Hochschule Ostwestfalen-Lippe
University of Applied Sciences

UNIVERSITÀ
DEGLI STUDI DI TRIESTE

Production Engineering and Management

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PREFACE

The annual International Conference on Production Engineering and Management takes place for the sixth time this year, and can therefore be considered a well-established event that is the result of the joint effort of the OWL University of Applied Sciences and the University of Trieste. The conference has been established as an annual meeting under the Double Degree Master Program ‘Production Engineering and Management’ by the two partner universities.

The main goal of the conference is to provide an opportunity for students, researchers and professionals from Germany, Italy and abroad, to meet and exchange information, discuss experiences, specific practices and technical solutions used in planning, design and management of production and service systems. In addition, the conference is a platform aimed at presenting research projects, introducing young academics to the tradition of symposiums and promoting the exchange of ideas between the industry and the academy. Especially the contributions of successful graduates of the Double Degree Master Program ‘Production Engineering and Management’ and those of other postgraduate researchers from several European countries have been enforced.

This year’s special focus is on Direct Digital Manufacturing in the context of Industry 4.0, a topic of great interest for the global industry. The concept is spreading, but the actual solutions must be presented in order to highlight the practical benefits to industry and customers. Indeed, as Henning Banthien, Secretary General of the German ‘Plattform Industrie 4.0’ project office, has recently remarked, “Industry 4.0 requires a close alliance amongst the private sector, academia, politics and trade unions” in order to be “translated into practice and be implemented now”.

PEM 2016 takes place between September 29 and 30, 2016 at the OWL University of Applied Sciences in Lemgo. The program is defined by the Organizing and Scientific Committees and clustered into scientific sessions covering topics of main interest and importance to the participants of the conference. The scientific sessions deal with technical and engineering issues, as well as management topics, and include contributions by researchers from academia and industry. The extended abstracts and full papers of the contributions underwent a double-blind review process. The 24 accepted presentations are assigned, according to their subject, to one of the following sessions: ‘Direct Digital Manufacturing in the Context of Industry 4.0’, ‘Industrial Engineering and Lean Management’, ‘Management Techniques and Methodologies’, ‘Wood Processing Technologies and Furniture Production’ and ‘Innovation Techniques and Methodologies’.

As the editors of the proceedings, we would like to thank all contributors, the referees who accepted the burden of reviewing the abstracts as well as the full papers and the members of the Organizing Committee and Scientific Committee for planning such an effective conference.

Franz-Josef Villmer *Elio Padoano*

CONTENT

SESSION G
Innovation Techniques and Methodologies

SESSION A

Direct Digital Manufacturing in the Context of Industry 4.0

ASSISTANCE SYSTEMS IN MANUAL ASSEMBLY

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Abstract
Due to the continuing trend towards more complexity of products with an increasing number of variants and smaller lot sizes, the assembly often takes place - despite relatively high labor costs in Western industrialized nations - manually or partially automated. An outsourcing or relocation of assembly function abroad is not suitable in most cases.
Therefore, it is increasingly important to reduce process variations and waste in manual assembly processes. Assistance systems have the potential, depending on the situation, to assist the worker in his work, to reduce error rate and to increase productivity. In a first part of the paper an overview will be given to different types of assembly assistance systems. Then a morphological chart is developed, which can provide assistance in selecting or comparing assembly assistance systems. With the help of this chart an assembly assistant system is presented. Finally a quick look is taken at further research being done in this area.

Keywords:
Assistance systems, Manual assembly, Morphology

1 INTRODUCTION

More than seven million people in Germany work in manufacturing. In addition to this large number of employees, the industry also has a high export quota of around 45%, which is of significant economic importance to the sector [1]. A number of major manufacturing industries (e.g. electrotechnical industry, mechanical engineering sector, automotive industry) have one thing in common, namely the companies operating in these sectors usually have large assembly areas. Due to the continuing trend towards more complexity of products with an increasing number of variants, smaller lot sizes and shorter life cycles, assembly often takes place - despite relatively high labor costs in Germany - manually or is partially automated. An outsourcing or relocation of assembly function abroad is not suitable in most cases, since the assembly is at the end of the value chain of a company, has a comparatively high logistical and organizational complexity and outsourcing may in consequence have a negative impact on delivery reliability. Due to the large number of employees in manual or hybrid assembly areas and the resulting economic

and occupational concerns, the design of assembly systems becomes more important, both from the employer's and the employees' perspective [2].
Since the mid-1990s, the design of working systems in assembly has also been influenced in Germany by the principles of the Toyota production system [3]. Focusing on adding value, flow and pull principles in combination with a strong standardization of work processes and a strong breakdown of work are some of the main principles of the system. Many companies in Germany have developed production systems based on the Toyota Production System [4] [5], most of which focus especially on the labor-intensive activities in manual or hybrid assembly. Order information with a description of the assembly task is still provided to employees in assembly (varying sections) mostly on paper or is displayed on screens [6]. Based on a survey conducted by Wiesbeck, mostly traditional design elements such as text, tables, or drawings are currently used by companies [7]. Animations or videos are hardly ever used to guide assembly workers. The current way of providing information to assembly employees has several disadvantages:

- When employees have to continuously turn back to look at the display or have to rustle through order papers, it results in additional, adverse body movements.
- Employees cannot fully absorb information due to the unsuitable display of assembly information, so that employees' movements may be delayed or assembly errors may occur as a result of misinterpretation of information.
- Order documents may be damaged or lost. They do not represent an ideal production process that is digitally-supported throughout.

Current requirements for assembly systems contradict the evolution of the technological possibilities for the design of manual and hybrid assembly systems. In particular, this includes innovative assistance systems that give employees situational-based assistance in performing the assembly task. These assembly assistance systems include, for example, cooperative robots, wearables, light and laser-based assistance systems as well as ultrasound-based localization systems. In combination with work design methods and Lean Management (e.g. Low Cost Intelligent Automation), assistance systems can significantly improve the effectiveness and efficiency of the assembly. Effectiveness refers here to the quality of the task processing (e.g. a low error rate) while efficiency refers to the lowest amount of resources being used (e.g. task completed in a low amount of working hours).

2 CONCEPT AND DESIGN OF ASSISTANCE SYSTEMS

An assistance system is a technical system that receives and processes information from its environment in order to support people in carrying out their tasks. The support provided by the system can also include a warning about hazards or automatic intervention in dangerous situations [8]. Employees receive information through a task system, process the information and give the system feedback on input systems. The information output is usually visual, auditory or tactile. The information is processed using human senses and cognitive processes. The subsequent information is entered manually or by foot via actuators, verbally through speech input, using gesture recognition or tracking systems, or through human motion detection (e.g. [9]).

When designing the assistance system, the compatibility principle should be considered. This means that information presentation and actuator technology (for physical assistance systems) should be designed in such a way that they mirror the mental model formed to process the task and human logic as much as possible [10]. Many of the signals in the work process require human interpretation. This interpretation is also known as the decoding of signals and means that the user decodes input data on the necessary actions [11]. With the number of transformation steps necessary for decoding, the time needed and the probability of an operational error both increase, given that the cognitive capacity to maintain intermediate results is limited. Therefore, work design measures aim to reduce the necessary transformation steps [11]. The information necessary to execute the work should first be presented in such a way that pictorial information, rather than abstract, conceptual information, is used as much as possible. Second, the information should be made available - in terms of space and time - so that they comply with the necessary actions [11]. These two requirements thus ensure that the necessary information are made available pictorially at the right time and in the right place, so that the decoding complexity and in turn, the use of mental resources, are kept to a minimum and the task is carried out in an effective and efficient manner. The compatibility principle described corresponds in particular to the individual principles of dialogue design. These include task appropriateness, self-descriptiveness, compliance with expectations, suitability for learning, controllability, error tolerance and customizability. These principles should be considered when developing and evaluating assistance systems (DIN EN ISO 9241-110:2006 [12]).

According to Geiser [8], four interdependent models (task, user, environment and interaction) should be distinguished when designing an assistance system (Fig. 1). A modeling with a description of the interactions between essential model variables can effectively support the process of determining requirements and roughly conceptualizing an assistance system.

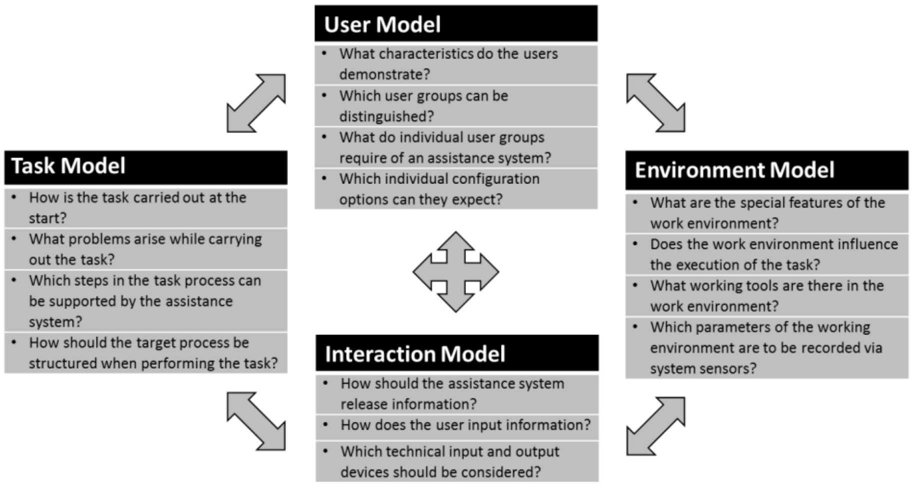

Figure 1: Modeling to support the design process of an assistance system.

At the core of each assistance system is a **task model**. In most cases, the user is guided with step by step instructions through the process. As such, system-guided interaction techniques dominate assistance systems [13]. When designing an assistance system, the task is to break it down into individual activities and present it in a process model. Questioning and observing users, and evaluating existing process indicators (e.g. error rate), can help identify activities and decisions that could be supported by an assistance system. The results produce an initial target process, which provides assistance and support and may be considered appropriate to the task. The purpose of the **user model** is to identify essential characteristics of the user with the goal of determining differences between users to form user groups and, in particular, to become familiar with what users and user groups require of assistance support. The **environment model** includes a description of typical spatial arrangements of users and objects (e.g. products, tools, computers) and of environment variables (e.g. noise, vibrations, light). In addition, the automatic detection of environmental variables via sensors is established in the model. The **interaction model** establishes the terms of the information input and output. Based on these terms, the relevant technical systems are selected for input and output.
The four models influence each other. The conceptualization of an assistance system is an iterative process, in which repeated usability test phases have to be planned according to DIN EN ISO 9241-210:2010 [14]. For example, the user model significantly influences the task and interaction models, in particular the scope and nature of the assistance function, the

choice of input and output units and the dialogue design. The environment model in turn has a large effect on the interaction model since certain environment variables (e.g. noise) can have an adverse effect on certain forms of interaction (e.g. voice input) and the models must be compatible. At the same time task and user models have an effect on the environment model because based on these first two models, one can assume that automatic detection of environmental variables will be required. This often consists of documenting environmental parameters and detecting deviations from the target state.

3 CONCEPT AND MORPHOLOGY OF ASSISTANCE SYSTEMS IN MANUAL ASSEMBLY

Manual assembly assistance systems are technical systems that receive and process information to assist employees in carrying out their assembly tasks. Assembly tasks (assembling) refer to all manual and mechanical operations in place to ensure the creation of a detachable or non-detachable connection of geometrically-defined entities [15]. Assembly operations always consist of joining and handling operations. In addition, assembly operations can also consist of adjusting, controlling and various auxiliary operations (e.g. cleaning, unpacking, printing, oiling) [16] [17].

Manual assembly assistance systems can be classified according to various criteria. The results can be summarized in a morphological box. The purpose of the morphology method is to present a solution space by breaking down the complex situation into individual characteristics and characteristic values [18]. Through morphology, the characteristic values of a specific assistance system can be presented by relating the individual features of the characteristics. A solution idea is generated analytically by changing one or more characteristic values for benchmarking purposes and the individual assistance system can be further developed. An initial morphology of a manual assembly assistance system is shown in Figure 2.
Based on the type of system support, one can distinguish between physical (e.g. cooperative robots lifting a load) and informational (e.g. displaying the content of the next work step) assistance [19] [20]. Physical assistance systems are designed to ensure the feasibility of the task and to reduce the physical strain on employees [19]. Informational assistance systems are designed to avoid uncertainties and mental stress among employees. Both types of assistance systems particularly aim to increase productivity and quality.

Manual assembly assistance systems can be broken down into stationary assistance systems, mobile assistance systems, hand devices and wearables. Data is transferred either through a cable or wireless connection (e.g. ultrasound, Bluetooth, RFID or WiFi).

