.

## 5 TESTING AND EVALUATION

The testing and evaluation of the proof of concept will be divided into three parts. The first part is the testing of the equipment in order to make sure that all manufactured apparatus perform to specifications. The second part is the testing of the physical feasibility of the concept. The section of the testing period will concentrate on changeover time, integration of intelligent tools, the GUI, integration of manual operators to the system, system diagnosability, and the introduction of new assemblies to the system and their resulting effects. In other words, the 4 focus areas specified in section 3.2: reduction of changeover time, customized flexibility, scaling up/down, and changes in functionality, will be tested in regard to the requirements. All these factors will have to live up to the target time specified and not exceed the maximum time or minimum requirements.

The third part of the evaluation will be performed using a simulation model developed by the University of Southern Denmark in Sønderborg. From the simulation, critical KPIs will be developed and the RMS proof of concept will be evaluated accordingly. Additionally, the proof of concept will be compared and benchmarked to an existing manufacturing platform in terms of productivity, changeover and flexibility. Further research will concentrate on the analysis of these results and the improvement of the design accordingly.

## 6 SUMMARY

Though extensive research has been done on the implications of RMS, its design, and its contribution to the industry, there are no examples with an industrial application of RMS. MCG recognized the potential of RMS as a future manufacturing concept and decided to examine it in an industrial environment. Based on literature written in the area and several state-of-the-art examples, a design for a reconfigurable assembly system was proposed and further developed. The design stays true to the basic principles of reconfigurability and builds upon them. For instance, modularity was implemented at the module level (modular tools and conveyors) and not only at the system level. Integrability was also introduced to these components to create “plug & play” interfaces. New aspects of RMS were taken into account, for example: mobility – tools were designed as light as possible and BUs are equipped with a retractable wheels system to easily mobilise them. A simulation program is developed alongside the physical proof of concept to test determined KPIs for the concept and to evaluate and benchmark it in an industrial application.

## 7 ACKNOWLEDGMENTS

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# Energy-Efficient Manufacturing on Machine Tools by Machining Process Improvement

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**Abstract**
This paper aims to provide information on process improvement for energy-efficient manufacturing. A machine tool is the most energy consuming equipment in plants. There are effective ways to reduce energy consumption of machine tools such as reducing required energy, shutting down the power to standby equipment, and shortening the cycle time. This paper introduces several approaches for process improvement such as optimizing the cutting conditions and the inclination angle of the tool in 5-axis machining. Minimizing use of fluid and using control functions are also effective.

**Keywords:**
Machine tool; Energy; Machining process

## 1 INTRODUCTION

Since the Kyoto Protocol was adopted in 1997, interest in energy saving and carbon dioxide reduction has been increasing. Furthermore, electricity shortage in the Kanto area is a serious issue due to shutdown of the Fukushima nuclear power plant after the Great East Japan Earthquake. Most of the nuclear power plants in Japan are still halted and demands for energy saving have been raised from the industrial circle especially after the rise in power rates in the Kanto, Kansai, and Kyushu areas.

A survey of recent papers shows that many researchers have studied process improvement in the machine tool industry. I. Inasaki [1] investigated reducing fluid use during machining. D. Dornfield generated an efficient tool path, introduced a workpiece setup method [2], and explored power consumption monitoring on machine tools [3]. In order to satisfy the social demands for energy saving as a machine tool manufacturer, we considered two approaches: (1) Decreasing power consumption while manufacturing machine tools and (2) Manufacturing energy-saving-type machine tools to decrease power consumption at users' plants. If we compare these approaches, it is clear that the latter can save significantly more energy in total. In order to satisfy demands for energy saving on machine tools, there are two possible methods: (a) Improving the machine tools themselves to be energy-saving type and (b) Decreasing power consumption by optimizing the machining methods or cutting conditions. In the case of (a), energy saving can be achieved without users being conscious, whereas in the case of (b), energy saving by optimizing cutting conditions can be applied to existing machine tool facilities as well. It is preferable to advance improvement in both the cases. In the past, dry cutting 1), efficient path 2), and power consumption monitoring 3) were the focus of studies for energy saving on machine tools. In this paper, we consider energy saving on machine tools from the viewpoint of both (a) and (b).

## 2 ENERGY SAVING BY IMPROVING MACHINE TOOLS

First, the example cases are introduced. They are currently being studied and already in practical use regarding energy saving on machine tools.

### 2.1 Reducing Mass of Moving Parts [4]

In order to reduce power consumption on machine tools, the design of a machine itself needs to be changed to decrease the mass of moving parts and achieve low inertia. A number of such technologies are used for transportation equipment including aircrafts and automobiles. Lightweight materials such as carbon fiber and aluminum have been increasingly utilized. It is considered to take similar measures on machine tools as well.

Machine tools require dynamic rigidity, damping characteristics, and thermal stability; therefore, it is not possible to change materials to new ones only because they weigh light.

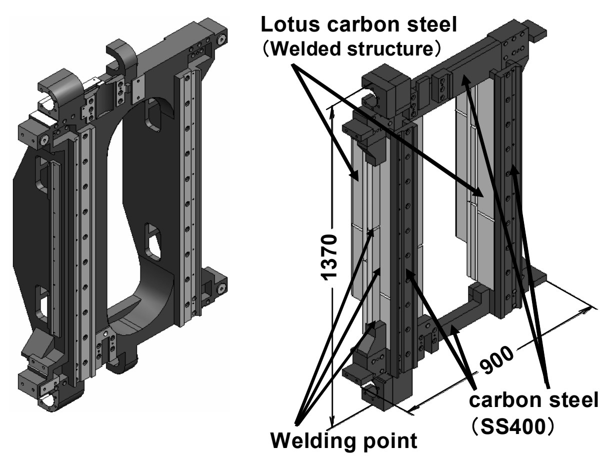


Figure 1: Structure of horizontal machining center that uses porous metal.

Development of aluminum alloy (1), concrete (2), fine ceramics (3), and FRP (Fiber Reinforced Plastics) (4) is undergoing for actual products so that they can be applied to the machine tool structure. However, there are still issues to be solved such as: the machine rigidity is low and thermal expansion coefficient is high with aluminum alloy; thermal conductivity is low with concrete; price is high and machinability is low with fine ceramics and FRP. A study on lotus-type porous carbon steel is advancing as a new material for lightweight structure 4) and we anticipate its practical application. Experimentally, we used it for a saddle on a horizontal machining center (Figure 1), and the weight of the saddle was reduced by 41% and that of the moving parts by 18%, resulting in 40% reduction of the total weight. Furthermore, it was also effective in suppressing residual vibrations; however, the static rigidity was reduced by 20%. The power consumption during no-load running was reduced by 15% to 20% as a result.

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### 2.2 Energy Saving during Standby Period

The operation data on 10,000 units of machine tools were gathered through the remote monitoring system. The average power distribution time was 268 hours/month and the average operation time was 150 hours/month, thus the difference was 118 hours/month. During these 118 hours, the machine power was on but the machine was halted or under setting up procedures for such as workpiece exchange. While the machine was halted, there was no need to operate coolant pump, chip conveyor, servo motor, and display. Therefore, to reduce power consumption on the machine manufactured by Mori Seiki, gravity axes are halted by electromagnetic brake if any operation is not performed for 5 minutes, and the equipment is turned off when the power is not required. This function is similar to the idling stop function on automobiles. Energy saving effect by this function may vary depending on operation status or machine types, but generally it is amounted to several hundred watts to several thousand watts.

### 2.3 Energy Saving on Coolant Pump

Usually on machine tools, the on-off control is used for coolant pump. Coolant is switched on by specifying an M code in a program before starting machining and switched off by specifying an M code after the end of cutting. Coolant has functions for cooling down tools and workpiece materials, improving cutting ability by its lubrication effect, and flushing chips. Some cases require a large quantity of high-pressure coolant depending on parts to be cut or amount of chips produced during cutting, and other cases don't. In either case, coolant is generally adjusted by a throttle valve. We considered using an inverter to get an energy-saving effect. Especially, on machines which are operated for a long time without an operator attended, usually high-pressure coolant pumps for chip removable and cooling are used; and power consumption by coolant pumps is very large. Therefore, significant effect is expected if the power consumption can be reduced. On the 24-hour machining line at Mori Seiki, 60% of the entire power is consumed by coolant pumps. The test for reducing high-pressure coolant pumps was conducted. The purpose of high-pressure through-spindle coolant pumps is to stabilize machining without chip clogging during deep-hole machining of aluminum. For the above purpose, the coolant pump with 5.5 kW and discharge pressure of 7 MPa was used. An experiment was conducted to verify and determine the pressure for machining with smaller power consumption and less chip clogging.

Figure 2 shows summary of the experimental equipment. High-sensitive tool dynamometer was mounted on the table and aluminum workpiece was held on it. Then, the cutting thrust was measured while the workpiece was cut using a carbide drill of 3.2 mm in diameter with DLC (Diamond-like Carbon) coating.

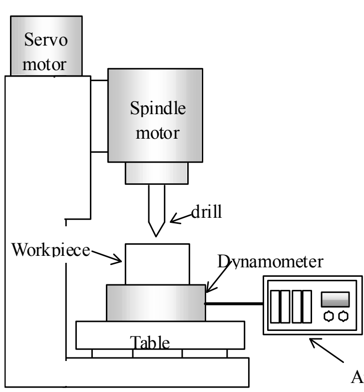



Figure 2: Experimental equipment.

The depth L of machining was 64 mm to fulfill "L/D = 20". The spindle speed was set at 8,000 rpm and the feed per revolution at 0.2 mm/rev. Water-soluble type coolant was used with the internal lubrication system and the pressure was (1) 1.5 MPa, (2) 3.5 MPa, and (3) 6.5 MPa. As a result, the thrust force was (1) 192 N, (2) 165 N, and (3) 192 N. In the experiment (1) with 1.5 MPa, the thrust force increased due to chip clogging at the bottom of the hole. In experiment (3), the thrust force increased due to high coolant pressure. Thus, we determined that the discharge pressure of 3.5 MPa was just right as an experimental condition. Then, the pump with an output of 5.5 kW was changed to the one with an output of 3.7 kW, and mass production started at a discharge pressure of 4 MPa by using the inverter control on the coolant pump while feeding back the discharge pressure using a pressure sensor.

As a result, the power consumption per unit became 8.5 kWh/day whereas it was usually 24.3 kWh/day, resulting in reduction of the power consumption by 65%.