CHARACTERISTICS	CHARACTERISTIC VALUES					
TYPE OF SYSTEM SUPPORT	Physical			Informational		
TYPE OF THE ASSISTANCE SYSTEMS	Stationary (fixed installation)	Mobile (mobile installation)		Hand device	Wearable - Head - Upper body - Arms/Hands - Legs/Feet	
DATA TRANSFER	Linked by cable			Wireless		
TYPE OF SUPPORTED OPERATIONS	Joining	Handling	Adjusting	Controlling	Auxilliary processes	Setting up the assembly system
SCOPE OF PROCESS SUPPORT	Partial process(es)			Total process		
HUMAN-MACHINE INTERFACE	Unimodal			Multimodal		
TYPE OF INFORMATION OUTPUT	Visual (optical)	Auditory (acoustic)	Tactile-kinesthetic (tactile)			
TYPE OF VISUAL INFORMATION OUTPUT	On-screen display	Representation in the working area (e.g. illuminated display, projection)	Working area display superimposed over the assembly object (e.g. in-situ projection, AR display)			
SCOPE OF THE VISUAL INFORMATION OUTPUT IN THE WORKING AREA	No output	Selective presentation (e.g. illuminated display, marking aids)	Limited display of symbols, images or drawings	Extensive presentation of items such as images, videos and animations (multimedia)		
TYPE OF THE INFORMATION INPUT/ SYSTEM CONTROL	Manual (via actuators)	Verbal (voice control)	Gesturing (tracking system)	Automatic (sensory)		
SCOPE OF USER CONFIGURATION	Set configuration of information input and output	Individual configuration of information output	Individual configuration of information input and output			
USER RECOGNITION	None	Registration and uploading of user profiles	Automatic registration and uploading of user profiles			
SITUATION/ MOTION DETECTION	None	Via measurement sensors	Via optical sensors	Other		
COMPATIBILITY/ INSTALLATION EFFORT	Entire workplace has to be newly configured	Basic adjustments made to the workplace	Minor adjustments made to the workplace	No adjustments made to the workplace		
FLEXIBILITY IN RECONFIGURING THE WORKPLACE	Substantial adjustments to be made to the main hardware	High software reconfiguration effort (done by qualified specialists)	Average software reconfiguration effort (done by specialists on site)	Low software reconfiguration effort (done by user on site)		

Figure 2: Morphology of assistance systems in manual assembly.

Stationary assistance systems are installed at a particular workstation (e.g. mounted projection device). Mobile assistance systems, however, are mobile solutions that can be moved to mount an object. Such solutions can be used, for example, in the context of injection molding, stamping and forming die assembly [21]. Hand devices (e.g. tablet PCs) or wearables (e.g. smartwatches) can display the information required for the assembly process in an appropriate form at the assembly site (e.g. AR display, illustrated assembly instructions) or record information of all kinds from the environment (measurement of entity values, gesture recognition, etc.).

In turn, wearables can be classified according to the part of the body where they are worn. Typical body parts are the head (smart glasses), hands (smart gloves) and wrists (smartwatches). For example, the company ProGlove developed a glove that is equipped with various sensors and is suitable for the following uses: "Hands-free scanning of goods, monitoring and training of workflow sequences, identification of tools and parts to avoid incorrect usage, 100% documentation of goods and processes" [22].

Depending on the type of supported operations, the support may be taken from joining, handling, adjusting, controlling and/or auxiliary operations. In addition, the configuration of an assembly system using assistance functions can be supported. The scope of the process support will be distinguished by whether the assistance system supports all operations or one/multiple sub-processes (e.g. pick-to-light function supports the "targeted flow to container" sub-process).

Moreover, it can be distinguished whether the man-machine interface is unimodal or multimodal in design. Unimodal means that a specific channel is available for receiving information, mostly visual, and another for entering information, mostly manual. Multimodal interfaces, however, take account of various input and output modalities [9].

Another classification can be made according to the type of information output. Of the human sensory organs, only visual, auditory and tactile-kinesthetic sensory modalities are addressed through optical, acoustic and tactile display [8]. If different forms of coding are used, such as text, voice and image, it is multimedia [8].

A simple way of displaying information is a touchscreen display that shows the assembly instructions. Other types of information display that can help guide employees include illuminated displays (e.g. pick-to-light) or projections directly in the workplace, or even images superimposed on the assembly object, which can be implemented using an in situ projection or AR display. Furthermore, the scope of the information output is described to indicate whether it is a selective display or a limited display of symbols, images or drawings - as it is the case with laser projectors for example - or whether multimedia presentations are possible in the form of images, videos and animations.

Analogically, one can differentiate between the types of information input. The information is entered manually using the actuators (e.g. buttons, switches), verbally through voice input, using gesture recognition, through tracking systems that detect human movements (e.g. [9]) or automatically by sensors, where the state of the working object respectively the status of the work process is monitored.

Assistance systems can also be differentiated based on the extent to which the user is given the opportunity to configure input and display systems, as well as the level of support provided by the assistance system according to the user's requirements. In this context, one can also determine whether users can log in to the assistance system or are automatically logged in, so that the preferred system configuration of a user is automatically established.

Situation recognition is another possible feature of an assistance system. Sensors record environmental data. The system controller processes these data and informs the user, for example, in case of deviations from the target state. In addition, sensors are used to determine the state of task processing (task model) and to automatically display for the user - once he/she has successfully completed the task (e.g. removal of the correct component from shelf) - the next step to perform (e.g. assemble the component). In this case the morphology between measurement sensors (e.g. resistive, capacitive, inductive, piezoelectric or mechanical sensors) and optical sensors (e.g. CCD sensor, CMOS APS sensors) is determined.

The compatibility of assistance systems can be described in terms of the respective complexity of implementing existing work systems. As such, the degree to which adjustments to the current working system are required plays a role.

To evaluate the flexibility of an assistance system, one can consider the effort involved in reconfiguring a work system that may be necessary to change variants. One decisive factor is whether a substantial hardware conversion is required and how much effort it takes to reconfigure the respective software. The highest possible suitability for use can be achieved with a simple and intuitive configuration option that enables the user to make configuration adjustments on site (excellent usability).

4 CLASSIFICATION OF A MANUAL ASSEMBLY ASSISTANCE SYSTEM IN THE MORPHOLOGY

The stationary version of the projection-based assembly assistance system developed by the Industrial Engineering Lab and the company Assembly Solutions [23] includes an informational assistance function. It is distinguished by the fact that it supports various operations and generates self-descriptive and multimedia assembly instructions. These are displayed in direct view of the user and also superimposed over the assembly object as shown in Figure 3. The display includes text and image content as well as animations and video sequences for an appropriate representation of the assembly instructions, a pick-to-light function for selecting the correct components in the right quantity as well as markings or positioning representations directly on the place of assembly (in situ projection).

The system also has an auditory output that can provide information acoustically (e.g. by means of a headset). Work instructions are displayed intuitively and relative to the situation, and consider ergonomic aspects.

Figure 3: Projection-based assembly assistance system.

The assistance system provides a multimodal operating concept, which includes manual, verbal and gesture-based information input. Thus, the user can navigate through the system via push button or touch pad, voice input or optical gesture recognition. The user can load his/her configured user profile in which information input and output can be configured individually.

The goal of the assistance system is, among other things, to shorten learning time and increase process capability (efficiency). Procedures can be described and visualized in a short amount of time (efficiency) [23].

Currently, the system still has no situational recognition feature. However, it is flexible and can be quickly adapted to company-specific circumstances. Compatibility and flexibility can both be considered high, as only minor adjustments are required to the workplace and when performing reconfigurations on site.

The classification of the manual assembly assistance system in the morphology is shown in Figure 4.

CHARACTERISTICS	CHARACTERISTIC VALUES					
TYPE OF SYSTEM SUPPORT	Physical	Informational				
TYPE OF THE ASSISTANCE SYSTEMS	Stationary (fixed installation)	Mobile (mobile installation)	Hand device	Wearable - Head - Upper body - Arms/Hands - Legs/Feet		
DATA TRANSFER	Linked by cable	Wireless				
TYPE OF SUPPORTED OPERATIONS	Joining	Handling	Adjusting	Controlling	Auxilliary processes	Setting up the assembly system
SCOPE OF PROCESS SUPPORT	Partial process(es)	Total process				
HUMAN-MACHINE INTERFACE	Unimodal	Multimodal				
TYPE OF INFORMATION OUTPUT	Visual (optical)	Auditory (acoustic)	Tactile-kinesthetic (tactile)			
TYPE OF VISUAL INFORMATION OUTPUT	On-screen display	Representation in the working area (e.g. illuminated display, projection)	Working area display superimposed over the assembly object (e.g. in-situ projection, AR display)			
SCOPE OF THE VISUAL INFORMATION OUTPUT IN THE WORKING AREA	No output	Selective presentation (e.g. illuminated display, marking aids)	Limited display of symbols, images or drawings	Extensive presentation of items such as images, videos and animations (multimedia)		
TYPE OF THE INFORMATION INPUT/ SYSTEM CONTROL	Manual (via actuators)	Verbal (voice control)	Gesturing (tracking system)	Automatic (sensory)		
SCOPE OF USER CONFIGURATION	Set configuration of information input and output	Individual configuration of information output	Individual configuration of information input and output			
USER RECOGNITION	None	Registration and uploading of user profiles	Automatic registration and uploading of user profiles			
SITUATION/ MOTION DETECTION	None	Via measurement sensors	Via optical sensors	Other		
COMPATIBILITY/ INSTALLATION EFFORT	Entire workplace has to be newly configured	Basic adjustments made to the workplace	Minor adjustments made to the workplace	No adjustments made to the workplace		
FLEXIBILITY IN RECONFIGURING THE WORKPLACE	Substantial adjustments to be made to the main hardware	High software reconfiguration effort (done by qualified specialists)	Average software reconfiguration effort (done by specialists on site)	Low software reconfiguration effort (done by user on site)		

Figure 4: Classification of the described manual assembly assistance system in the morphology.

5 OUTLOOK

Modeling with a description of the interactions between essential model variables can effectively support the process of determining requirements and roughly conceptualizing an assistance system. Beyond that, the

morphology of the aforementioned features and characteristic values provide assistance in selecting or comparing assembly assistance systems. In addition, a morphology can help to show the potential of an assistance system for further development. To make detailed comparisons, the morphology should be made more concrete.
The market for assistance systems in an industrial context is developing very rapidly. There are various approaches and technologies to support assembly operations - however, their respective application possibilities and limits are still mainly unexplored. In addition to technological developments, it is necessary to develop guidelines to accompany the process of selecting and configuring assistance systems from a user perspective. Moreover, when implementing assembly assistance systems, it should be taken into account that before a system can be implemented, the potentials of work structuring should first be implemented. Employees should also be included in the change process to a great extent, so that the system meets their needs and is accepted well.

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SPECIAL REQUIREMENTS FOR ADDITIVE MANUFACTURING OF DENTAL FRAMEWORKS

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Abstract
Additive Manufacturing (AM) describes a number of technologies that generate three-dimensional objects directly from CAD data by joining volume elements. Dental technology is one sector in which the benefits of AM come into effect, as parts such as frameworks or implants are unique objects often with freeform shapes. These objects are difficult and expensive to produce with subtractive or formative technology.
During the last decades, the application of digital technologies in the dental industry has increased. Therefore AM has also evolved to become a standard dental framework manufacturing process. While previously the dental laboratory did the complete manufacturing of dental frameworks, AM parts are usually produced by service providers, thus increasing the number of process participants. Under these circumstances, a reliable high quality production must be ensured. This requires a comprehensive Quality Management (QM) concept for the whole process chain. A first step in the development of this QM concept is the definition of the product requirements, from which process specifications can be determined. These specifications build the basis for evaluating the process capability of the Additive Manufacturing process.

Keywords:
Additive Manufacturing, Dental frameworks, Quality management, Digital manufacturing

1 INTRODUCTION

The term Additive Manufacturing (AM) describes a number of different technologies that enable the creation of parts directly from three-dimensional CAD-data, by additive joining of layers or volume elements [1]. Since the advent of the first AM machines in the late 1980s, developments in this field have led to a large variety of technologies for the processing of plastic, metal and also ceramic material. Today, a number of AM technologies show a degree of maturity that allows their application for final part production. AM is well suited for the production of individual parts, e.g. for medical or dental applications, as the production costs are mostly independent from lot sizes [2].

Until now, skilled workers mostly produced individual dental prosthetics manually. With progress in the development of AM technologies, they are increasingly becoming standard technologies for the production of dental prosthetics, such as crowns or bridges. Examples for possible AM applications in dental prosthetics production are 3D-printing of wax models for precision casting, or Additive Manufacturing of metal frameworks by Selective Laser Melting (SLM). This paper focuses on the latter.

Gebhardt states that experts in dental technologies consider additively manufactured dental prosthetics and implants worldwide revenue growth rates of 15% per year to be realistic, as predicted by the Albany Transparency Market Research Institute [3]. It is to be expected that this development will have a considerable impact on the dental sector, especially as many providers are small laboratories. For example in 2015 the German professional association “Verband Deutscher Zahntechniker Innungen” counted 8.328 dental laboratories with 65.663 technical employees, which equals an average of less than eight employees per laboratory [4].

While the general applicability of AM technologies for the production of dental restorations has been subject to different research work [5, 6], concepts for a systematic Quality Management process are still rare. The first step within the development of a suitable Quality Management concept must be the definition of the process requirements; these requirements need to be deduced from the characteristics required of the final product. At the same time the complete process chain, including its degree of digitalization, has to be considered.

2 THE PROCESS CHAIN IN DENTAL TECHNOLOGY

2.1 Conventional Manufacturing

The conventional dental restorations manufacturing process chain consists of several process steps, which are exclusively manual work. Dentists and dental laboratories are the main providers of this process, as shown in Figure 1. While the dentist performs the preparation of the tooth substance and takes the imprints at the beginning of the process, most of the restoration production steps are carried out by the dental laboratory. The final step is fitting the patient with the restoration, which is again conducted by the dentist.

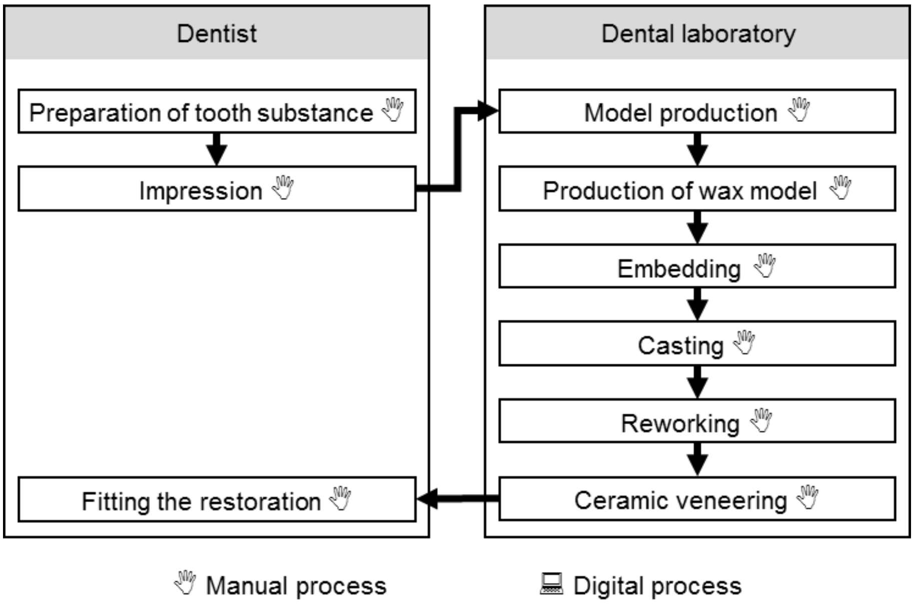

Figure 1: Conventional dental technology process chain, according to [7].

In spite of careful preparation during all process steps, reproducibility is still limited and the susceptibility to errors is high. The quality of the final product, in this case, heavily depends on the dental technicians' diligence and specialist knowledge. [8]

2.2 CAD/CAM Manufacturing

The potentials of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) usage in dental technology were recognized in the 1970s. From this point on various researchers and companies worked on adapting the industrial CAD/CAM applications to the needs of dental technology. The first commercial systems, focusing on the production of ceramic inlays, were launched in 1985 [7].

Currently, a number of systems with different levels of digitalization are used, though the trend aims for a completely digital process chain, starting with the intraoral capturing of the data by direct scanning of the jaw [9]. Figure 2 shows the lowest and the highest possible level of digitalization in the dental framework production process chain. In the first case the wax model is produced in a conventional manner. In the next step the digital data is created by scanning this model. This data is then used for CAM dental part production. For the highest level of digitalization, the physical modeling is replaced by digital processes, beginning with the intraoral scan of the jaw, to create a digital imprint. Processes with a medium level of digitalization can also work by scanning the plaster model of the jaw [7, 8]. In general, the reworking of the CAM-produced parts and the ceramic veneering, as well as the preparation of the tooth substance and the oral fitting are still manual processes.

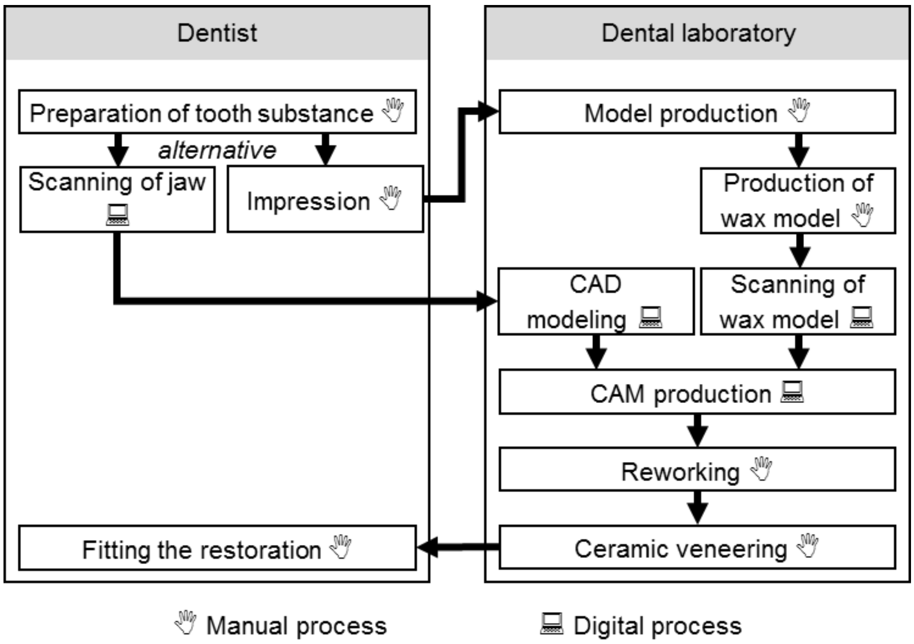

Figure 2: Digital process chains in dental technology, according to [7].

The choice of a certain level of digitalization depends on a number of different factors. On the one hand, the technical equipment of the dental laboratory and the dental practice is important, as well as the dentist´s or technician´s attitude towards digital production. On the other hand, various technical reasons influence the choice. The precision required is one major factor that determines the choice of the scanning device. While lower accuracy is sufficient for smaller restorations, for larger restorations, e.g. bridges, a higher degree of accuracy is needed.
Intraoral scanning devices show lower measurement accuracy due to their limited size and possibility of the patient moving during the scanning process. Thus their application is often limited to data capturing for smaller restorations, though some systems are available that are also suited to the production of three- or four-unit bridges [7, 10].

CAM production of dental restorations includes a number of different technologies: Subtractive Manufacturing, such as milling or grinding, is applied, as well as Additive Manufacturing, for example SLM. The choice of the most suitable technology depends on the accuracy required and the material to be processed, as well as on production costs.
Enabling the production of restorations under standardized conditions and with consistent quality is one of the advantages of CAD/CAM production in dental technology [7]. The increasing digitalization of the processes causes a development from manual to industrial production.

2.3 Additive Manufacturing

Additive Manufacturing by SLM is well suited for the production of metal frameworks for crowns and bridges, as different metal materials can be processed without the use of product-specific tools or molds. Here, this technology is an interesting alternative to conventional precision casting and Computer Numeric Control (CNC) milling or grinding.
The basic principle of SLM technology is to spread a layer of powder on a build platform and selectively fuse this powder in the area where the part has to be generated. After that the platform is lowered, a new layer of powder is spread and fused again. This procedure is repeated until the final product height is reached and thus the product is generated layer by layer, surrounded by the residual powder. Typical achievable quality characteristics according to machine manufacturers are a dimensional accuracy of 0.02 to 0.05 mm and surface roughness R_z of 20 µm [11, 12].

3 QUALITY MANAGEMENT

Dental restorations, like all medical products, are subject to a large number of regulations. In manual production, that is common for the conventional process chain, the compliance with quality requirements is monitored by final product quality control. The skilled workers are responsible for evaluating their own work.
In industrial production, the quality management focus is shifted towards process capability. This means that the production process has to be designed in such a way that a consistent high level of compliance with the quality requirements is ensured. The production within the specification limits is evaluated by sampling inspection and application of statistical methods [13]. For individual parts, such as dental restorations, regular inspection is limited to non-destructive testing. As dental restorations usually consist of freeform surfaces, dimensional inspection is especially demanding. Consequently, it is extremely important to have a production process that operates reliable within the specification limits.
Currently the SLM process still has some disadvantages compared to subtractive processes. Besides the dimensional accuracy limits and surface quality (cf. chapter 2.3), it also shows lower reproducibility.

4 PRODUCT REQUIREMENTS

4.1 General Requirements

Regarding this reserach, only few quality requirements for dental frameworks are defined, as they are an intermediate step in the production process of dental restorations. Nevertheless, specifications for materials and for the final restorations exist and many requirements can be transferred to the intermediate product.

In general, the quality demands for dental frameworks can be subdivided into chemical, physical, mechanical and geometrical properties. Chemical properties, e.g. biocompatibility, corrosion resistance and resistance to tarnishing, are subject to different dental material standards. Physical properties are also subject to standards relating to density, solidus and liquidus temperature and thermal expansion. These standards also include minimum requirements for different mechanical properties [14, 15, 16].

An overview of the requirements according to German standards is given in table 1.

Table 1: Standardized quality requirements for dental frameworks, according to [14, 15, 16].

Category	*Characteristic*	*Standard*
Chemical	Biocompatibility	DIN EN ISO 10993
	Corrosion resistance	DIN EN ISO 22674:2006 ISO 10271:2001
	Resistance to tarnishing	DIN EN ISO 22674:2006
Physical	Specific density (compared to material specification)	DIN EN ISO 22674:2006
	Solidus and liquidus temperatures (compared to material specification)	DIN EN ISO 22674:2006
	Linear thermal expansion (compared to material specification)	DIN EN ISO 22674:2006
Mechanical	0.2% Proof stress (absolute value)	DIN EN ISO 22674:2006
	Elongation at break (absolute value)	DIN EN ISO 22674:2006
	Young´s modulus (absolute value)	DIN EN ISO 22674:2006

In addition to these standardized requirements, different quality needs can be ascertained according to the application of the final part, as well as from the production process. These include geometrical properties, e.g. dimensional accuracy or surface roughness, as well as a number of qualitative characteristics, for example visual appearance or processability.
In contrast to the well-defined standardized characteristics, no generally accepted specified values and tolerances exist for these properties. Their evaluation is based on the process participants' individual expertise. While this approach delivers satisfactory results for the final product, it makes the application of quality management techniques, such as determination of process or machine capability, extremely difficult.
Few attempts to define dimensional tolerances can be found in literature. For example, Uckelmann determined maximum values for the deviation in shape of 50 µm for crowns and 100 µm for larger bridges [5]. This specification is based on studies regarding the maximum acceptable gap width between the edge of the dental restoration and the remaining teeth. It needs to be taken into consideration that these values are only valid for the crown margin of the final restoration and thus are not necessarily transferable to all the dimensions of the metal framework.
Another important factor is the surface roughness. While a certain roughness is helpful for the ceramic veneering to form a strong bond between the metal framework and the ceramic material, the interface to the remaining teeth needs to be very smooth. This leads to varying requirements for different areas of the framework, which are not universally defined.

4.2 Specific Requirements for Additive Manufacturing

These product requirements can be transferred into requirements for the Additive Manufacturing process. An approach for this is made based on the authors´ experience. Not all of the defined requirements can be influenced by the parameter settings of the SLM process. For example the chemical properties mostly depend on the composition of the alloy used. The microstructure that is formed during solidification is the only factor influencing the process for these properties. It may differ from the one formed in a casting process due to different thermal conditions. Nevertheless, it can be assumed that a material will usually fulfill the chemical requirements once it is qualified. The same applies to the physical properties, e.g. solidus and liquidus temperature or thermal expansion. They are subject to the raw material production.
In contrast to this, the density of the final part is strongly influenced by the SLM process. Only complete powder melting, without vaporization of single alloy components, will lead to a fully dense part. This density also has a strong influence on the mechanical properties. They are further influenced by the microstructure and the surface quality of the part, the latter can be particularly influenced in the SLM process. Besides its impact on the mechanical properties, the surface roughness additionally affects the adhesion of the ceramic veneering.

The dimensional accuracy is also influenced by the parameters of the SLM process. It is, for example, strongly dependent on the layer thickness, the powder grain size and the laser beam focus diameter. Accuracy can be improved by reducing all three parameters, however, this results in a decrease of building speed and will thus lead to higher production costs.
Based on analysis of the required properties, density, 0.2% proof stress, elongation at break, dimensional accuracy and surface roughness can be identified as the crucial quality needs that can be influenced by the SLM process. The parameters and their required values are listed in table 2.

Table 2: Required parameters for dental frameworks.

Parameter	*Required value*
Specific density d	± 5% from material specification [15]
0.2% proof stress $R_{p0.2}$	≥ 360 MPa 1) [15]
Elongation at break A	≥ 5% 1) [15]
Dimensional accuracy Deviation in shape	50 or 100 µm [5]
Surface roughness	Not defined

1) DIN EN ISO 22674 defines requirements for mechanical properties according to the intended application of the material. Dental frameworks can belong to type 3 or 4. In each case the higher value is considered here.

4.3 Comparison to the State of the Technology

Comparisons to references can be considered to get an initial impression of the ability of the SLM process to reliably fulfill these requirements. Though the specified dimensional accuracy of 0.02 - 0.05 mm (cf. chapter 2.3) in principle meets the required value of 50 µm, the reference frame is not completely clear. The specified value does not necessarily refer to the deviation in shape, so that the two values are not exactly comparable.
A clear definition of a required surface roughness is not given. Nevertheless, the achievable values presumably do not fulfill the requirements for the smooth interface between the restoration and teeth. Here manual or mechanical post processing work is inevitable.
As little research work deals with the repeatability of the SLM process and, furthermore, results for one material are not transferable to other materials, pre-tests were carried out for dental materials. In this case tensile specimens were produced by SLM as well as by precision casting. Two different dental laboratories performed the precision casting and the SLM samples were produced on a Realizer SLM 50 machine with a predefined data set for the CoCr material used. Tensile tests with six samples each were performed according to DIN EN ISO 22674 [15]. Figure 3 shows the tensile bar that was used according to this standard.