## 3 ENERGY SAVING BY OPTIMIZING CUTTING CONDITIONS

On machine tools, power consumption can be categorized to the one for spindle and feeding motors and the one for peripherals such as hydraulic pump, coolant system, and cooling unit. The former depends on the cutting power and the power consumption can be determined according to the cutting amount. The latter does not depend on the cutting power and it is generally proportional to the cycle time; therefore, the power consumption decreases as the cycle time decreases. Thus, with faster cutting conditions and shorter cycle time, the total power consumption may be reduced. Here, it is verified how the power consumption varies according to the cutting conditions such as cutting speed or feeding. Also, the use of 5-axis machining has been increased recently and optimization of the tool tilting angle is being studied. Therefore, the optimum tilting angle is considered from the viewpoint of power consumption.

### 3.1 Experimental Equipment and Method [5]

A series of experiments were conducted to figure out the influence of cutting parameters on power consumption. Total power and that of the spindle were measured by connecting a clamp-type watt-hour meter to the spindle motor power cable of the machining center and to the power cable of the input power source.

The test workpiece as shown in Figure 3 was used to measure the power. Three types of tools were used: 80 mm face mill with four carbide alloy inserts (multi-layer coated with TiA1N + AlCrN), 10 mm end mill with two flutes (carbide, multi-layer coated with TiAlCr+TiSi), and a 10 mm drill (multi-layer coated with TiAlCr + TiSi, point angle of 135 degrees, helix angle of 30 degrees). The workpiece material was carbon steel S45C.

The machining sequence was as follows:

- The top face was machined with the face mill.
- The side face was machined with the end mill.
- Four 20 mm-deep holes were drilled with the drill.

The cutting speed and the feed rate per revolution were changed in three stages, shown in Table 1. The cutting speed in conditions #1 and #2 was the median value of the range recommended by the tool maker. The feed rate per revolution was changed between the median value and the maximum value in the recommended range. In condition #3, the cutting speed and the feed rate per revolution were set at the maximum value of the recommended range.

### 3.2 Experimental Result

Table 2 shows the power consumption per tool in each cutting condition. The total power consumptions when using the face mill in each condition were 12.55 Wh, 9.62 Wh, and 9.08 Wh, respectively. The power consumption ratio between conditions #1 and #3 was 72.4 %. The power consumption in condition #3 was the lowest.

The total power consumptions when using the end mill under conditions #1, #2, and #3 were 33.73 Wh, 21.73 Wh, and 17.18 Wh, respectively. The power consumption ratio between conditions #1 and #3 was 51%. The power consumption in condition #3 was the lowest. Power consumption changes dramatically according to cutting conditions.

The power consumptions in conditions #1, #2, and #3 when using the drill were 12.02 Wh, 11.25 Wh, and 10.50 Wh, respectively. The power consumption ratio between conditions #1 and #3 was 87%. The power consumption in condition #3 was the lowest.

Table 2 shows that the power consumptions of the spindle during face milling were 4.93 Wh, 4.39 Wh, and 4.27 Wh under conditions #1, #2, and #3, respectively. Feed rate per revolution in condition #2 was 1.5 times greater than that of condition #1. At the same cutting speed, the material removal amount was 1.5 times larger. However, the power consumption of the spindle was only 1.12 times larger. Condition #3 had the same feed rate per revolution with 1.25 times faster cutting speed and 1.25 times larger chip volume compared with condition #2. However, power consumption of the spindle was only 1.03 times larger.

The power consumptions under conditions #1, #2, and #3 when using the drill were 12.02 Wh, 11.25 Wh, and 10.50 Wh, respectively. The power consumption ratio between conditions #1 and #3 was 87%. The power consumption in condition #3 was the lowest.

Power consumptions of the spindle during end milling were 5.43 Wh, 4.49 Wh, and 4,56 Wh under conditions #1, #2 and #3, respectively. Due to small cutting resistance during this machining, the influence of cutting condition on power consumption was minute. Power consumption depends on the cycle time. The power consumptions during drilling were 4.85 Wh, 4.69 Wh, and 4.95 Wh in conditions #1, #2, and #3, respectively. Compared with condition #1, condition #2 had 1.25 times greater feed rate per revolution, the same cutting speed, and 1.25 times larger chip disposal amount. However, the power consumption of the spindle was only 0.97 times greater.

While conditions #2 and #3 had the same feed rate per revolution, condition #3 had 1.44 times faster cutting speed and 1.44 times larger material removal amount, but the power consumption of the spindle was only 1.06 times greater. Total power consumptions under conditions #1, #2, and #3 were 60.09 Wh, 51.42 Wh, and 46.89 Wh and cycle times were 101.0 sec, 79.1 sec, and 66.6 sec, respectively. Hence, condition #3 is the most efficient in terms of power consumption and cycle time.

## 4 ENERGY SAVING BY OPTIMIZING TILTING ANGLE [6]

### 4.1 Experimental Equipment and Method

With a typical ball end mill machining model, contour machining on an inclined surface with angle α was discussed in this experiment (Figure 4). A general inclined cutting method was applied with pick feeds arranged from higher to lower height. Figure 4 depicts their order from 1 to 2 and to 3. The 5-axis vertical machining center was used in this experiment. This machine consists of linear axes -- X, Y, and Z -- and two rotary axes -- B and C. The traverse angle on the B axis inclined the tools relative to the workpiece. The spindle motor power consumption was measured by using a clamp-type ammeter connected to the input power source cable. A ball end mill with carbide inserts which is multi-layer coated with TiAlN+AlCrN was used for the experiment. Die steel 40CrMoV5 (ISO), HRC51 was used as the workpiece material. Tool overhang L was 60 mm, and the diameter D was 20 mm, thus L/D = 3. Standard cutting conditions based on the medium values of which recommended by the tool manufacturer were adapted; the cutting speed v of 80 m/min and the feed rate f of 0.15 mm/tooth. The amount of material removal during the cutting process of 0.2 mL per path, and the power consumption per material removal unit (Wh/mL) was used to evaluate this experiment.

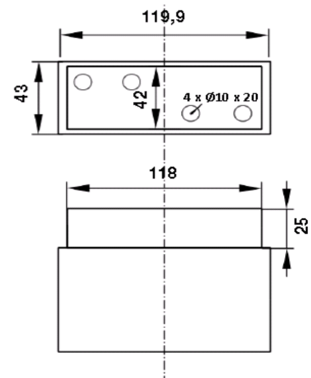



Figure 3: Test work piece.

| Tool | Cutting condition | #1 | #2 | #3 |
|---|---|---|---|---|
| Face mill | Cutting speed Vc :m/min | 200 | 200 | 250 |
| | Feedrate per a tooth f: mm/t | 0.2 | 0.3 | 0.3 |
| End mill | Cutting speed Vc :m/min | 90 | 90 | 130 |
| | Feedrate per a tooth f: mm/t | 0.1 | 0.15 | 0.2 |
| Drill | Cutting speed Vc :m/min | 90 | 90 | 130 |
| | Feedrate per a revolution f: mm/rev | 0.28 | 0.35 | 0.4 |

Table 1: Cutting conditions.

| Total Power Consumption | | | | | | |
|---|---|---|---|---|---|---|
| | Cutting condition | Cycle time (s) | Power consumption (Wh) | | | |
| | | | Facemill | Endmill | Drill | Total |
| Machining | Condition(1) | 101.0 | 12.550 | 33.726 | 12.018 | 69.093 |
| | Condition(2) | 79.1 | 9.622 | 21.729 | 11.247 | 51.419 |
| | Condition(3) | 66.6 | 9.084 | 17.182 | 10.498 | 46.888 |
| Air cutting | Condition(1) | 101.0 | 6.065 | 27.403 | 8.259 | 50.735 |
| | Condition(2) | 79.1 | 5.707 | 21.457 | 7.068 | 44.172 |
| | Condition(3) | 66.6 | 4.448 | 14.458 | 6.641 | 34.126 |
| Note | Conditions when machining is conducted | | Without coolant | With coolant | | Power consumtption of the devices about operations, such as ATC and approach of each axis is included. |

| Axis | | | | | | |
|---|---|---|---|---|---|---|
| | Cutting condition | Cycle time (s) | Power consumption (Wh) | | | |
| | | | Facemill | Endmill | Drill | Total |
| Machining | Condition(1) | 101.0 | 4.928 | 5.427 | 4.848 | 15.311 |
| | Condition(2) | 79.1 | 4.395 | 4.490 | 4.692 | 13.658 |
| | Condition(3) | 66.6 | 4.266 | 4.564 | 4.946 | 13.857 |
| Air cutting | Condition(1) | 101.0 | 0.542 | 2.129 | 0.807 | 3.556 |
| | Condition(2) | 79.1 | 0.511 | 1.553 | 0.678 | 2.801 |
| | Condition(3) | 66.6 | 0.560 | 1.472 | 0.838 | 2.872 |
| Note | Conditions when machining is conducted | | Without coolant | With coolant | | Power consumtption of the devices about operations, such as ATC and approach of each axis is included. |

Table 2: Power consumption by tool.

To compare the actual spindle motor power consumption per material removal unit, power consumption during cutting was subtracted from power consumption during non-cutting.

### 4.2 Experimental Result

To investigate the relationship between power consumption and inclined angles, an experiment was conducted with the following conditions; feed length of 100 mm per path, cutting depth in the axial direction ap of 1.0 mm, pick feed distance in the slope direction p of 4.0 mm, and material removal amount per path of 0.38 mL. Power consumption and machined surface roughness for the workpiece were measured at angles of every 5° from 0° to 60°. Spindle load values were also measured to evaluate the validity of the results of power consumption. Tool life was measured as an additional experiment. The same tool was repeatedly used and the tool life was determined by the total distance when the flank wear width reached vB=0.3 mm.

Figure 5 shows the measuring results of power consumption according to different inclined angles. The power consumption was stable until the inclined angle reached 20° and it increased as the inclined angle increased. The highest power consumption was recorded around 45° and 60°. Thus, the energy efficiency was improved when inclination angle α reached 20° if only power consumption is considered.

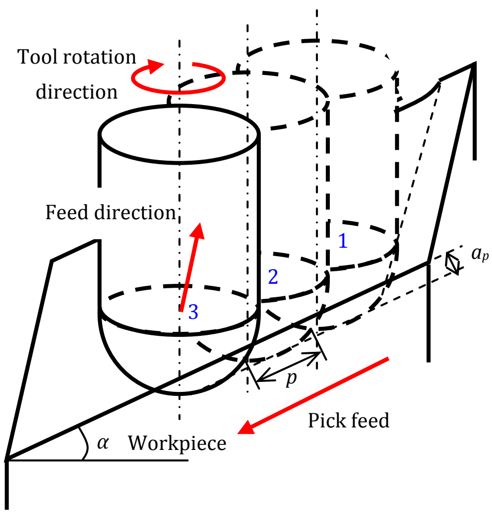



Figure 4: Verification test by tool tilting angle.