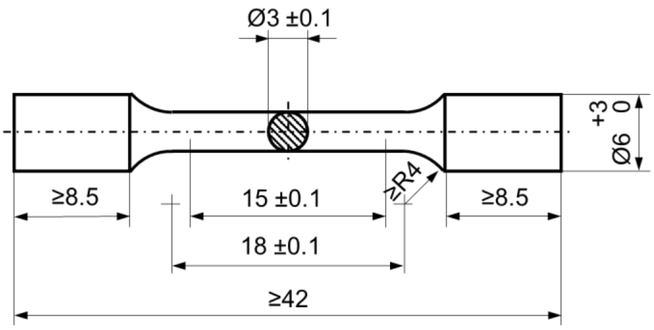

Figure 3: Tensile bar, according to [15].

Additional diameter measurements were carried out for these samples with a micrometer gauge. [17] Though it does not directly evaluate the shape deviation, this measurement of the dimensional accuracy can give a rough idea of the viable accuracy. For all sets of samples the mean values were calculated as well as the standard deviation. The results compared to the required values (cf. table 2) are shown in Figure 4.

It can be observed that in this test the SLM parts fulfill the requirements for the mechanical properties and the density. Compared to the precision cast parts, the mechanical properties of the SLM parts are higher and tend to show a smaller standard deviation. But a definite statement is not possible due to the small number of samples.

The SLM parts as well as the precision cast parts show small variations in density compared to the specified limits. As the density strongly influences the mechanical properties, it can be assumed that the given material specification tolerance of ± 5 % is far too high for the entire process. For dimensional accuracy evaluation, only a dimensional diameter tolerance was calculated. This is not comparable to the shape deviation.

As all the SLM samples for the pre-test were built within one build job, process variations are not considered. For a comprehensive understanding of the determining factors, further tests with parameter setting variations are necessary, consideration also needs to be given to repeatability.

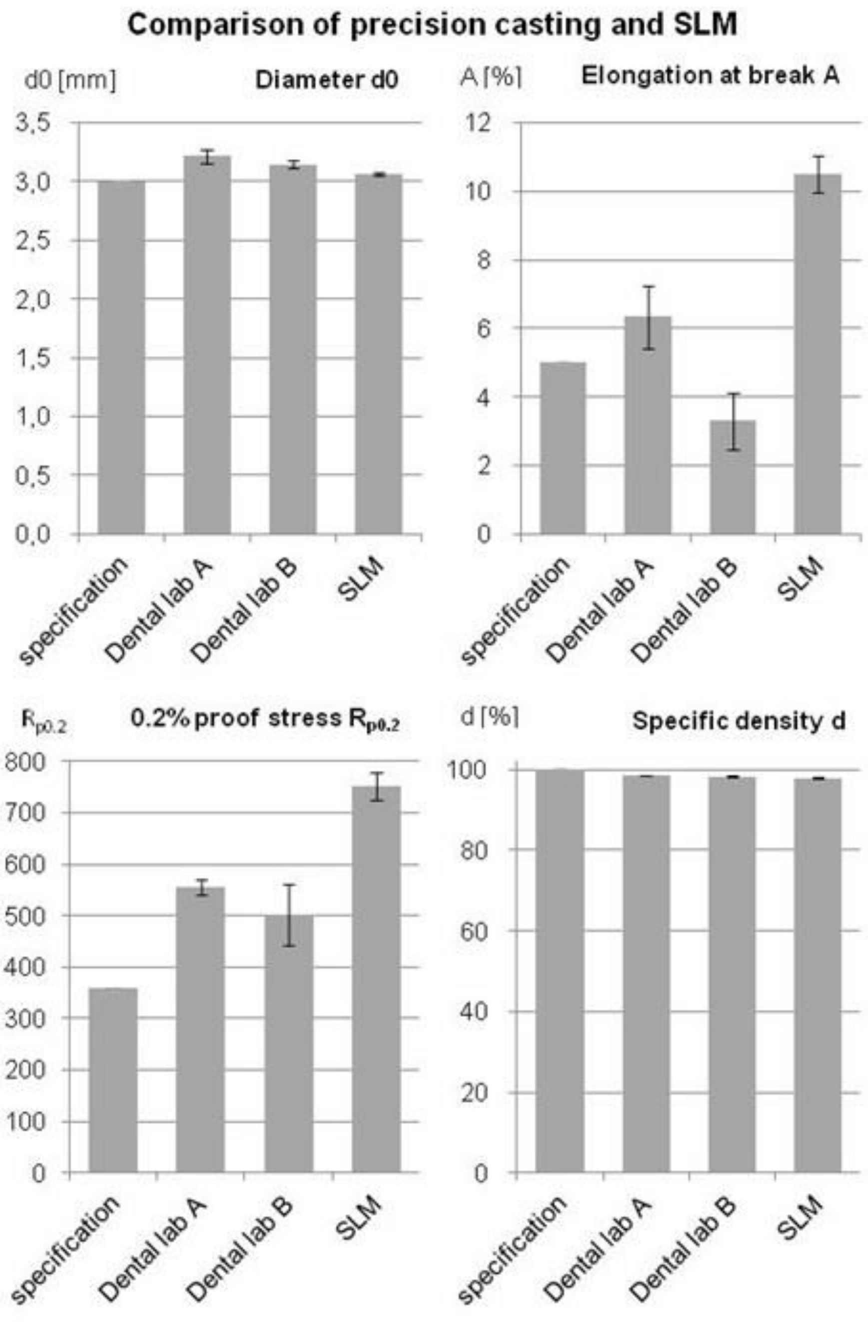

Figure 4: Comparison between precision cast and SLM samples, according to [17].

5 CONCLUSION AND OUTLOOK

The process capability of the whole process, which includes SLM, has to be developed to an acceptable level to ensure a reliable high dental framework quality. This includes the process capability of the SLM process itself, as well as the capability of up- and downstream processes.

One of the major difficulties for this is the lack of clearly defined requirements. Many of the existing specifications only describe a minimum standard and thus form a tolerance range limited on one side only, which is not sufficient for a complete determination of the process capability [13]. Other specifications, for example the density tolerance, are too high to enable a reliable production based on these values and for properties such as roughness no specifications exist.

As a result of this, one of the first steps in the development of a capable production process must be the definition of applicable requirements, including properly specified tolerances for each parameter. Interrelations between the different properties need to be taken into account, as well as the whole process chain influencing factors. The scanning device precision, for example, impacts the available tolerance range for the production process.

Based on these definitions, the current process capability of the SLM process can be analyzed and necessary improvements can be identified.

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COMBINING MATERIAL EFFICIENCY AND PART RELIABILITY BY PRODUCT OPTIMIZATION APPLYING ADDITIVE MANUFACTURING

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Abstract
Nowadays, the material efficiency and part reliability are two major issues in product development. Thus a product optimization often requires complex structures that are hard to be manufactured conventionally. Additive Manufacturing (AM) however offers great potentials for producing complex shaped parts economically. Different approaches are feasible to exploit these potentials based on the part's application from shape optimization of structural components to the integration of functions and other entities of assemblies.
Several parameters are defined that influence the costs and quality of the future product and carefully have to be balanced.
To do so, the use of already known tools for the optimization and design needs to be reconsidered and adapted to the special characteristics of AM. As not all optimization potentials can be realized perfectly, a decision methodology is required to obtain the relevant potentials and to get to a trade-off between all requirements including the ecological impact.
The paper shows different approaches for product optimization with AM and procedures for decision making in order to get to the optimal solution.

Keywords:
Product Optimization, Additive Manufacturing, Decision support, Ecological sustainability

1 INTRODUCTION

The part optimization has always been an important topic for developing successful and reliable products. The layer-based Additive Manufacturing (AM) technology enables a high potential and completely new approach for the optimization of parts [1] [2]. The technology's specific characteristics make it possible to design parts for their function rather for their manufacturability [3]. Nevertheless, the product optimization can be extended much further. The flexible production supports the individual customization of products while the often proclaimed 'complexity-for-free' forces designers to approach a part design completely different. While AM's characteristics have often been stated and analyzed a methodological approach for a product optimization has not yet been investigated to exploit the technology's full potential. Only if these potentials are well understood and implemented systematically into the design process a technical as well as economic sound product can be realized. Especially the part reliability can be increased through the design for the part's function leading to durable products increasing the customer's satisfaction in the end. Besides that, environmental issues can be addressed. Waste during the production process can be reduced and lightweight structures improve the environmental impact positively, e.g. through a lower fuel consumption [4] [5].

In this process several decisions have to be taken due to sometimes conflictive goals. That means not every optimization criteria can be always fully exploited. In this course a balance has to be found between different optimization criteria. A multi criteria decision support can be used to support this trade-off [6].

2 SAMPLE PART

In order to show the potential of product optimization in combination with material efficiency and part reliability a sample part from the automotive industry is used. In particular the product optimization process was conducted on an upright and brake system of a formula student car from Paderborn University team: "UPBracing Team" as shown in Figure 1.

Figure 1: Formula Student car from UPBracing Team with enlarged suspension and sample part upright (left) and brake caliper (right).

The upright is a structural part that connects the hub to the suspension elements wishbone and steering rods as well as the brake caliper. As the suspension is exposed to many different load cases like acceleration,

deceleration, cornering and overloads like potholes it is highly difficult to devise a proper design fulfilling the requirements of each complex load case. Therefore, an optimal structure providing enough stiffness while using least material for lightweight design comes to sophisticated organic shapes with freeform shells and struts. Thus, in recent years this part often was designed with the help of topology optimization, but mainly for conventional manufacturing methods such as milling. This hampers the use of the simulated optimal topology optimization results as the results have to be interpreted and simplified to enable a secure and cost efficient milling process. The design is consequently restricted to the manufacturability.
Since AM of metal parts has matured and supplies high quality parts with reliable material properties, this 21st century manufacturing technology gains more attraction with respect to the actual manufacturing of proper end parts. As only few manufacturing constraints have to be kept in mind and highly complex structures are possible without extra costs including undercuts and freeform surfaces, AM and Topology Optimization shape a perfect combination [1]. Thus, this combination is a basic tool for product optimization.

3 OPTIMIZATION POTENTIALS

For matching the right potential to the considered product, a detailed product and potential analysis is essential. The optimization potentials of AM can be clustered in six main potentials based on their core characteristics. The two core characteristics are tool less manufacturing and the three dimensional material generation via two dimensional layers set up by one dimensional voxels. Thereby the six main potentials “complexity for free”, “graded materials”, “monolithic design”, “function integration”, “individualization” and “product piracy prevention” arise as indicated in Figure 2 [2].

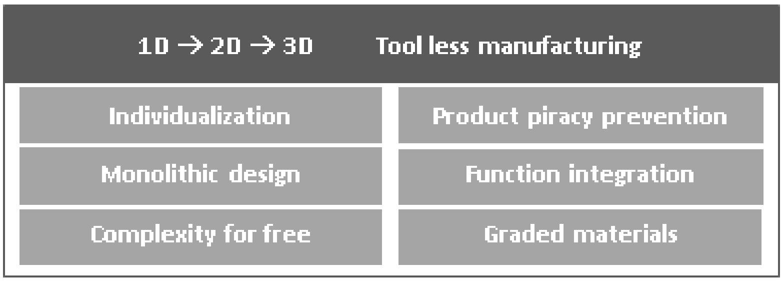

Figure 2: The six main potentials based on the two core characteristics of AM [2].

Information gathering is crucial to decide whether a product is worth being redesigned and if a change of traditional, proved manufacturing methods to AM should be conducted. The biggest optimization potential can be exploited by rethinking the product open minded integrating different parts and functions into one. With respect to the chosen sample part this would be a rethinking of the assembly including the upright, the brake system and the other attached elements. By use of special sheets requesting basic information of the assembly and possibly combinable adjacent parts one can identify possible combinations and exclusions of entities (cp. Figure 3) [2].