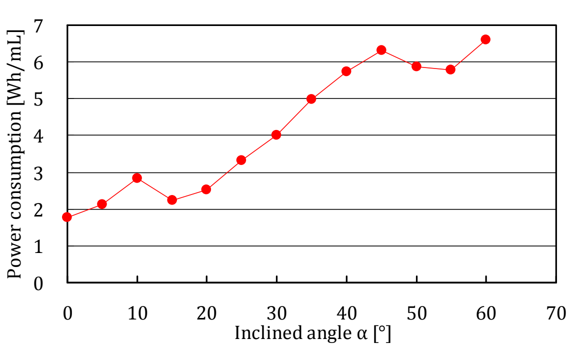



Figure 5: Relation between power consumption of spindle motor and spindle tilting angle.

Tool life and surface quality were evaluated at four inclined angles of 0°, 15°, 45°, and 60°. Table 3 shows the results of the machined surface roughness of the workpiece. At the bottom of the ball end mill with the inclined angle of 0°, the worst surface roughness was recorded. The results of measuring surface roughness at 15°, 45°and 60° were not significantly different -- 2.2 μm to 3.5 μm.

Figure 6 shows the effect of inclined angles on the tool wear measurement test. The tool life expired at the feed distance of around 120 m at inclined angles of 0° and 45°. At the inclined angle 60°, feed length extended to 170 m while at 15° it extended to nearly 180 m.

Figure 7 shows the differences of power consumption due to the tool wear progression. Power consumption continues increasing at the inclined angles 45° and 60° as the tool wear progressed. However, power consumption increases were smaller relative to tool wear progression at the inclined angle 15°. At the inclined angle α = 15°, power consumption recorded was 1.4 Wh/mL using a new tool. However, 1.9 Wh/mL was recorded when using a tool that had exceeded a feed distance of 120 m. On the other hand, at the inclined angle α = 45°, power consumption was 5.8 Wh/mL using a new tool, with 8.9 Wh/mL recorded using a tool with feed length of 120 m. Also, total power consumption during the 120 m cutting process at α = 15° was 866 Wh and at α = 45° was 4058 Wh. Thus using inclined angle 15°, power consumption was reduced by approximately 79 %.

Considering power consumption and tool life as the principal evaluation parameters, inclined angle 15° was the most energy efficient setting based on the experimental results.

| Slant Angle | Surface Roughness Ra |
|---|---|
| 0° | 6.38 |
| 15° | 3.27 |
| 45° | 2.18 |
| 60° | 2.75 |

Table 3: Measuring result of surface roughness.

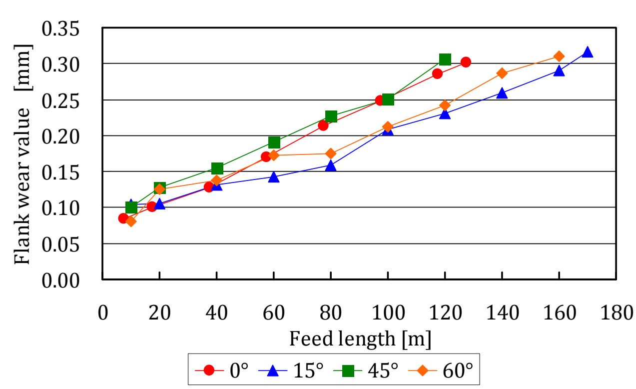



Figure 6: Tool wear measurement result.

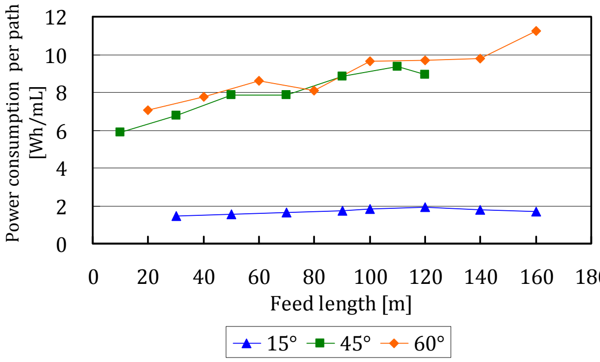



Figure 7: Power consumption according to the tool wearness progressed.

## 5 DUST VACUUM AND COOLING BY CHIP VACUUM SYSTEM FOR CFRP (CARBON FIBER REINFORCED PLASTICS) MACHINING

### 5.1 CFRP Machining

CFRP has recently been drawing an attention as a material for aerospace components, but machining of such composite materials with coolant causes problems when disposing and separating cutting powder dusts from coolant. The waste also has negative influence on the environment. Furthermore, the dusts produced during dry machining of CFRP bring harmful effects on the human body. Besides, the cutting tools are exposed to high cutting temperatures resulting in a short tool life. In order to overcome such problems, a chip vacuum system has been developed. The system enables to vacuum the harmful dusts while dry machining of CFRP, and also a longer tool life can be expected by the cooling effect.

### 5.2 Experimental Equipment and Method

Figure 8 shows overview of the chip vacuum system. Chips are vacuumed into dust collector through inside of the spindle. Typical machining processes of aerospace parts -- (1) face-mill machining and (2) drilling -- were tested with chip vacuum system.

Figure 9 (a) shows the cutting conditions of the developed face mill by section. Chips are vacuumed through the center of the face mill. Heat sink cover was set to reduce temperature of cutting chip and surface of the workpiece. Figure 9 (b) shows the cutting conditions of the developed drill by section. The hollow-type drill was developed to vacuum cutting chips effectively.

Table 4 shows cutting conditions of each process. Temperature of tool was measured by thermography.

### 5.3 Experimental Result

In this experiment of the face-milling process, 90% of cutting chips were discharged by the vacuum system. Figure 10 shows temperature of the tool during face-milling. The temperature with the chip vacuum system was decreased by 18℃. Figure 11 shows temperatures of the tool during drilling. The temperature with the chip vacuum system was decreased by 80℃.

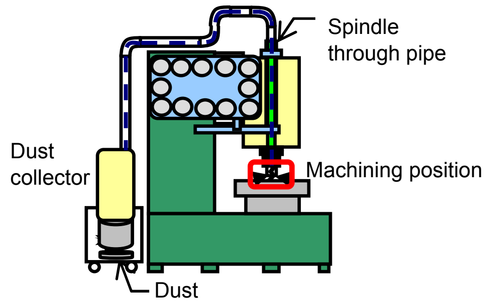
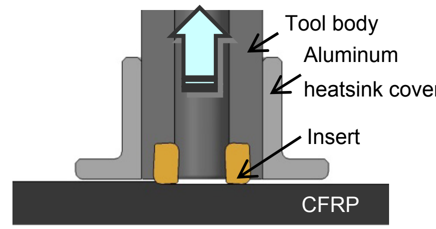
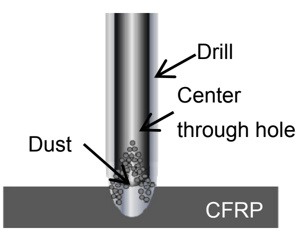



Figure 8: Overview of chip vacuum system.




(a) Cross-section drawing of face-mill




(b) Cross-section drawing of drill

Figure 9: Overview of developed tools.

| Tool | Face-mill | Drill |
|---|---|---|
| Tool diameter [mm] | 25 | 10 |
| Spindle speed [$min^{-1}$] | 3000 | 4500 |
| Feed speed [mm/min] | 7000 | 900 |
| Axial depth of cut [mm] | 0.5 | 44 |
| Radial depth of cut [mm] | 20 | |

Table 4: cutting conditions.

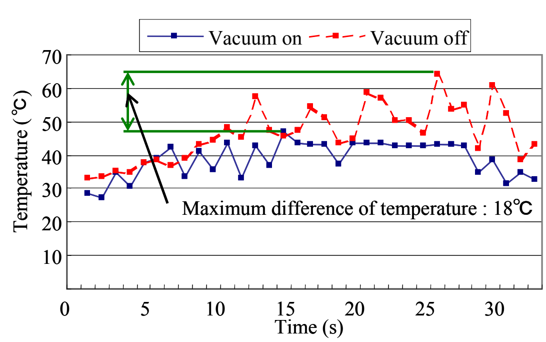



Figure 10: Tool temperatures during face-milling.

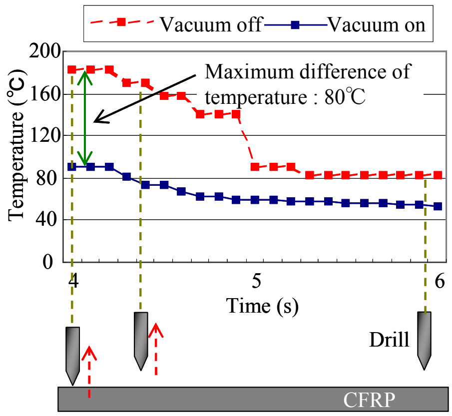



Figure 11: Tool temperatures during drilling.

## 6 CONCLUSION

This paper introduced reduction of power consumption on machine tools. A machine tool is the most power consuming machine in plants where metals are machined. Effects of the energy saving on machine tools greatly contribute to the society.

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# The Impact of E-mobility on Automotive Supply Chain

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**Abstract**
This paper examines the most important changes to the traditional automotive supply chain needed for the introduction of electric vehicles. Potential critical components of electric vehicles have been also considered. An empirical investigation was carried out to analyse these aspects and to understand enterprises perceptions about the development of the electric vehicle market. Data were collected using an on-line questionnaire and then analysed by a principal component analysis and a statistical analysis. The aim of the survey was also to evaluate which sort of electric vehicle and body style enterprises are investing more, as well as the degree of importance they attribute to the electric vehicle market.

**Keywords:**
Electromobility; supply chain; survey; principal component analysis

## 1 INTRODUCTION

According to the definition of Fine [1], the term *supply chain design* is defined as “choosing what capabilities along the value chain to invest in and develop internally, and which to allocate for development by suppliers”. Through the process of supply chain design, companies define strategies to manage their supply chains and their configurations in terms of definition of the operational processes and of the members of the supply chain responsible for performing these processes. The term *new product development process* means “the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product” [2]. It is the primary means of generating innovation in companies and allows them to adapt their offer according to the changing consumer preferences and the technological advances. From these considerations, it is evident the importance of an effective management of new product development process, the absence of which might potentially cause a business risk. New product development and supply chain design are strongly interconnected and their coordinated management is essential for a successful introduction on the market of new products. In fact, companies must choose the strategy and the configuration of the supply chain that is suitable to the characteristics of a new product.