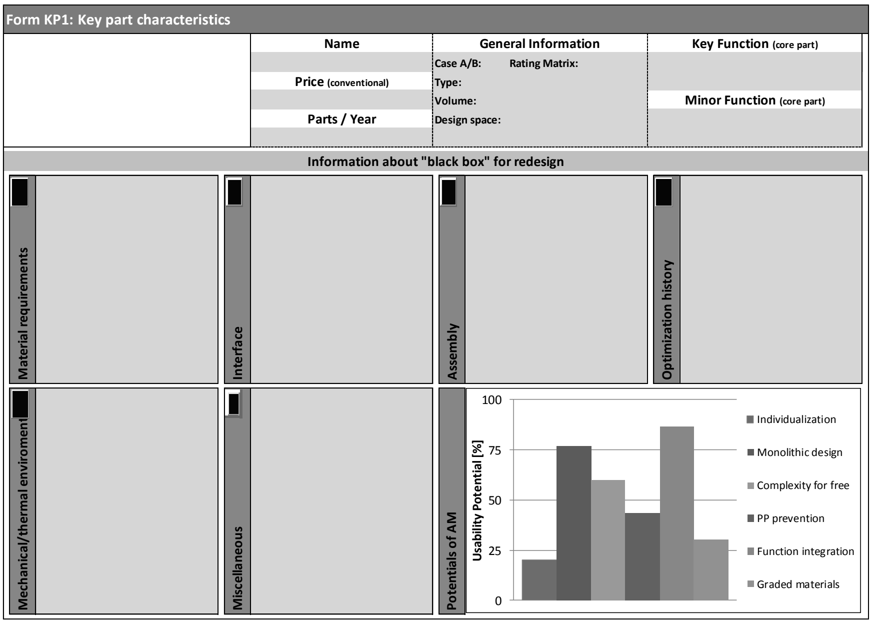

Figure 3: InfoForm “key part characteristic” for gathering of part information and potential selection [2].

Furthermore, this information can be used for selection of optimization potentials. Thereto, for each column a rating of the six main potentials of AM is used, channeling the creative energy in the right direction. These sheets are used to determine the specific optimization potentials for the given sample part. The potentials will be described in detail in the following.

3.1 Material efficiency

Material efficiency usually is one of the first goals in product development as, based on the intended purpose, often a lightweight design is stated in the requirements specification. Lightweight design has become more and more important in recent years, not only due to better performance as for race cars, but also due to environmental aspects as for aircrafts. Lastly, less material consumption during manufacturing and for the part in general saves costs [7].

But material efficiency can be interpreted in other ways, too. Material efficiency can also refer to the waste reduction during production. For highly complex structures made by conventional, cutting manufacturing technologies often huge amounts of raw material have to be invested and are cut away to get the final geometry. The proportion of raw material to used material is named "buy-to-fly ratio". A change to AM technology can reduce this ratio by remarkable values as only the actual part material is needed plus support structures.

Furthermore, material efficiency can be understood in a way that the appointed material is used best, thus stress and strain are as high as allowed for the material and that there is no material that is low burdened. This can be achieved best by topology optimization. During the automated numerical solving of FE-models, decision algorithms reduce the number of elements wherever they are not really needed [8]. The result is a material distribution with best material efficiency, as unused material is removed and the remaining material is burdened as high as allowed with regard to stress, stiffness and fatigue constraints.

3.2 Part reliability

AM enables a product design optimized for function and not for manufacturing. The often said mantra "form follows function" can be implemented best with AM. The first main potential of AM as shown in Figure 3 is "complexity-for-free". There is no need for stating allowances for accessibility of a cutter so that undercuts and holes as well as very complex freeform shapes are possible.

A product optimization with regard to part reliability can achieve optimized shapes that aim at reducing stresses. On the one hand this can be an overall stress reduction, on the other hand this can be an optimized notch geometry with a very low notch factor. Thus, the fatigue strength can be enhanced and the part's reliability is improved.

Furthermore, the reliability strongly depends on a proper mounting and on correct environmental influences. Hence, a product optimization can be a support for proper mounting like specific aids on part or more simplified mounting mechanisms. A monolithic design would decrease the required mounting processes and thereby reduce the number of fault-prone processes. Furthermore, the environmental influences like temperatures can lead to a decrease of part reliability. Thus, this should be kept in mind and controlled by use of heat radiating elements or protective plates for heat, aggressive media or impacts of debris. These elements can directly be integrated and do not have to be added with additional weight, mounting processes and extra costs, even if they are of highly complex shapes.

3.3 Product optimization

The final product optimization is a combination of the use of the single optimization potentials. A proper mounting of parts, especially for bolted connections can be optimized by use of in-process marking of the parts. An additional printing of the needed tightening torque of each bolt reduces the risk of wrong mounted bolts. Especially for assemblies with many bolts that have to be tightened in a complex procedure with different torques like cylinder heads, a detailed explanation can be printed directly on the part. Thus, no additional paper instruction is needed and the mechanic has his operation instructions directly at hand.

For hydraulic elements like the brake caliper further optimization is possible when rethinking the routing of the hydraulic pipes. The expected complex shape of topology optimization for weight reduction and stiffness increase can be used to directly include the pipes as the complexity is not restricted and the pipes do not have to be drilled. Thereby, they can smoothly follow the already existing material while avoiding sharp edges. Straight drilled and then perpendicular joining pipes lead to sharp inner corners that increase the danger of stress risings and cracks hampering the structural reliability of the part. The smoother the pipes are designed further optimization is achieved by a better flow of the medium. As less turbulences occur in these areas the pressure drop in the tube is decreased and a higher flow rate can be realized. For pressure oriented purposes like in this case the flow rate and thus the pressure drop is not the design driving argument. More important for this case is the reduction of dead-ends in the channels. Drilling mainly causes channels that are not needed for the purpose but caused by the manufacturing. These dead-ends can cause entrapped air that has a way higher compressibility than the brake fluid or oil and thus cause pressure loss. A better routing of the channels enhances the air removal and thus increases the part performance.

3.4 Multi Criteria Decision Analysis

In the process of a product optimization there are several oppositional influence factors where a trade-off has to be found. In order to support this process a decision support can be applied. The optimization is influenced by various factors from the market, the company and its branch as well as by the application itself. This leads to the problem that at the same time multiple factors have to be taken into account exhibiting different values and significance. For the optimal solution a thorough and rational decision making process is mandatory and improves the companies' specific added value.

Decision making is an extensive research field at an entrepreneurial level for both, strategic and operational decisions as wrong ones can have a fatal impact on the business success. The prescriptive theory deals with the process of finding a solution to achieve a possibly high degree of fulfillment [9]. In this model the “decision field” comprises the number of possible choices which represent the action alternatives. It contains also the

boundary conditions as well as the consequences. The latter defines the effects of the occurring impacts of the decision variables while the boundary conditions reflect the environment. The target system is defined within the "decision rule" and encompasses the optimization criterion as a leading command variable to evaluate the criteria and the preferences which allow for the weighting as a transparent evaluation scheme of subjective assessment [10] [6].
Usually, there is more than one objective relevant for product optimization so that the decision making can be classified as a Multi Criteria Decision Analysis (MCDA) problem. The multitude of aims requires the structuring of relevant factors in order to control the rising complexity that develops with every influence factor. It furthermore enables the IT processing of the problem through a defined structure. In order to apply the MCDA method first the problem identification has to be started. Then, the problem structuring provides the basis for the development phase which is followed by the modeling phase and ends with the selection phase during which the decision making provides a proposal for a solution [11].
There are different approaches to solve MCDA problems. They are usually based on the pairwise comparison of an attribute such as the cost-utility analysis which is an often applied approach. Outranking models are similar but they do not use an explicit scale but utilize strict and weak preference values. This is usually beneficial for use cases that exhibit inhomogeneous units and significances for their attributes. THE PROMETHEE approach uses preference functions to choose between single alternatives. Threshold values and indifference regions are defined in order to be able to value the differences [12] [13] [14].
Table 1 shows an excerpt of the decision criteria parameterization where costs, time and weight shall be minimized and the process stability maximized. Depending on the criterion different types of preference functions are chosen determining how the threshold influences the result. This has been derived with 'Visual PROMETHEE Academic' and 'Microsoft Excel' and the result is shown in Figure 4. The major development criteria are reliability in combination with stress reduction, weight and waste reduction, production costs and assembly time. Through this choice standardized parts are dispensed and high unit quantities cannot be realized.

Table 1: Parameterization of selected decision criteria.

Criterion	Min/ Max	Pref.- function	q-value, σ-value	p-value	Unit
Material costs	Min	Type 3	n/a	70	$
Weight	Min	Type 3	n/a	500	g
Assembly time	Min	Type 4	1	15	min
Process stability	Max	Type 5	0	5	%

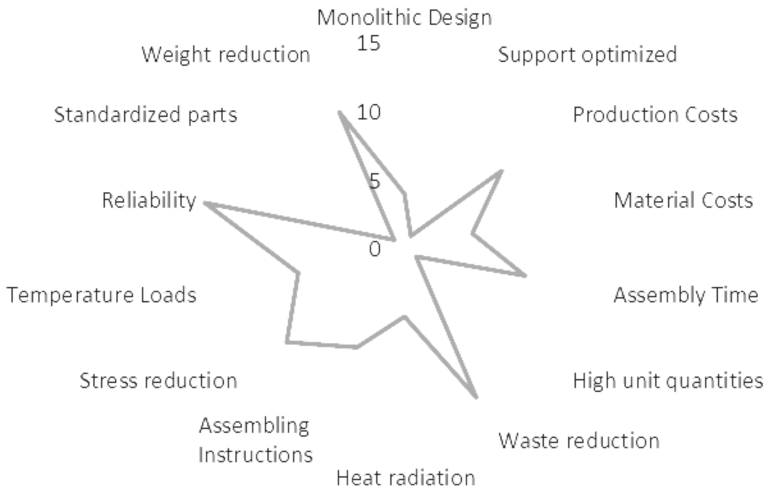

Figure 4: System diagram for the sample part.

4 USE CASE

Decision support has suggested to optimize the sample part mainly in the direction of a reduced assembly indicating a most integrated monolithic design including as much entities of the assembly as possible. The beforehand described potentials represent a feasible selection of part optimization potentials with regard to the decisions made. In the following the actual implementation of potentials to the sample part and their impact on assembly performance is shown.

In concept stage a single monolithic design as suggested was critically reviewed from usability side. The assembling of brake caliper with brake disk is impossible with regard to the existing overall assembly including the hub. Only with a change of the overall assembly including parts that cannot be changed in this stage of development a one-bloc design is possible. Thereby, the concept of choice is an upright with a direct mounting of a two part brake caliper. This enables a structural perfect connection to the upright while keeping the usability high. On this basis a topology optimization was conducted. Figure 5 left shows the design space (blue/yellow) where the material distribution can be optimized and non-design space (orange, cyan, purple) where material is needed due to other restrictions like interfaces.

After optimization process with regard to all load cases and constraints (max displacement 0.10 mm, max stress 160 MPa) the result is an optimized material distribution using least material but exploiting the remaining material best (see Figure 5 right). Thereby, an optimal **material efficiency** in terms of using least material best, is achieved. Furthermore, the efficiency is increased with regard to less waste production by change of manufacturing technique from conventional milling to AM. Thus, the buy-to-fly ratio was decreased from around 16 to 1.4 being a high benefit in terms of economic and ecologic production. The overall weight of the assembly has been reduced by 13% (712 g to 621 g including upright, brake caliper and bolts).

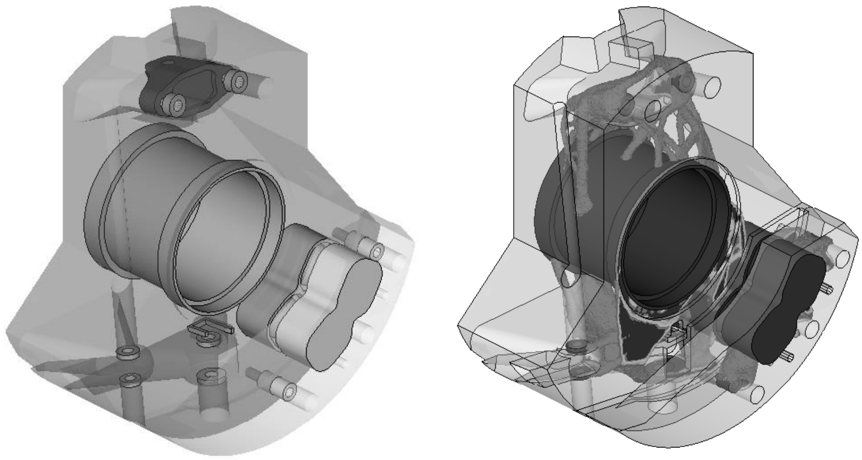

Figure 5: Left: design and non-design space, Right: topology optimization result.

A product optimization in terms of **part reliability** comes hand in hand with the optimized geometry for material efficiency. As the material distribution only follows mechanical aspects and not manufacturing constraints, the final geometry is designed with very organic shapes without critical stress risings in sharp notches. By use of a voxel based topology optimization shape regaining methodology as proposed in [15] a semiautomatic transfer of the optimization result to CAD geometries is possible. Figure 6 shows the stress plot of reanalyzed geometry. It can be seen that the stresses are distributed very homogenous except the inner notch of the brake caliper. This stress rising might be optimized with a further specific shape optimization of this area, but cannot be fully avoided due to the bending of brake caliper when braking force is applied.

As the part reliability, especially in the context of a highly burdened structural part including the brake system, is strongly dependent on the thermal environment a product optimization should include heat transmission elements. Therefore, additional cooling ribs are designed directly on the brake calipers. As these are included in the same manufacturing process and made from the same material without any disconnections, optimal heat transfer between the actual part and the ribs is guaranteed. This leads to an efficient cooling of the brake caliper, reducing the temperature loads. During racing the brake often is heated and cooled down very often. Thus, temperature induced stresses occur inside the assembly that can be reduced by efficient cooling.

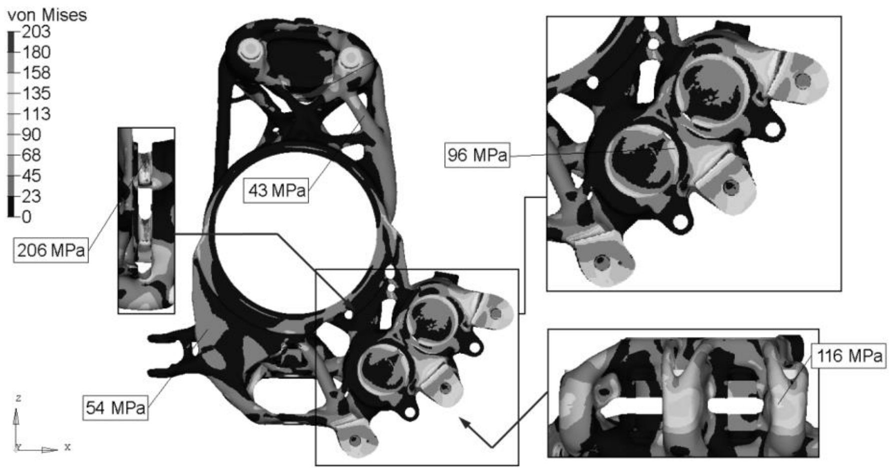

Figure 6: Plot of von Mises stress, showing very homogenous stress distribution except notch base in brake caliper.

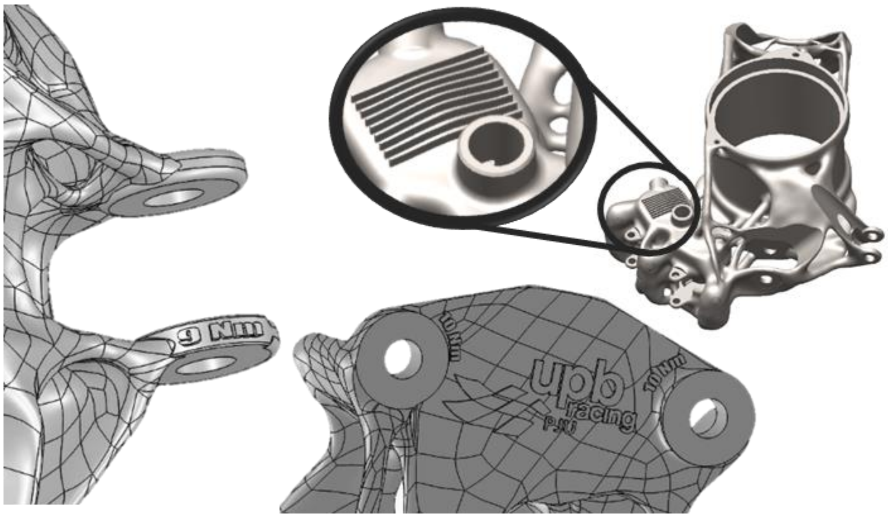

Figure 7: Final design of sample part, including cooling ribs for temperature loads reduction and assembly instruction markings.

Further product optimization can be achieved by routing optimization. The pressure channels are positioned without additional material and with a smooth bending without stress risings at the lowest point in mounting position. At the highest points both sides have a locking screw with venting function. Thus, no air can be trapped, but easily removed by opening the channels at the highest point. Hereby, the overall performance of the braking system can be increased as the compression of oil is not hampered by easy compressible entrapped air bubbles. Markings as shown in Figure 7 enable a proper mounting as the mechanic has the needed tightening torque directly at hand.

5 CONCLUSIONS AND SUMMARY

Additive Manufacturing enables a far-reaching product optimization with many different optimization criteria, which have to be evaluated and selected carefully to get to the optimal solution. The technology provides a huge design freedom which can be exploited in many different ways. It becomes possible to design the parts for their function rather than their manufacturability. This enables a high potential to make the part more reliable as the design can be optimized for the load cases while minimizing the material usage. The design freedom can be furthermore applied for additional benefits such as in process marking of assembling instructions. Due to a variety of optimization criteria that can be followed not all are usually compliant with each other but contradictory. For daily design process the selection can be conducted on basis of the part's requirements. In more difficult and expensive cases or for a detailed scientific view on a new class of parts the help of a decision support is reasonable. The effort is significant but for parts with several dependencies and influence factors it can be useful to get to the optimal solution which then can be adapted on other products with less effort. Nevertheless, the experience of the engineer is important to keep all potentials in mind and to exploit the worthwhile potentials best.

ACKNOWLEDGMENTS
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TOPOLOGY OPTIMIZATION AND ADDITIVE MANUFACTURING – A PERFECT SYMBIOSIS?

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Abstract
Additive Manufacturing (AM) increasingly enables the realization of structures, which have a much greater freedom of design und can therefore better use nature as a design ideal. Bionic design principles have already been introduced into general design approaches, and several topology optimization systems (TO) are available today to increase structural stiffness and to enable lightweight design. AM and TO, used in synergy, promise completely new application areas. However, staircase effects resulting from a layer-by-layer build process and unavoidable support structures which must be mechanically removed afterwards are disadvantageous with respect to surface texture and strength properties.
The present article addresses the question of how far the notches resulting from the staircase effect of Additive Manufacturing and the support structures removed decrease the strength of components. Most engineers try to follow the inner flow of forces in a part's design by smoothening surfaces in notched areas. Considering this, a selected component is investigated with finite element analysis (FEA) with special regard for the concentration of stress arising from surface notch effects. An outlook is given as regards how a reduction of the notch effect from the staircase effect can be achieved effectively.

Keywords:
Additive Manufacturing, Topology optimization, Staircase effect, Support structures, Stress concentration, Lightweight construction, Design rules, Notch effect

1 INTRODUCTION

Additive Manufacturing increasingly enables the realization of structures, which use nature as an ideal. Bionic design principles have already been incorporated into general design approaches for several decades. In particular, SKO (Soft Kill Option) and the CAO (Computer-Aided Optimization) are methodical access keys to optimize design and engineering procedures, as well as the build processes of objects. Without the capabilities of Additive Manufacturing, such structure optimization is limited by conventional manufacturing procedures which imply many restrictions in form, geometry and design. Cavity shapes, undercuts, nonlinear holes and many other features are typical shortcomings within conventional processes. This includes the manufacturing of shapes resulting from topology optimization (TO). Therefore, structural optimization can theoretically only unfold its full potential by using Additive Manufacturing.

However, Additive Manufacturing does not only offer advantages for structural optimization, but also includes several disadvantages. Curved contours or surfaces, which are not vertically or horizontally oriented in the build chamber, lead to the so-called staircase effects. Another disadvantage is the need for support structures underneath overhanging parts of objects which then have to be removed after the Additive Manufacturing process.

Both effects lead to a variety of small notches on the object's surfaces, which in turn reduce the strength of the set structure. That is especially disadvantageous, because such optimized structures are typically subject to extremely high stress levels.

While TO is leading to an optimal geometry with equalized stress levels, it cannot currently cope with the outer and inner notches and with the typical disadvantages of AM such as surface roughness due to the layer-by-layer material build-up and the need for support structures underneath overhanging geometries. In this article the attempt is undertaken to gain an initial insight into the shortcomings of the two methodologies and to find a synergistic solution besides pure freedom of design.

2 STATE OF THE ART

Additive Manufacturing had its advent in the late 1980s, and topology optimization procedures have been known since roughly the same era. Topology optimization has mainly been used for mass reduction processes in industries such as aircraft and vehicle production, but was most often applied in combination with standard design processes and conventional, i.e. non-additive, manufacturing technologies. The situation completely changed at that juncture when additive manufacture was outgrowing rapid prototyping and made its way into end-use parts.

2.1 Short description of Additive Manufacturing

In recent years, a large number of Additive Manufacturing (AM) technologies have been developed, beginning with the production of prototypes (Rapid Prototyping). The main characteristic of these technologies is the creation of parts directly from three-dimensional CAD data, by additively joining layers or volume elements [1]. While the first Rapid Prototyping technologies were, due to the choice of material and resulting mechanical properties, almost solely suitable for producing visual models or prototypes, a number of technologies is also currently eligible for the production of end-use parts.

Because of this, a classification of Additive Manufacturing in Rapid Prototyping and Rapid or Direct (digital) Manufacturing according to the intended use of the product is common at present [2]. In this paper, the term “Additive Manufacturing” is used to describe the entire field of technologies, as many of them can be used for producing end-use parts as well as prototypes.
As the production of parts by Additive Manufacturing makes the use of special tools or molds obsolete, AM technologies are particularly appropriate for the production of small lots or unique parts [3].

2.2 Short description of topology optimization

Topology optimization means optimization of the material distribution in a mechanical structure by placing or leaving material in certain areas of equally leveled von Mises stresses. The optimization can be performed for different goals. For example the aim can be to produce a part in lightweight design, or to produce a part with massively increased stiffness. At a practical level, the optimization is carried out using a finite element program. A design space which describes the maximum available volume of the part must be defined, and areas where the material should not be reduced have to be identified also. Every optimization system requires a design variable. In the topology optimization, this variable is frequently the equivalent density [4] of each finite element. For elements with lower stresses, the solver seeks to allocate them with lesser density, and elements with higher stresses are given a higher equivalent density. With the adapted equivalent density the solver starts analyzing the existing structure. Eventually elements with lesser equivalent density will be eliminated (“killed”), and a material distribution that contains only elements with a high equivalent density then remains. Thus, using topology optimization nowadays means that elements with fewer stresses will be “killed” - in analogy to the way in which phagocytes act in bones or other biostructures. Therefore, this method is often named SKO (Soft Kill Option) [5]. Figure 1 depicts a part subjected to topology optimization. The left side shows the result after optimization. To obtain a design as shown on the right of Figure 1, the initially rough geometrical and surface structure, as shown on the left, has to be smoothened by hand using for example non-uniform rational B-splines (NURBS) in a CAD tool.

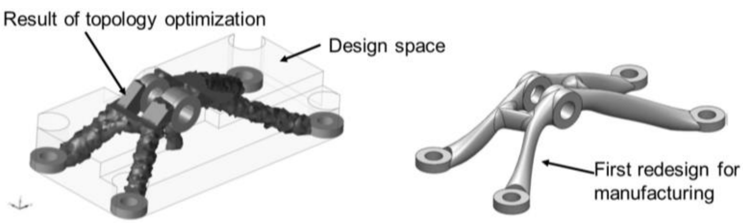

Figure 1: Design space for topology optimization and first redesign for manufacturing [6].

Once a lightweight construction part is designed, there are still notches in the design which will reduce the strength of the part. Avoiding notches must be the third step after classical topology optimization. Often the notches in the design are reduced by placing radii at the affected areas. To obtain a well-designed part with less stress concentration at notches a computer-aided optimization (CAO) [5] must be performed. In the CAO process, elements will be added at areas with high stress gradients to decrease the overall stresses on part surfaces. In future, it will be necessary to combine SKO and CAO, by firstly carrying out a SKO, i.e. the classical topology optimization, and subsequently a CAO once smoothening of the results of the SKO has been done.

2.3 Combining Additive Manufacturing and topology optimization

Topology optimization enables the creation of a geometrical structure in a given volume which is of the lowest weight or the highest stiffness, while Additive Manufacturing is a layer-by-layer manufacturing technology which provides the greatest freedom of design compared to all existing manufacturing technologies.

Combining AM and TO is therefore a logical step in order to achieve synergies from the two worlds for design and production. Currently, most approaches are undertaken when weight reduction really counts, e.g. in the aircraft industry, in the automotive sector, and in applications where inertia is to be minimized to enable the fastest possible acceleration of parts. The technical advantages are obvious here.

In such cases, smart reduction of weight not only means technical advantages, such as faster acceleration, but also economic benefits, since less material comes with lower material cost and, in addition, means less manufacturing time when using AM.

In the aircraft industry, the biggest impact is on lifetime costs due to reduced fuel consumption. To a lesser extent this can also be seen in automotive (passenger car and truck) applications.

On the other hand, additively built parts show surface textures which are completely different to those of conventional manufacturing. Staircases from layer-by-layer processes und support structures lead to generally more adverse effects of AM because strength and fatigue strength decrease [6,7].

3 CASE STUDY

For this case study, we have selected an aircraft damper bracket, which represents a typical part in the aviation industry. The original bracket (reference) is a milled part (Figure 2).

The damper bracket has been selected, because it is a small part with high requirements on lightweight design and reliability. The compact dimension makes it possible to build a number of parts in one build job using selective laser melting technology (SLM). Different load cases as occurring in practical use of the part have to be taken into account for the lightweight optimization.

Figure 2: Damping bracket of an aircraft by milling [8].

3.1 Design process

Several optimization steps are needed to find an acceptable lightweight design of the bracket. After defining the design space, i.e. the maximum available volume that includes the interface and connection areas to other parts, the applicable load cases then have to be defined. With the information from these first two steps a classical topology optimization can be started. The TO result is a rough structure (Figure 1, left-hand side) and represents an initial engineering design. When the bracket has to be produced with SLM, the design of the bracket has to follow the design rules of that AM technology. The design (Figure 1 right-hand side) needs support structures underneath all major overhanging elements of the object. Using the necessary support structures such as reinforcing ribs (Figure 3) makes it possible to build a hollow structure (Figure 4) [9].