These aspects are always more interesting for automotive companies that are moving, or that have the intention of doing it, towards the production of electric vehicles (EVs), or that would integrate them into traditional vehicle production lines. Indeed, sustainable passenger mobility, and hence alternative powertrain concepts (e.g., full electric, hybrid), will gain an increasing significance in the next 20 years [3].

The integration of alternative powertrain concepts into passenger cars will require completely new components and competences. It must be pointed out that the EVs supply chain differs considerably from the conventional vehicles one, especially concerning the linkages to other industry sectors, such as energy suppliers [4]. Moreover, many components, currently used in internal combustion engine vehicles, will be no longer needed in a full EV (e.g., exhaust, intake, $O_2$ sensor, EGR etc.). At this regard, some types of small- and medium-sized enterprises (SMEs), currently not present in the traditional automotive supply chain, will be notably involved in the next development of EVs supply chain, providing new automotive components and facilities [4]. A full development of EVs supply chain will be achieved only if companies will succeed in merging automotive and EV competences from industry, research and development, and educational resources.

This paper contributes to evaluate the most important changes needed to the traditional automotive supply chain for the introduction of EVs, and to identify the potential vehicle critical components. An empirical investigation by a survey was carried out to analyse these aspects and to understand enterprises perceptions about the development of the EV market.

## 2 THEORETICAL FRAMEWORK: SUPPLY CHAIN AND NEW PRODUCTS

It is vital for companies to continuously introduce variations to existing products, as well as radically new products to remain competitive in the market. However, the ability to design new products in response to technological evolution and/or market trends is not a sufficient condition to ensure the survival of a company. In fact, new designed products might not be manufacturable at all, from a costs point of view. For this reason, product design and production processes design must be coordinated, instead of being perceived as two separate sets of decisions and activities occurring in a sequential way [5]. In recent decades, the increasing demand heterogeneity has led to a proliferation of products and to a reduction of their life cycle, as well as to stocks obsolescence risk. In this situation, the time-to-market assumes a strategic importance [6]. In addition, there is a growing trend toward outsourcing of production and design activities, representing even 60-80% of sales value [7]. Therefore, the only coordination of design decisions involving production processes and products is no longer sufficient, thus a coordination with the decisions related to supply chain context is also needed [5]. This leads to an extension of the conventional Concurrent Engineering integrating supply chain concepts, leading to the development of the so-called 3 Dimensional Concurrent Engineering (3-DCE) [8]. According to Fine [1], 3-DCE can be defined as the simultaneous and coordinated design of products, manufacturing processes, and supply chain. Fine [1] also suggests that the necessity of integration of these three processes appears as an obligation once recognized the strategic importance of the supply chain. In the 3-DCE, several authors (e.g. [6] [9])

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focused on the analysis of the relationships between product and supply chain, and, in particular, between the new product development process and the supply chain design process. The literature (e.g., [10] [11]) has identified the need to match product features with those of supply chain. This can be done not only by choosing the strategy and the configuration of supply chain which are suitable to product features, but also trying to anticipate, during the product design, constraints related to the supply chain. This is necessary to avoid launch delays of new products due to non-readiness of supply chain, and to control costs and maximize the service performance of supply chain [9]. Most of academic researches [12-14] have dealt with supply chain in new product development process only in the final stages, while not so many studies are on the issues of the earliest stages.

## 3 METHODOLOGY

### 3.1 Questionnaire Layout

The first step of this study was the design of a questionnaire to evaluate the main aspects affecting EV supply chain. A first version of this questionnaire was pre-tested during the trade fair for sustainable mobility “Klimamobility 2012” in Bolzano (Italy). Direct interviews were carried out with representatives of logistic and engineering enterprises division to discuss about the relevant aspects of supply chain policies and features. After this pre-testing, suggestions to revise or eliminate some questions, that could seem unclear and/or of limited relevance, were obtained. In its final form, the questionnaire consisted of 3 sections:

- Section 1. Examination of general aspects about the surveyed enterprise (enterprise size, market segment, and role of respondents);
- Section 2. Understanding of the potential changes needed to the automotive supply chain when EVs are considered.
- Section 3. Understanding of the most critical EV components and of the enterprise perceptions regarding some market aspects.

### 3.2 The Data Collection

The second step of this study was to identify the enterprises sample to be surveyed. The following databases were used:

- EVtransPortal (www.evtransportal.org), a non-profit organization dedicated to helping people around the world to find sustainable transport through electric drive vehicle technology.
- Europages (www.europages.it), a leading enterprise in the activation of business-to-business contacts in Europe. Its website references over two million of suppliers including manufacturers, service providers, wholesalers, and distributors.

By consulting these databases, more than 1000 companies were found. 800 companies were contacted by email, including the link to the Google Docs questionnaire available in English, German, and Italian, attaching a cover letter explaining the research aim. The data collection began in September 2012 and lasted four months. Due to the nature of the arguments, the questionnaire was addressed to project managers, marketing managers, and key account managers. Moreover, respondents were also invited to pass the questionnaire to the most appropriate business functions. Overall, 89 questionnaires were collected, of which 87 valid for a statistical analysis; the average response rate was of about 10.9% (=87/800). Questionnaire parameters were preliminary assessed by computing the Cronbach's alpha coefficient. Results (Table 1) show that alpha coefficient is always above the recommended value of 0.7 according to [15].

| Factor description | Loading |
|---|---|
| Item 1 = Suppliers will adapt to the demand of new products | .870 |
| Item 2 = Modify the existing production lines for new products | .811 |
| Item 3 = Modify the production capacity (e.g., man-machine hours) | .825 |
| Item 4 = Internal training for workers | .821 |
| Item 5 = Make minor changes in marketing | .877 |
| Item 6 = Change some suppliers | .918 |
| Item 7 = Add of new production lines to those existing | .907 |
| Item 8 = Partial outsourcing | .897 |
| Item 9 = Internal research and development for new products | .921 |
| Item 10 = Recruitment of new skilled workers | .908 |
| Item 11 = Establish relationships with new customers | .912 |
| Item 12 = Totally new suppliers | .897 |
| Item 13 = Create new production facilities | .902 |
| Item 14 = Total outsourcing | .911 |
| Item 15 = Transition to a lean supply chain | .902 |
| Item 16 = External research and development for new products | .913 |
| Item 17 = Make important changes in marketing | .897 |
| Item 18 = Consider collaboration agreements as a joint venture | .910 |

Table 1: Reliability analysis using Cronbach's alpha coefficient.

### 3.3 Statistical Analysis

A statistics analysis was carried out to provide an overview of the sample of surveyed enterprises. Such analysis was performed on questions belonging to section 1 of the questionnaire. A principal component analysis (PCA) was then performed on answers of section 2 to identify the potential changes to supply chain that should be adopted by enterprises when introducing EVs. In this study the potential changes were obtained through an analysis of 18 items. PCA analysis reduces the number of principal components from p to k, with $p \geq k$. Since one of the objectives of the PCA is to obtain factors that explain the correlations among variables, these variables must be somehow related to each other. It is difficult that a common factor exists if the correlations among the variables are weak. The presence of significant correlations were verified with Kaiser-Meyer-Olkin test (KMO) and Bartlett's test. KMO test is an index that allows the magnitude of the observed correlations to be compared in respect to the partial correlations; the value must be > 0.70. Bartlett's test is applied to the correlation matrix; the null hypothesis is that the correlation matrix is equal to an "identity matrix". Finally, a statistical analysis was performed on questions belonging to section 3 of the questionnaire. All the analyses were performed by IBM SPSS (Statistical Package for the Social Science), a tool used for survey authoring and deployment (IBM SPSS Data Collection), data mining (IBM SPSS Modeler), text analytics, statistical analysis, and collaboration and deployment.

## 4 SURVEY RESULTS

### 4.1 Characteristics of Enterprises

According to the Commission Recommendation 2003/361/EC of 6 May 2003, surveyed enterprises were grouped into micro- (<10 employees), small/medium- (11-250 employees), and large-sized enterprises (>250 employees). Results, listed in Table 2, show that surveyed enterprises were mainly micro-sized (44.9%) and SMEs (37.9%). The percentage of large-sized companies may seem high; this is due to the fact that the questionnaire was sent to a proportionally higher number of large-sized companies, in respect to micro-sized companies and SMEs in order to obtain statistically significant data.

| Enterprises size | N | % |
|---|---|---|
| Micro | 39 | 44.9% |
| Small/medium | 33 | 37.9% |
| Large | 15 | 17.2% |

Table 2: Size of the surveyed companies.

Table 3 reveals that the sample surveyed consists of companies operating in different fields. Specifically, the sample mainly included automotive suppliers (54.0%) and research & development companies (17.2%).

| Industry field | N | % |
|---|---|---|
| Automotive suppliers | 47 | 54.0% |
| Research & development | 15 | 17.2% |
| Energy suppliers | 9 | 10.4% |
| Vehicles manufacturers | 7 | 8.0% |
| Charging stations | 6 | 6.9% |
| Other | 3 | 3.5% |

Table 3: Industry sectors of the surveyed companies.

The last question of section 1 asked respondents to indicate their job within the company. As mentioned before, the questionnaire was addressed to project, key account or marketing managers, which in most cases (61.0%) were the actual respondents (Table 4). In other cases, respondents were CEO (24.1%), technical managers (8%), and designers (6.9%).

| Role of the respondent | N | % |
|---|---|---|
| Project manager | 34 | 39.2% |
| CEO | 21 | 24.1% |
| Key account manager | 11 | 12.6% |
| Marketing manager | 8 | 9.2% |
| Technical manager | 7 | 8.0% |
| Designer | 6 | 6.9% |

Table 4: Role of the respondent to the questionnaire.

### 4.2 Principal Component Analysis (PCA)

Section 2 of the questionnaire aimed to identify the possible changes of automotive supply chain by a PCA. Respondents were asked to specify their level of agreement or disagreement on 18 proposed items, following a 5-point Likert scale, a psychometric scale commonly used in research employing questionnaires. According to this scale, the following values were used: 1 = very unimportant; 2 = unimportant; 3 = indifferent; 4 = important; 5 = very important. KMO and Bartlett's test (table 5), and PCA were performed on the 18 items.

| Kaiser-Meyer-Olkin measure of sampling adequacy | | .752 |
|---|---|---|
| Bartlett's test of sphericity | Approx. Chi-square | 903.496 |
| | df | 153 |
| | Sig. | .000 |

Table 5: KMO and Bartlett's test.