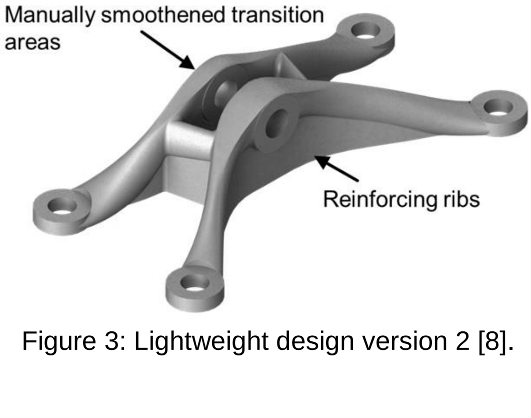

Figure 3: Lightweight design version 2 [8].

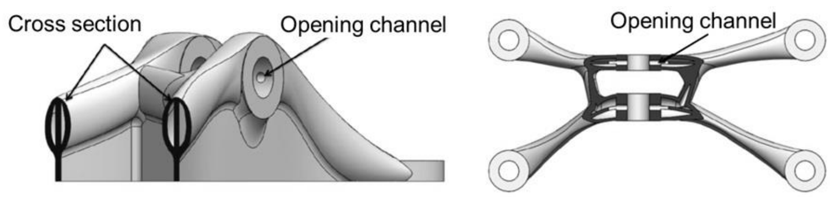

Figure 4: Detailed bracket design, powder channel [8].

The use of hollow structures requires an opening channel that permits the removal of any remaining powder after the SLM process.

Between those design steps, finite element simulations are carried out with the intention to check the stresses and to get an idea where and how the cross section needs to be changed, and where radii or other curved surfaces have to be placed to eventually lower the stress concentrations.

Figure 5 shows the process flow including the applied optimization steps.

For running the process, several computer programs have been applied. The geometry has been altered by a manual, i.e. non-automated, redesign in order to remain eventually below the permissible stress level. The final best design of this bracket is shown in Figure 6. In this case the mass of the considered part is reduced by nearly 50 % compared to the milling part.

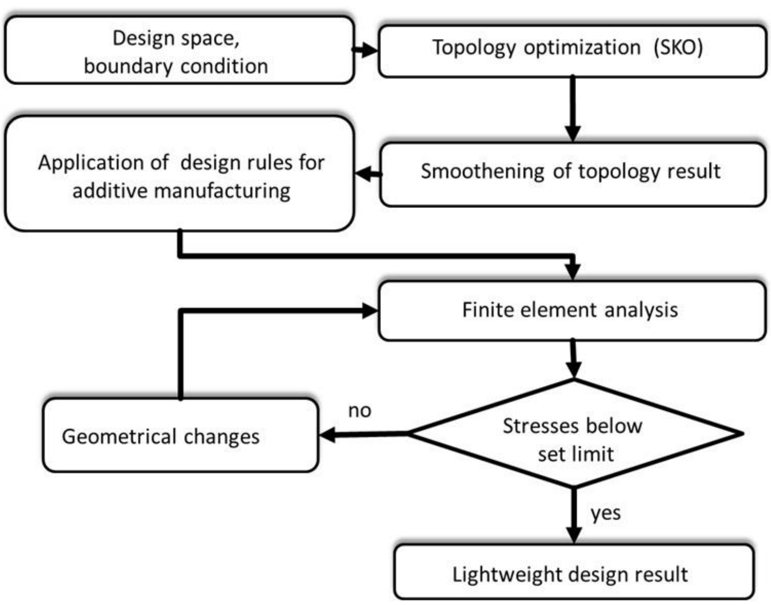

Figure 5: Process flow including the optimization steps.

Figure 6: Final design of bracket [8].

After building the bracket, several mechanical tests were carried out. The design can withstand the required loads. In all overload tests the bracket failed in the same way. The crack is located in exactly the area where the FEA simulation indicated the highest stress levels. Looking at the detail of the final design, it can clearly be assumed that a computer-aided optimization CAO would help to reduce the notch effects and subsequently the stress levels (Figure 7).

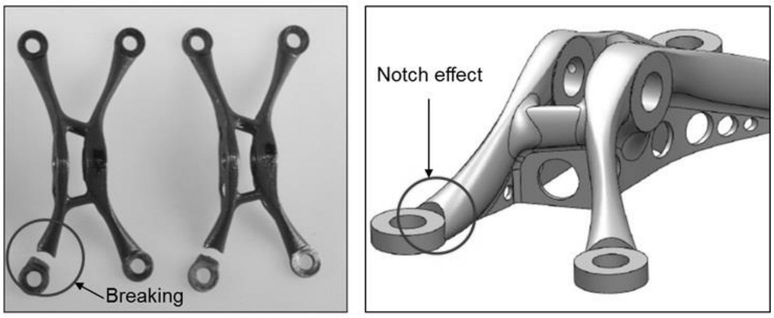

Figure 7: Test results / design [8].

3.2 Benefits of combining Additive Manufacturing with topology optimization

The above-mentioned case study shows a mass reduction of almost 50 % compared to the milling part. This is particularly noteworthy because the manufacturing processes compared (milling, injection molding, die casting), each with appropriate choices of materials and their limits, show results that are not nearly comparable (see Table 1).

Table 1: Comparison of mass reduction resulting with different manufacturing technologies and appropriate materials [8].

	MILLING PART	*INJECTION MOLDING PART*	*DIE CASTING PART*	*LASER MELTING*
Mass reduction	reference	-6.54%	-20.89%	-46.20%

Mass minimization directly means a reduction in manufacturing costs, due to less material and shorter build times. In metal AM processes the powder material used is extremely expensive, since the powder has to exactly comply with the specifications for the applied SLM process as well as those of the final application of the built parts. Build times per part correlate directly with the amount of powder used. Machine hour rates are also expensive, since SLM machines are on the expensive side of production equipment.
In consequence, Additive Manufacturing of topology optimized object offers great potential for weight-driven applications such as in the aircraft industry.
Mass reduction not only delivers lower production costs when using AM, but the most effective cost saver is the reduction of fuel costs during the aircraft's lifetime. According to Reeves [10], one kilogram weight reduction results in €2,600 of fuel savings per year based on long-haul air traffic. This, of course, calls for a total cost calculation which includes manufacturing as well as lifetime costs (Fig. 8) [11].

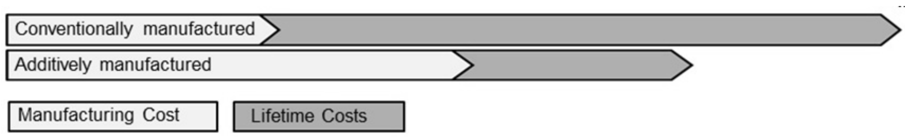

Figure 8: Comparison of total costs of the bracket including manufacturing and lifetime costs.

4 NOTCH EFFECT DUE TO STAIRCASE EFFECT

To prove the mechanical strength of an AM build part, a smoothened CAD model is generally used. Due to the staircase effect, which is unavoidable in non-vertical and non-horizontal areas of additively layer-by-layer manufactured objects, small shoulders and notches are always recognizable on the surface, resulting in locally increased stresses. The localization of such high stresses is known as stress concentration or notch effect. It is measured by the stress concentration factor α_k. This factor is defined as the ratio of peak stresses in notched and nominal stresses in unnotched

geometries under the same load conditions [12]. The nominal stress is most often used as the reference stress.
In the following, stress concentration factors have been calculated with the finite element method (FEA) for two different manifestations of staircase effects.

4.1 Outer staircases at a tensile bar

In the first case, a tension bar is built in an AM process with an orientation of 45 degrees (Figure 9). The tension bar of a nominal width of 0.157 mm is built layer by layer with a layer thickness of 50 µm and a radius of 10 µm in the corners. A tension of 50 MPa has been taken as the face load.

4.2 Stress concentration in the tensile bar

The nominal stress in the tensile bar is 50 MPa, which, of course, corresponds to the tractive force normalized on the cross-sectional area. The highest stress level reached is 140 MPa, and the highest stress concentration is located at the inner corner of the staircase (Figure 9). In this particular case, the stress concentration factor $\alpha_k = 2.8$. The value of the stress concentration factor strongly correlates with the ratio of the corner radius, the width of the bar and the ratio of nominal width, as well as the ratio of the notch depth and the bar width [12].

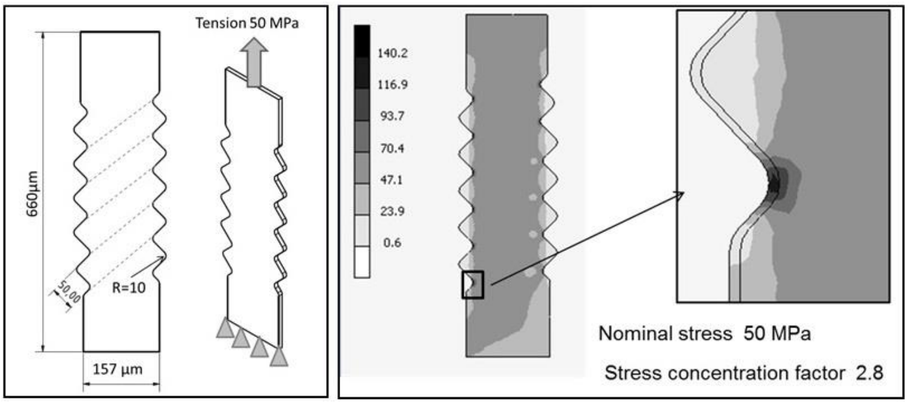

Figure 9: Specimen of a tensile bar with outer staircases.

4.3 Inner staircases on a tensile bar with hole

The second case is a tensile bar with a hole. That specimen is manufactured in an AM process in a vertical orientation (Figure 10). In this case, the layer thickness is 50 µm. It is assumed that the grain size is 20 µm, and the staircase effect is a model with small agglutinated dots. The dots have the diameter of the assumed grain size. This tensile bar is 3.14 mm in width.

The width of the remaining cross section at the center of the whole is 1.04 mm. In this case the stress concentration factor of a tensile bar with a smooth hole is compared to the stress concentration factor of the tensile bar with a rough and staircased hole.
The chosen dimensions of this specimen follows commonly used wall thicknesses and hole diameters of additively manufactured metal structures.

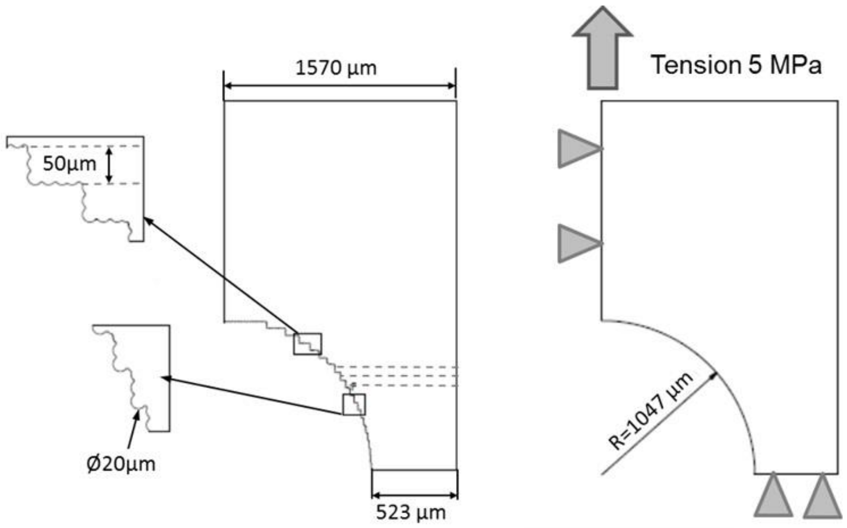

Figure 10: Specimen of tensile bar (quarter-symmetric model) with hole.

4.4 Stress concentration on the tensile bar with hole

The stress concentration factor of a tensile bar with a hole (Figure 11) is well known from literature [12]. The stress concentration factor is approx. $\alpha_k = 2$. Assuming that the surface of an additively built part looks like the surface of the hole in Figure 10, the stress concentration factor changes from $\alpha_k = 2$ to approximately $\alpha_k = 4$ at the lower symmetry plane of the hole.
In the upper part of the hole, the stress concentration factor increases to 2 (Figure 12). The stress concentration factor increases by a factor of 2 from the smooth hole to a hole with inner staircases, bearing in mind the factor of 2 is for the chosen dimension. The factor will change in cases with different grain sizes and corner radii.

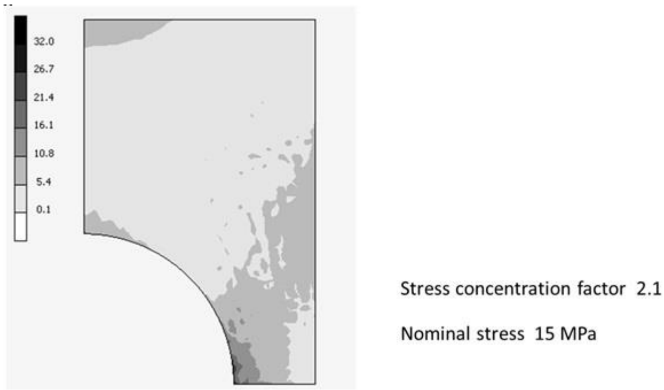

Figure 11: Stress concentration in a tensile bar with hole without staircases.