The KMO value is > 0.7, while the Bartlett's test value leads to the rejection of the null hypothesis of no correlation among the variables (p-value > 0.05).

As a further step, three criteria were used for choosing the number of components (Heuristic Criteria).

1. According to the Kaiser's rule, components with eigenvalues greater than 1 must be used (Table 6).

| Components | Eigenvalues |
|---|---|
| 1 | 7.656 |
| 2 | 3.797 |
| 3 | 1.958 |
| 4 | .961 |

Table 6: Eigenvalues.

Our case suggests to use the first three eigenvalues.

2. Cattell's Scree test: this technique is based on the visual inspection of the eigenvalues scree plot. The interpretation works well in case of very strong empirical factors. Subjectivity problems may occur in presence of not very strong factors or of two or more discontinuities.

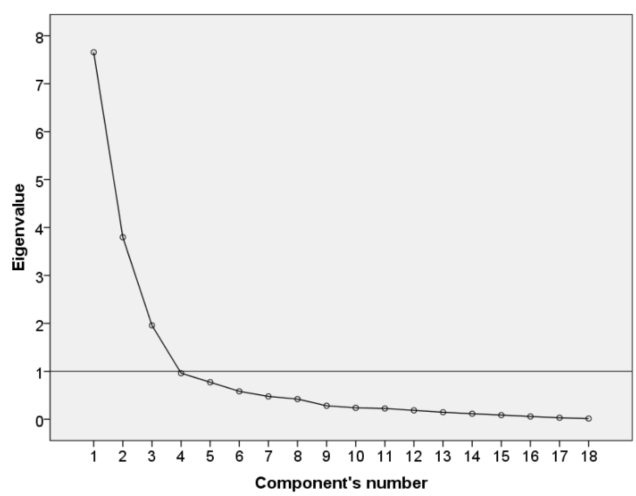


Figure 1. Cattell's Scree test.

The Screen Plot in Figure 1 shows that the number of components is four, because the diagram exhibits an abrupt change of slope in correspondence of this value.

3. Using only those components that represent 70-80% of the overall variability:

$$\frac{\lambda_1+\cdots+\lambda_k}{\lambda_1+\lambda_2+\cdots+\lambda_p} \approx 70-80\% \quad (1)$$

where the numerator represents the variance of the first k principal components, while the denominator represents the variance of all the principal components. Table 7 shows that the first three λ values are covering 74.5% of the total variance, while if considering the forth eigenvalue the cumulative variance is 79.8%.

| Component | Initial eigenvalues | | |
|---|---|---|---|
| | Total | Variance % | Cumulative % |
| 1 | 7.656 | 42.533 | 42.533 |
| 2 | 3.799 | 21.097 | 63.630 |
| 3 | 1.959 | 10.878 | 74.508 |
| 4 | .961 | 5.338 | 79.846 |
| 5 | .772 | 4.290 | 84.136 |
| 6 | .582 | 3.232 | 87.368 |
| 7 | .476 | 2.644 | 90.012 |
| 8 | .421 | 2.337 | 92.349 |
| 9 | .281 | 1.563 | 93.912 |
| 10 | .238 | 1.322 | 95.233 |
| 11 | .225 | 1.248 | 96.481 |
| 12 | .185 | 1.030 | 97.511 |
| 13 | .146 | .810 | 98.321 |
| 14 | .115 | .639 | 98.961 |
| 15 | .086 | .477 | 99.438 |
| 16 | .057 | .319 | 99.757 |
| 17 | .030 | .168 | 99.925 |
| 18 | .014 | .075 | 100.000 |

Table 7: Total variance explained.

Since two out of three methods returned the same result, it was decided to use the first three variances, $\lambda_1$, $\lambda_2$, and $\lambda_3$.

Since the eigenvectors provided by SPSS in the "Components Matrix" were not normalized to a unit length, and since this was a factorial analysis, eigenvectors were divided by the square root of the respective eigenvalues. Table 8 shows the obtained results.

| Item | Comp1 | Comp2 | Comp3 |
|---|---|---|---|
| x1 | 0.3732 | 0.2602 | 0.2745 |
| x2 | 0.3664 | 0.2876 | 0.0697 |
| x3 | 0.4000 | 0.0520 | -0.0518 |
| x4 | 0.3922 | 0.0932 | 0.0707 |
| x5 | 0.3779 | -0.0905 | -0.0550 |
| x6 | 0.2665 | 0.3152 | 0.2579 |
| x7 | 0.2529 | 0.3185 | 0.2633 |
| x8 | 0.2493 | 0.3223 | 0.1718 |
| x9 | -0.0003 | 0.3393 | 0.2576 |
| x10 | 0.0250 | 0.3333 | 0.2925 |
| x11 | -0.1740 | 0.3290 | 0.2894 |
| x12 | 0.1186 | 0.2958 | 0.2851 |
| x13 | 0.0936 | 0.2910 | 0.2707 |
| x14 | 0.0243 | -0.0024 | 0.2783 |
| x15 | 0.0789 | -0.0463 | 0.2888 |
| x16 | 0.0380 | -0.0762 | 0.2749 |
| x17 | 0.1014 | -0.0987 | 0.2777 |
| x18 | 0.0201 | -0.0322 | 0.1998 |

Table 8: Normalized eigenvectors.

The main components were expressed using three linear equations ($Y_1$, $Y_2$, $Y_3$), where the combination coefficients were the components of the eigenvectors corresponding to the three eigenvalues chosen:

$$Y_1 = 0.3732(x1) + 0.3664(x2) + 0.4000(x3) + 0.3922(x4) + 0.3779(x5) + 0.2665(x6) + 0.2529(x7) + 0.2493(x8) - 0.0003(x9) + 0.0250(x10) - 0.1740(x11) + 0.1186(x12) + 0.0936(x13) + 0.0243(x14) + 0.0789(x15) + 0.0380(x16) + 0.1014(x17) + 0.0201(x18)$$

$$Y_2 = 0.2602(x1) + 0.2876(x2) + 0.0520(x3) + 0.0932(x4) -0.0905(x5) + 0.3152(x6) + 0.3185(x7) + 0.3223(x8) + 0.3393(x9) + 0.3333(x10) + 0.3290(x11) + 0.2958(x12) + 0.2910(x13) - 0.0024(x14) - 0.0463(x15) - 0.0762(x16) - 0.0987(x17) - 0.0322(x18)$$

$$Y_3 = 0.2745(x1) + 0.0697(x2) - 0.0518(x3) + 0.0707(x4) - 0.0550(x5) + 0.2579(x6) + 0.2633(x7) + 0.1718(x8) + 0.2576(x9) + 0.2925(x10) + 0.2894(x11) + 0.2851(x12) + 0.2707(x13) + 0.2783(x14) + 0.2888(x15) + 0.2749(x16) + 0.2777(x17) + 0.1998(x18)$$

Based on the weights reported in these equations, it can be concluded that:

- Component $Y_1$ mainly takes into account minor changes to be made to traditional automotive supply chain. It also includes some important changes such as "establish relationships with new customers", "internal research and development for new products", and "change some suppliers".
- Component $Y_2$ mainly takes into account important changes to be made to supply chain. It also includes some items belonging to the other categories such as "suppliers will adapt to the demand for new products", "internal training for workers", "external research and development for new products", and "make important changes in marketing activities".
- Component $Y_3$ mainly takes into account radical and important changes to be made to supply chain. It also includes one item (suppliers will adapt to the demand for new products) belonging to the "minor changes" category.

For each pair Comp1-Comp2, Comp3-Comp1, and Comp3-Comp2 a scatter plot has been created (see Figure 2, Figure 3, and Figure 4, respectively).

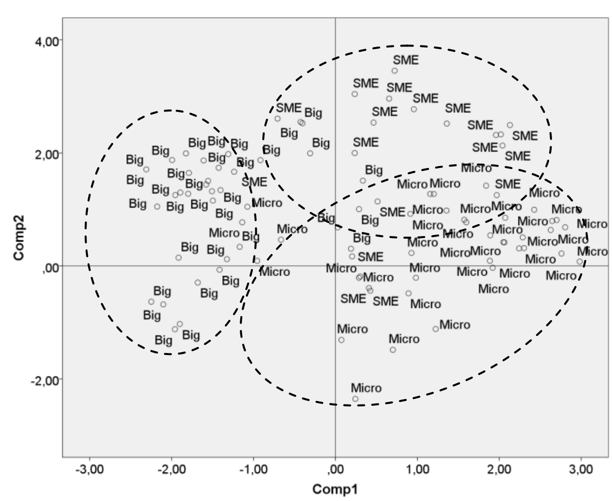


Figure 2: Comp2 vs. Comp1.

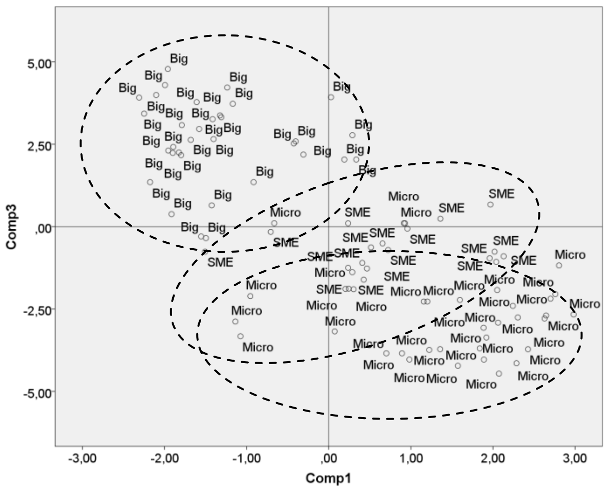


Figure 3: Comp3 vs. Comp1.

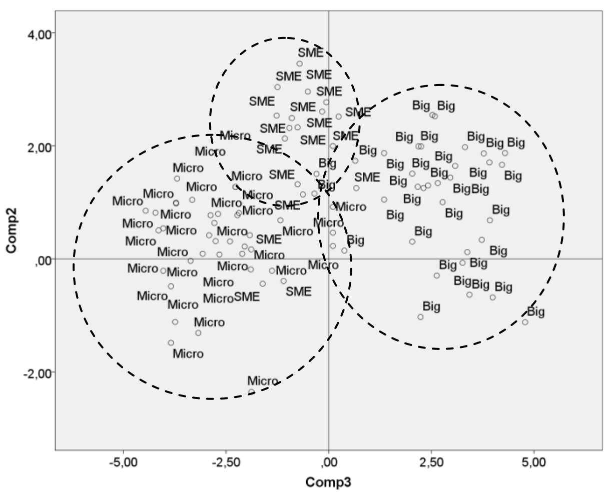


Figure 4: Comp2 vs. Comp3.

Micro-sized companies show higher performance against component 1, but lower scores were obtained against component 2 and 3. In general, it is possible to deduce that micro-sized companies prefer minor changes to supply chain, paying limited attention to other major changes. SMEs show very high performance against component 2, and sufficient score against component 1, indicating a greater need to change traditional automotive supply chain. Large-sized companies are characterized by high performance against component 2 and 3, indicating that a mix of several and radical changes are needed to introduce EVs in traditional automotive supply chain.

### 4.3 Questions about Vehicles

The first two questions of section 3 asked respondents to indicate which sort of EV or field their company is investing more, and which body styles it is developing as an EV. The ensuing results are listed in Table 9. 80% of micro-sized companies, 60.6% of SMEs, and 57.1% of large-sized companies, indicated that they are investing in battery electric vehicles (BEVs), while 12.5% of micro-sized companies, 39.4% of SMEs, and 21.4% of large-sized companies are investing in hybrid electric vehicles (HEVs). It should be noted that 21.4% of large-sized companies are also investing in plug-in hybrid electric vehicles (PHEVs). Furthermore, all the companies, regardless of their size, declared their interest for city cars. 17.9% of micro-sized companies and 9.1% of SMEs declared that they are also investing in coupe/roadster, while large-sized companies were also interest for sedan, even though within limits.

| **Electric vehicle** | **Company size** | | |
|---|---|---|---|
| | **Micro** | **SME** | **Large** |
| HEV | 5 (12.5%) | 13 (39.4%) | 3 (21.4%) |
| PHEV | 0 | 0 | 3 (21.4%) |
| BEV | 32 (80%) | 20 (60.6%) | 8 (57.1%) |
| Other | 3 (7.5%) | 0 | 2 (14.3%) |
| | 40 | 33 | 14 |
| **Body Style** | | | |
| City car | 39 (100%) | 33 (100%) | 15 (100%) |
| Sedan | 3 (7.7%) | 0 | 2 (13.3%) |
| Station wagon | 0 | 0 | 0 |
| Multi-purpose vehicle | 0 | 0 | 0 |
| Suv | 0 | 0 | 0 |
| Coupe/roadster | 7 (17.9%) | 3 (9.1%) | 0 |

Table 9: Favourite EV and body style.

Two other questions asked respondents to indicate if market creates an environment that encourages innovation towards EVs, and the degree of importance attributed to the EV market. According to Table 10, 51.3% of micro-sized companies, 69.6% of SMEs, and 33.3% of large-sized companies do not completely agree that the current market is promoting innovations regarding EVs. Despite these results, 90.3% of micro-sized companies, 69.7% of SMEs,

| **Judgment** | | **1 (strongly disagree)** | **2** | **3** | **4** | **5 (strongly agree)** |
|---|---|---|---|---|---|---|
| The market creates an environment that encourages innovation towards electric vehicles | Micro | 3 (7.8%) | 10 (25.6%) | 7 (17.9%) | 13 (33.3%) | 6 (15.4%) |
| | SME | 0 | 6 (18.1%) | 17 (51.5%) | 5 (15.2%) | 5 (15.2%) |
| | Large | 0 | 2 (13.3%) | 3 (20%) | 7 (46.7%) | 3 (20%) |
| **Judgment** | | **1 (very unimportant)** | **2** | **3** | **4** | **5 (very important)** |
| Degree of importance that respondents attributes to the market of electric vehicles | Micro | 0 | 0 | 3 (7.7%) | 4 (10.3%) | 32 (82%) |
| | SME | 0 | 0 | 10 (30.3%) | 6 (18.2%) | 17 (51.5%) |
| | Large | 0 | 1 (6.7%) | 6 (40%) | 3 (20%) | 5 (33.3%) |

Table 10: Market analysis.

and 53.5% of large-sized companies, attributed a high degree of importance to the EV market.

Last question asked respondents to indicate the degree of criticality of some components and features of an EV. Using a 5-point Likert scale, the following values were used: 1 = very uncritical; 2 = uncritical; 3 = indifferent; 4 = critical; 5 = very critical. Table 11 shows the obtained results.

| Item | Mean (S.D.) |
|---|---|
| Battery packs | 4.41 (.857) |
| Driving range (km with a full tank) | 3.90 (1.356) |
| Flywheel / transmission | 3.31 (1.184) |
| Safety in the case of collision | 3.14 (1.112) |
| Size of the passenger compartment | 2.98 (.970) |
| Consumption (km / litre) | 2.97 (1.280) |
| Coefficient of aerodynamic drag (cx) | 2.93 (1.104) |
| Body frame | 2.62 (.852) |
| Hi-Tech appearance | 2.28 (1.178) |
| Acceleration | 2.17 (.918) |
| Top speed | 2.13 (1.025) |

Table 11: Critical components.

On the basis of the above findings, there are four major critical aspects to consider (>3): battery packs (4.41), driving range (3.90), flywheel/transmission assembly (3.31), and safety in the case of collision (3.14). Instead, aspects such as top speed (2.13), acceleration (2.17), and hi-tech appearance (2.28) were considered not so critical. However, it should be stated that the standard deviation appears to be quite high (from .857 to 1.280).

## 5 SUMMARY

Respondents were asked to indicate their level of agreement or disagreement on 18 different changes to be made to traditional automotive supply chain to integrate EVs production. A PCA was performed to understand the positioning of companies towards the implementation of different changes proposed by this research. SMEs suggest that to establish relationships with new customers and suppliers, to implement internal research and development, to add new production lines to existing ones, the partial outsourcing and a mix policy of internal training and recruitment of skilled workers would be required.

Micro-sized enterprises indicate that internal training for workers, internal research and development, modifications of production capacity, changes to existing production lines, change of some suppliers, minor changes in marketing activities, and establishing relationships with new customers are the most important turns required to integrated supply chains.

Largest enterprises argue that a radical change in the automotive supply chain is needed; in this way, new production facilities might be created by adopting new marketing policies, benefiting from both internal and external research and development, and building relationships with new customers and suppliers. They were also convinced that a transition to a lean supply chain might be a strategic goal. All the companies declared that existing suppliers should adapt to the demand for new products.

All the surveyed companies, regardless of their size, are especially investing in BEVs and, to a lesser extent, in HEVs (favouring city cars), although the market is not promoting an environment that encourages innovation towards EVs. Battery packs and driving range are the most critical features considered in design of an EV; flywheel/transmission group and safety in case of collision are also considered as critical. On the contrary, hi-tech appearance and vehicle performances, as well as top speed and acceleration are not significant.

## 6 ACKNOWLEDGMENTS

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# Configuration of a Multi-use Battery Production

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**Abstract**
Electric vehicles are widely regarded as one solution of future mobility. However, they still pose multifarious challenges as the increase in demand for electric vehicles, the diversity of battery variants, the development of new battery designs and the alternative usable manufacturing technologies in the production process. Hence a battery assembly which enables its changeability and its reuse is required. Furthermore expensive raw materials, safety aspects and a so far not fully automated process chain require the integration of quality assurance aspects during assembly planning. Therefore product developers and machinery and plant engineers are supported in planning a quality ensured changeable and reusable – a so called multi-use – battery assembly. To this end, a configurator has to be developed to provide the planner a decision support. The configurator has to deduce from product-specifications single assembly stations for its battery assembly, evaluates them regarding their changeability and reuse as well as the OEE and costs of the entire assembly line and gives a prioritized list of assembly alternatives as the output.

**Keywords:**
Electric Mobility; Production Planning; Changeability

## 1 INTRODUCTION

Important drivers for the transition to an alternative vehicles economy consider reduced emissions, energy security and competitiveness effects. [1] This leads to the electric vehicle as a solution. However electric vehicles still pose diverse challenges to production science.

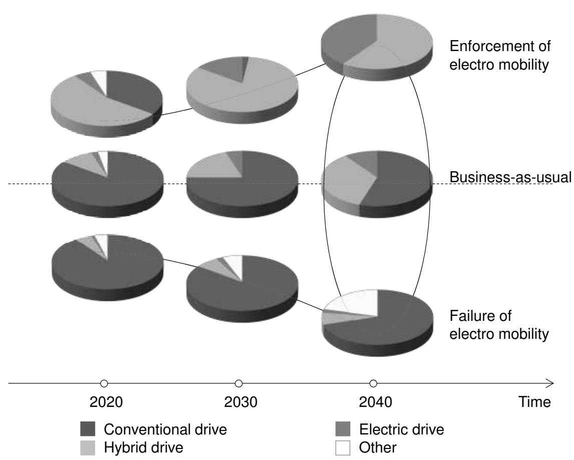


Figure 1: Market scenarios for the development of Germany's automobile industry. [3]

Although a vehicle based on electricity is believed to be the future, there are uncertainties regarding the development of demand quantities for electric vehicles and consequently lithium-ion batteries for automotive applications. Demand scenarios of partially electrically cars differ depending on the political influence. [2] In case of a non-political influenced market development an amount of (partially) electric vehicles of 45 % in the year 2040 is possible (see figure 1). [3]

The electric mobility faces further challenges regarding the diversity of variants and the development of new battery designs. Nowadays the production process of batteries is tailor-made for each product and focusses on high flexibility which leads to a moderate output. Also alternative production technologies can be considered. [4]

As well as the requirement of a transformable assembly line, quality management is a key factor during the battery production process. Semi-finished goods are already of high value (e. g. cell material, cell production) and quality management should ensure on the one hand that fault prevention is assured by using capable processes and on the other hand that no further value is being added to scrap. Another issue to note is the enhanced danger of fire and explosion during production and in the case of crashes during the life cycle. As a consequence it is inevitable to implement a sufficient quality management along the battery production process. [5]

Different external influences indicate the challenges for battery assembly in the future. [1] Therefore product developers as well as the machinery and plant engineers are supported in planning a changeable and reusable – a so called multi-use – battery assembly. To this end, a planning tool which enables the evaluation of different process alternatives has to be developed to provide the planner a decision support. The tool focuses on the battery assembly not on the cell production.

## 2 CATEGORIZATION OF TECHNOLOGIES

For a common understanding of the word technology and the future application, its different meanings are explained in the following paragraph.

A technology is knowledge that can be applied to solve practical problems [6]. This knowledge consists of natural sciences, social sciences and engineering aspects and is the solution of practical problems in R & D and production departments. The use of technology and the resulting material and immaterial products are referred to technics. [7]

### 2.1 Technology Categorization by the Functionality

Different technologies can be categorized by their functionality. Depending on the function three categories can be distinguished (see figure 2). Product technologies describe technologies that end

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in the product and thereby ensure its functionality. In contrast, process technologies are used for performance generation, for example manufacturing a product. [7]

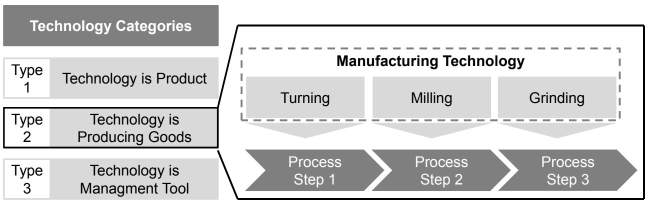


Figure 2: Technology categories. [8]

### 2.2 Technologies in Their Life Cycle

To rate technologies it is necessary to be able to distinguish them. The itemization of technologies allows conclusions on their relevance and reduces uncertainties. In addition, forecasts of future developments can be facilitated. However, a definite classification of technologies is ex ante difficult. [9] In one branch, a technology represents a basic technology as it is being categorized in a different industry as pacemaker technology, since the potential applications have yet to be identified [10].

As well as products and processes, technologies are also subjected to a life cycle [9]. The concept of the technology life cycle provides a better way for understanding the strategic applications that are accompanied with the technologies. The technologies pass four life cycle phases: development, growth, maturity and old age phase (see figure 3) [11].

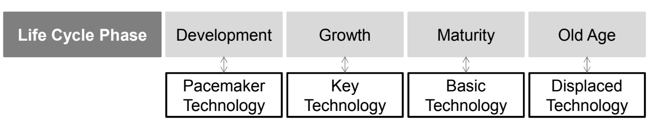


Figure 3: Technologies in their life cycle. [12], [13]

During the development stage of a technology, the practical applications are still very uncertain. Similarly, the procedure for achieving a usable technology is unclear. If the application potential for some companies or research institutions is large enough investment in new technology is made. The subsequent growth phase is characterized by a sufficient degree of certainty about a given application domain and some practical applications are already realized. The increase in benefits for further technical progress is smaller but more expensive. The know-how, which is underlying the technology, is increasingly available. Subsequently the technology is in the mature phase. Only small refinements are possible, however, benefit decreases. Once the technology is fully exploited in terms of its potential applications, it will pass over to the age phase. In this case, the technology will be replaced by a substitution technology, which has a higher potential. [11]

## 3 BATTERIES FOR AUTOMOTIVE APPLICATIONS

While in the past mainly nickel-metal hydride batteries and nickel-cadmium batteries were found in the hybridization of automobile applications today the lithium-ion batteries are used in (partially) electric vehicles because of their high energy density and other advantages. [14] For producing an efficiently working battery for automotive applications one of the prerequisite parts beside the used materials is the cell type. Comparing the three available cell types (round cells, pouch cells and prismatic cells) advantages such as a good energy and a high power density, a low self-discharge, an excellent thermal resistance and a short charging time convince. [15], [16] Therefore the article focusses on the battery assembly of lithium ion pouch cells.

### 3.1 Battery Assembly

Regarding pouch cells for the application in batteries for electric vehicles as the incoming product the battery assembly is divided into two sections: the module mounting and subsequently the battery assembly. In the first step the module, which consists of multiple cells, has to be mounted. Therefore cells are stacked and connected before cooling components can be installed. Different manufacturing technologies which can be used for connecting the cells are e. g. welding, screwing, riveting. After the module mounting several modules depending on the type of battery are connected and finalized to one battery. Figure 4 underlines the standard module mounting and the battery assembly process. Individual mounting steps as well as applicable manufacturing technologies for each process step depend on the battery type and its construction. [4]

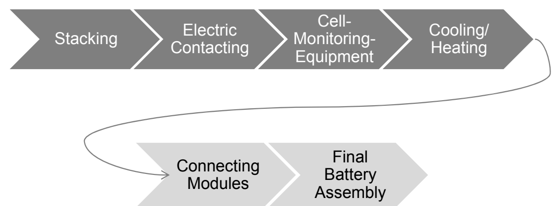


Figure 4: Battery assembly process. [4]

### 3.2 Quality Assurance during Battery Assembly

Quality management plays an important role along the entire production process of batteries from manufacturing the cell to assembling the battery. There are different criteria to be checked at each step during the assembly. When mounting the module it is important to control the torsional moment and for cooling components the leakproofness has to be verified. Subsequently the battery management system is assembled. Welding and soldering parameters are screened regarding electric indicators before the battery is tested. Finally the housing can be assembled as well as the battery can be tested as a whole with all its components. Especially the leakproofness, leak rate, torsional moment and welding parameters are validated conclusively. [4]

### 3.3 Configuration of a (Battery) Assembly

Regarding the configuration of a (battery) assembly previous approaches focus on solving assembly line design problem under consideration of line balancing to minimize total costs [17] [18] [19] or handling of multiple product on one assembly line [20]. As a further development Li describes a method to configure hybrid assembly lines based on product requirements. This approach assumes the linkage of product characteristics with assembly tasks without splitting an assembly station in separate station modules and its tasks which especially plays a role during the manual second section of a battery assembly. [21] In addition none of these approaches regard the integration of quality assurance during assembly planning.

## 4 EVALUATION OF CHANGEABILITY – BASICS AND STATE OF THE ART

Since the electric mobility faces many challenges which have an effect on the configuration of a battery assembly production process the changeability plays an important role. For that reason the changeability is explained in the following paragraph.

Describing changeability in one definition is not possible. Therefore, five different types of changeability are denoted: convertibility, reconfigurability, flexibility, transformability and agility. [22]

The concept of transformability is wider than the concepts of convertibility, reconfigurability and flexibility. When designing transformable production systems place for possible future changes is prefigured. Parts of the original production system can also be used for further changes. Therefore transformable systems provide generally mostly neutral solutions. However any additional changes causes effort to transform the system, but in comparison to less transformable systems the effort to react on changes is significantly lower. The primary change enablers include universality, mobility, scalability, modularity and compatibility. [23]

The approaches for the evaluation of transformability can be divided into qualitative and quantitative methods. On the one hand the quantitative evaluation methods include monetary approaches, originating predominantly from the static and dynamic investment calculation, such as the net present value analysis or real options method. On the other hand, there are several non-monetary quantitative methods. These include indicator systems as well as cost-benefit analyses. In addition to quantitative evaluation methods, there are qualitative assessment approaches. In particular, the scenario analysis, which focuses on derivation and valuation of future scenarios, the closely related life cycle assessment and the transformability potential value analysis that explicitly analyses the potential transformability of an object.

The existing evaluation methods of transformability consist of different approaches of the listed ones. Each method was adapted specifically to the topic of transformability. Depending on the focus, monetary aspects, such as the costs of transformability, or non-monetary benefits, such as the potential transformability or the optimal degree of transformability are conceivable. Figure 5 provides an overview of the used methods. [24], [25], [26], [27], [28]

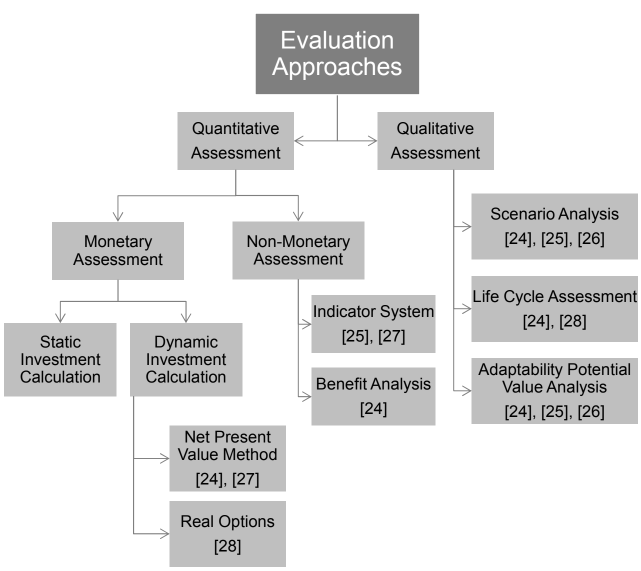


Figure 5: Overview of approaches for the evaluation of transformability. [24], [25], [26], [27], [28]

## 5 DEFICITS IN BATTERY ASSEMBLY PLANNING

Since the industry and technology concerning electric mobility are not fully explored there are still some deficits in terms of battery assembly and its changeability.

Currently there is no analysis available regarding alternative production processes and manufacturing technologies for battery assemblies. Furthermore, an automatic configuration of a battery assembly under consideration of single station formations is missing as well as the description of the interfaces in between the station modules. Relevant qualitative product and process parameters have not been captured momentarily nor has the quality strategy planning been integrated into the planning of the battery assembly (see chapter 3.3). Considering future developments in this market it will be necessary to develop a partially automatized planning method for battery assemblies based on customer individual product requirements, which is not available at the present time. There are still perspectives missing on common evaluations of changeability and/ or the reuse factor of immature technologies production processes (see chapter 4).

## 6 DEVELOPMENT OF A CONFIGURATOR FOR AN TRANSFORMABLE BATTERY ASSEMBLY PLANNING

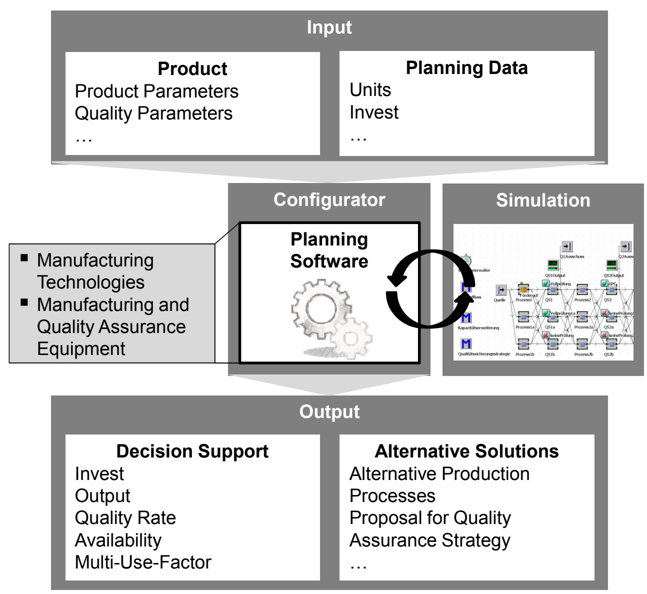


Figure 6: Basic idea of the configurator and its input and output parameters.

The idea of developing a configurator for a transformable battery assembly planning is to submit a partly automatic battery assembly planning including the selection of inspection devices depending on product features and on the evaluation of alternative process solutions. At the time a product developer has defined the first product idea and the management has set the planning data e. g. the amount of units per year the configurator generates a first glance how the battery assembly could look like while proposing possible manufacturing technologies and manufacturing equipment to realize the production process. The approach does not exclusively assist production developers. Also machinery and plant manufacturers can use the configurator for an efficient first planning of a battery assembly and for weighting different alternatives with regard to fixed output parameters. Therefore the configurator's basis is a database which includes knowledge about possible manufacturing technologies, manufacturing equipment and quality assurance aspects. The database is coupled with a material flow simulation which gives an idea of the output, the quality rate as well as e. g. the availability of the production process. The basic idea of the configurator is visualized in figure 6.

To develop the configurator the approach is split into three stages (figure 7). First step is the development of an automatic matching of product and process modules which is implemented in Microsoft Office Access followed by a second step; modeling a material flow simulation. Finally an evaluation of possible production process alternatives is described in the third step. In the following the approach is explained in detail.

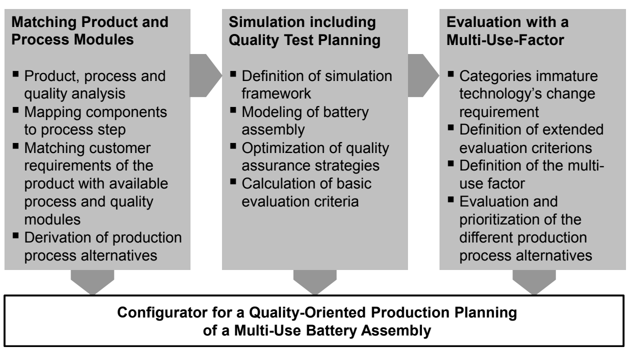


Figure 7: Approach to develop a configurator to create a multi-use battery assembly.

### 6.1 Matching Product and Process Modules

The first stage of developing the configurator starts with analyzing the product, the production process as well as the relevant quality characteristics to allow the linkage of product requirements with possible production process alternatives.

Hereby the following challenges have to be solved:

- Development of an automatic linkage which allows an association of product components with the specific process steps where the component is needed during production
- Considering that components which e. g. have to be joined together are not compulsory obstructed at the same production process step
- Modularization of the battery assembly
- Automatic linkage of product requirements with possible production process alternatives

The product has to be brought into a generic structure which contains many different product variants to allow an automatic mapping of single components to a specific process step. Therefore functional groups are described. The battery assembly process is mapped in an assembly priority plan. Thus, single product components can be linked to single assembly steps. Considering the modularization degree of the production process the battery assembly can be split into different observed objects. On one hand automatic assembly stations in the form of complete machinery are available to fulfill a fixed assembly task. That allows a simple allocation of machinery and assembly task. At this stage a machine is one production process module. On the other hand single assembly stations can be freely configured based on product requirements. The challenge lies in the configuration of assembly stations which are not available in the form of an existing machine. A assembly station which has to be configured contains a realization of a manufacturing technology e. g. a screwdriver, a manipulator to shift the manufacturing technology module, handling systems e. g. a gripper or a gantry, logistics and a periphery e. g. a safety housing. At that degree of modularization every assembly station contains of an variable combination of station modules.

In parallel a matching of product features with available production process modules and quality assurance modules to identify alternative production processes of the battery assembly is solved by identifying the product, alternative manufacturing technology and manufacturing equipment parameters which allow the linkage in between and the selection of corresponding production process modules. Therefore the interfaces and the implicit relations between all observed objects have to be defined. The matching is based on product parameters as the chosen material, the size, the weight, the processing and a lot more parameter on different hierarchic stages of the product, e. g. the battery, its modules and its cells. These product parameters as well as the planning data including e. g. a fixed number of units per year are compared with available machinery and their parameters. First, the manufacturing technologies which are possible for the realization of all requirements are matched. Subsequent to the technology selection the manufacturing equipment e. g. the manipulator has to be identified. This task is solved by using combinatorial analysis. The technology and fitting manufacturing equipment result in a suitable process module.

The suitable quality assurance modules derive from special product requirements e. g. tolerances and the manufacturing technology and equipment requests. Quality assurance modules consist of measurement technologies that can be used either as testing devices integrated in an assembly station as a station module e. g. a camera or as an independent quality station.

After having chosen the right process and quality assurance modules the operator has to arrange the production order if it differs from a standard battery assembly process. The lists of different battery assembly processes, its parameters and its order are input for the following material flow simulation.

### 6.2 Simulation Including Quality Test Planning

For every single production process alternative a separate simulation is initiated. Parameters as e. g. the working time, the single availability and quality rate of the chosen production and quality modules are input for the second stage, the material flow simulation, which delivers a possible number of units per year, a quality rate of the interlinked production process as well as the availability as output parameters. Moreover the automatic modification of quality modules parameter to find the best combination of quality test planning and its inspection scope are integrated in the simulation. The output parameters of the simulation deliver the base for the following evaluation of the different production process alternatives.

To reach this target first of all the simulation framework has to be defined. Therefore all input and output parameters are fixed as well as the simulation limits. Modeling the battery assembly is simplified by using an automatic method which builds the production process in the Siemens software PlantSimulation on the tabular information from the database. The standard Open Database Connectivity

(ODBC) is used as the interface between the database and the simulation to exchange the data table. Every simulation component is defined as a black box. The process independent design of the simulation enables short calculation times and a full automatically configuration. Single process modules can be tested on the scalability by parallelization if more capacity is needed. Additionally, the quality modules can be tested on the frequency of their quality test. Therefore, the trial administrator generates different quality test planning strategies and inspection scopes to balance cycle times according to the possible quality rate and product costs. The approach allows a fast modeling of a material flow even if the configurators' operator is not well versed in using simulation software.

### 6.3 Evaluation of Production Process Alternatives with a Multi-Use-Factor

Finally the different production process alternatives have to be evaluated and prioritized to provide the planner a decision support. First of all the evaluation considers the output parameters of the material flow simulation which are part of the OEE (overall equipment effectiveness). Additionally, next to the OEE, accruing investment and current costs and the multi-use (transformability and reusability) of the production process have to be considered as well.

The OEE is a key performance indicator which quantifies the effectiveness of a manufacturing operation's utilization. It is defined as the product of availability, performance and quality. [29] The consideration of accruing investments as well as the current costs depends on the level of information's detail. With regard to the immature lithium-ion technology the evaluation of changeability has to be defined in a new way. Therefore the demand of change for an immature technology has to be identified.

To investigate the maturity level of the lithium-ion technology it is subjected to the life cycle assessment. That allows identifying characteristics of the special technology to infer subsequently general technologies characteristics of this life cycle phase. Immature technology constitutes many challenges to a production system and the underlying level of the system e. g. the production process by the great performance potential and the associated changes as for example difficult demand forecasts, many product variants, product design changes, and replaceable manufacturing technologies. The focus is to consider the lithium-ion technology as the major change driver for the production system and using concrete characteristics of the transformation required for a production process of immature product technologies.

After analyzing the product technology of the lithium-ion battery technology it can be classified as technology of a transitional phase. Some of the technology features, such as the uncertainty regarding technical performance speak for a partial assignment to the development phase, while the maximum cost-performance ratio and the high numbers of patents are typical for the growth phase of a technology. Thus, the lithium-ion battery can be interpreted as a technology that is in transition from a pacemaker toward a key technology, in which it is already assigned with a larger proportion fulfilling indicators. Certainly the lithium-ion technology as pacemaker or key technology is not yet fully mature. Product technologies at this stage lead to special requirements for the production process. Major challenges as e. g. the different product designs or the high scrap require e. g. a simultaneous production of multiple product variants on one machine/ production process, a high process capability, quality assurance within the production.A production process of lithium-ion battery is thus not only influenced by a turbulent environment, but is especially forced by the immature product technology which forces changes in production processes. Hence, the lithium-ion technology can be identified as the main change driver for a battery assembly. Particularly in the areas which are affected by the immature technology the production process has to be designed transformable. Only a transformable production process is able to ensure a sustainable and stable production. Derived from the challenges of an immature technology the change enablers known from literature and their change potentials have to be weighted. After weighting change potentials of the change enablers their correlations have to be deduced. Finally a term to evaluate the transformability of an immature technology production process has to be developed.

As well as the transformability the re-use factor of the single process and quality modules has to be considered. Variables of the re-use factor are the probability of occurrence and the time of technological development. If e. g. a new material for the battery housing is known with its advantages in contrast to so far used materials but not field-tested yet it could have an impact in the future. It has to be estimated how probable it is to be launched and at which time. After that estimation it can be evaluated which process module should be used considering a possible material change in the future. Also the effect of the chosen process module on the rest of the production process has to be defined e. g. the need of an additional process step and associated investment. If e. g. a cluing process module is chosen to join the battery housing instead of a welding process module, an additional cleaning process step could be necessary and could have significant effects on the costs as well as on the OEE. In addition the comparison of the single modules OEE and the costs of the process module alternatives have to be identified and considered. Perhaps it is cheaper and more reasonable to implement a welding module today and substitute it in the future by a clueing module when the housing material is changed because its OEE justifies it then implementing a clueing module today. The transformability and the re-use factor are merged to the multi-use factor.

In conclusion the evaluation of different production process alternatives is complex regarding the different influence factors. As the result the evaluation provides the planner with a decision support by prioritizing all different alternatives with regard to the weighting of the planners' evaluation criterions.

## 7 CONCLUSION

Based on the challenges of the lithium-ion technology and its impact on the planning of the battery assembly production process the configurator shall enables product developers or machinery and plant manufacturers planning a changeable and reusable battery assembly. Therefore battery product requirements and assembly alternatives are analyzed and the combinatory basics to derive possible assembly alternatives from produced requirements are defined. Link the product requirements with possible assembly modules and configure assembly stations by using those single station modules were the main challenge which had to be solved. The structure for a material flow simulation to simulate e. g. the assembly lines' output and availability is developed while the quality assurance strategy optimization has to be integrated in the near future. The evaluation of stations alternatives by regarding transformability and reuse of single module for immature technologies as well as regarding the OEE and costs are in progress and have to be deepened.

The development of the configurator is part of the joint research project "Project quality-oriented, flexible battery production systems" (project number 16N12319). Thanks to the Federal Ministry of Education and Research (BMBF) who supports the project as part of the leading-edge cluster "Electric Mobility South West". The leading-edge cluster is managed by the state agency for electric mobility and fuel cell technology e-mobil BW and supported by the state of Baden-Württemberg as well.

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# Author Index