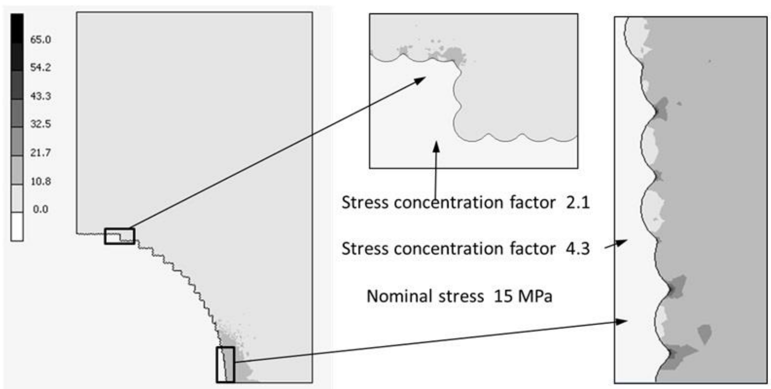

Figure 12: Stress concentration in a tensile bar with hole with staircases.

5 CONCLUSION AND NEXT STEPS

The case study of optimizing a damper bracket shows the general superiority of Additive Manufacturing in transforming delicate geometries from bionic design to physical parts. On the other hand, the freedom of design is not limitless with Additive Manufacturing. Apart from the necessary application of AM-specific design rules, the support structures and the staircase effects in particular have to be observed.
A number of static FEA simulations of tensile structures show the high stress concentration caused by AM staircases and the roughness due to the powder grains. Further investigation, which includes dynamic loads and fatigue, is required to complete these findings.

The Additive Manufacturing process should be routinely complemented by processes for smoothening rough surfaces of SLM parts [7]. The applicability and efficiency of such processes for small, winding and poorly accessible areas is a matter of future research.

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SESSION B
Industrial Engineering and Lean Management

ANALYSIS AND IMPROVEMENT OF THE PRODCTIVE ACTIVITY OF A PREFORMING CELL

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Abstract

As a result of the analysis of the processes, through the study of the production factors, with particular reference to the present machines, manpower used and operating practices, and the study of the material flow in a pre-forming cell located within the forging department of a company that produces blades for gas and steam turbines, the introduction of a new manufacturing process inside the cell was undertaken.
In addition to the heating procedures of the electric rotary furnace, the hot forging with the hydraulic press, the cogging operation with the pre-forming machine, and to the manual handling of the parts, an upsetting process was introduced to improve the technological features of the finished product.
A logical-mathematical model was developed, verified and validated with Arena simulation software to study the cell performance in the new productive configuration.
This method allowed the evaluation and experimentation of different productive scenarios, so as to verify the performance indicators, identify the operational constraints that may affect the system and evaluate alternative designs.

Keywords:
Production cell analysis, Simulation, Design support systems

1 INTRODUCTION

The analysis of the current configuration of a production cell, through the study of the production factors as machines, labor employed, working practices and material flow, detects the process needs and determines certain operational parameters for assessing appropriate actions to improve and introduce new processes based on objective data ("what if" situations of the real system).
To do this, a simulation approach is used: this involves the construction of a logical-mathematical model, which represents the system significantly. Then a verification and validation follows so that the results obtained from the simulation have a certain level of confidence with those resulting from the implementation of a processing in the production reality [1] [2]. A preforming

cell of rotor and stator blades for steam and gas turbines was therefore analyzed, consisting of several machineries and having the function of transforming metal bars (billets) into semi-finished pieces that may or must pass through one or more of the present machines (rotary electric furnace, vertical hydraulic press used for the upsetting operations and a horizontal pre-forming machine used for the cogging, or drawing out, operations, while the handling of the pieces is delegated to manual manipulators). The production system is Engineer-to-Order with blades having different shape, size and weight. The company's goal is to increase the upsetting operations without compromising the productivity of the cogging and optimizing the energy efficiency of the cell, with a view to continuous improvement.

2 PHASES OF BLADES PRODUCTION

The blade of a turbine is composed of three parts: the root, the airfoil and the shroud. The raw material is composed of billets with a square or round section of various diameters, which are stored in the initial stock and then cut to obtain pieces of the desired length. The production is divided into three departments: forging, machining and finishing.
In the existing preforming cell for the cogging operations the following machines are present:

1. Pre-forming mechanical-hydraulic horizontal machine dedicated to the drawing out (or cogging) operation which is an open-die forging process used to transform billets into longer preformed parts (volume distribution). The machine can process one piece at a time and the operator loads and unloads it in a dedicated area;
2. Rotary electric furnace, used to heat up the billets to temperatures suitable for the forging (1150°C). In “Automatic Mode”, the furnace warns the operator when the right time for loading/unloading operations is reached and gives useful information (time spent inside, number of pieces currently heating inside, pieces position etc.). The rotating furnace basin is circular so that for each billet a circular sector is dedicated, set by the operator. A control software supervises the operations;
3. Manual manipulators, which are hand trucks used by the operator for the movement of the pieces among the machines;
4. Operator, which deals with the management of operations. Work is divided into 3 shifts of 8 hours for 5 days a week. A qualified operator performs the sampling operations and writes down the cogging technical specifications.

The company plans to include a new upsetting operation, using the vertical hydraulic press.

3 CELL MODELING

The cell has been modelled following the steps that are typical of the production scenarios simulation:

1. Study of the machinery operations and operational constraints;
2. Study of the stages of processing and identification of operations sequences:
   - It is important to keep track of the steps and key actions in which all the resources are involved within the production cell, according to a cyclic sequence:
     - The pre-forming machine releases the wrought parts and the operator unloads the machine with the cart-gripper and piles the part up in the basket after marking it (1-2 of Fig. 1);
     - The operator moves the cart-gripper in front of the door of the rotating electric furnace and waits for the next billet to be ready to be unloaded (2-3 of Fig. 1);
     - The furnace door opens automatically and the operator grabs the hot billet and positions it over the forks on the lift truck in the loading area of the pre-forming machine. The operator launches the drawing sequence pushing a button commanding the beginning of the next processing cycle (3-1 of Fig. 1);
     - While the pre-forming machine is working, the cart-gripper is moved toward the input buffer to grab a new billet so to load the furnace with the ingot: when the furnace door closes, the furnace software starts counting the heating time of the part (4-3 of Fig. 1).

     Both the supply of pallets of the blank billets in the input buffer and the stocking of the baskets of worked parts from the output buffer are not an operator’s job task, and that is why these operations are considered external to the system;
   - Capacity of the furnace over time: Figure 2 shows the ideal situation of the loading of four pieces starting from an empty furnace. When the piece 1 has completed its heating time, it is ready to be unloaded and it is replaced with the 5 only after a delay relative to the discharge-charging time (Δsc of Fig. 2), which is the time during which the furnace is at a lower capacity and is the sum of some technical times.

     In addition to the standard "up to speed" working cycle, there are transient conditions such as in the loading/unloading situation from the empty/full oven and in the transition from one order number to the next.
   - Collection and elaboration of characteristic time intervals: for the determination of the time intervals of the activities the direct detection method is used. Standard time intervals for operator movements have been defined. A standard time of 15 minutes is set for the

changing order operations carried out by the operator on the preforming machine;

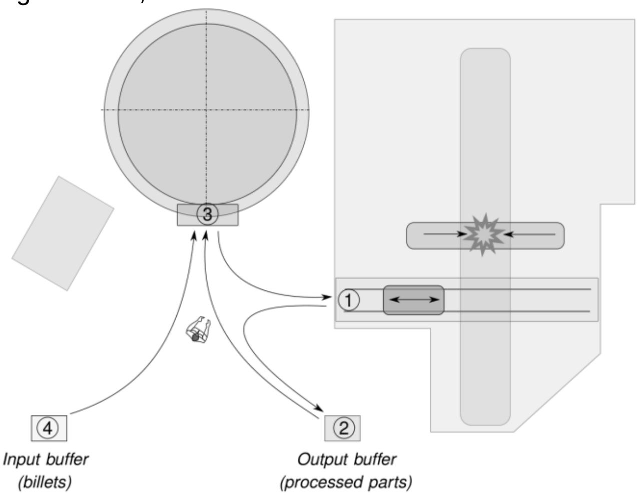


Figure 1: Movements of the operator with the hand truck.

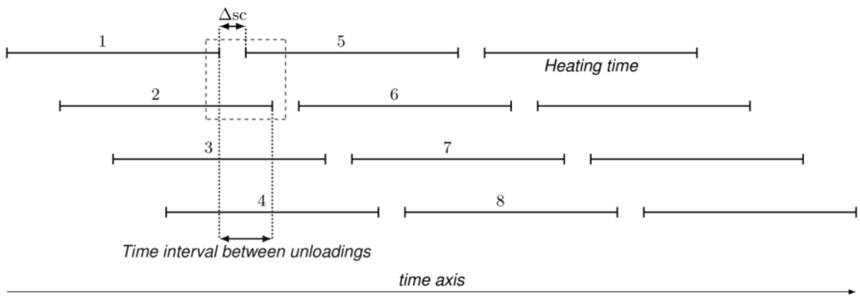


Figure 2: Furnace capacity in time, in an ideal situation with 4 pieces inside heating.

- Number of pieces heating on the basin, set on the furnace control software: in the ideal case of a furnace without any delay (instantaneous unloading-loading procedure), number of pieces can be obtained from:

$$\text{number of pieces} = \frac{\text{heating time of a piece}}{\text{time interval between two consecutive unloads}}$$

- In the real case the delay time between loading and unloading must be added to the numerator, while at the denominator the actual discharge rate consists of the cogging operation plus some handling operations;

3. Building the logical-mathematical model with Arena software, that provides:
   - Definition of the input: characteristics of the orders that are processed in time from the beginning to the end of the reference week and rates of processing steps;
   - Deterministic model as the time value are constants;
   - Resources: the furnace is modelled with variable capacity depending on the number of pieces inside for every order; the operator and the pre-forming machine are modelled as resources with a capacity equal to 1;
   - Flowchart diagram, which reflects the actual logical sequence of events that occur in the production cell in the reference week (Fig. 3). In Figure 3 the rectangular areas marked with different letters represent different logic:
     - Loading logic of the furnace from an empty basin (a);
     - Buffer of cold and blank billets (b);
     - Furnace in the heating operation and the unloading sequence carried out by the operator (c);
     - Furnace logic for the unloading-loading time intervals, even across several orders (d);
     - Phases of the cogging operations, when the operator loads the machine and when the piece has finished the process (e);
     - Unloading of the preformed part from the machine (f);
4. Verification and validation of the model: the correct functioning of the model has been checked (debugging) and the results were compared to the performance of the real system. This is done by comparing the actual times of production to those of the simulated process with reference to a fairly wide production time frame (a week). The histogram in Fig. 4 shows that the simulated production time follows sufficiently well the trend of real times, having a mean Cycle Time Ratio CTR (ratio between the Standard cycle time and the Real cycle time) of 95.2% in 3 weeks of validation.

   The simulated times are always lower than those of the real system (approximately 5% less). The variability of the production of the actual cell is attributable to:
   - Operator, who may call the unloading a few seconds before completing the unloading of the pre-formed part;
   - Set-up time of the machines, which is very variable;
   - Order changing times, which may lead to the discharge of some parts from the furnace to avoid too long an overheating time of the pieces;
   - Calculated real time of production.

The validated model can predict the times of production of a certain number of orders, with any number of pieces with different characteristics;

5. Analysis of the model output results: with reference to simulations carried out for the significant week, some results have been determined:
   - Average, minimum and maximum time values for the heating process that are 47.2, 38.0 and 65.0 minutes for the heating process and 2.9, 2.1 and 4.5 minutes for the cogging process;

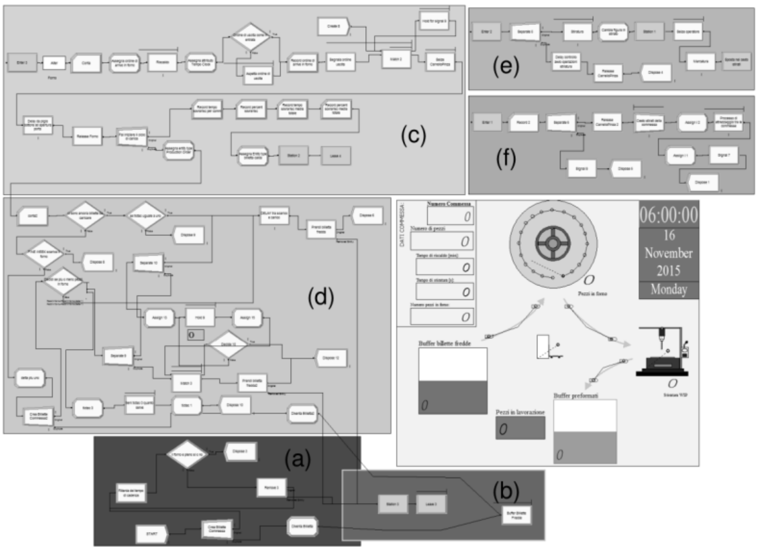


Figure 3: Flowchart of the cell model.

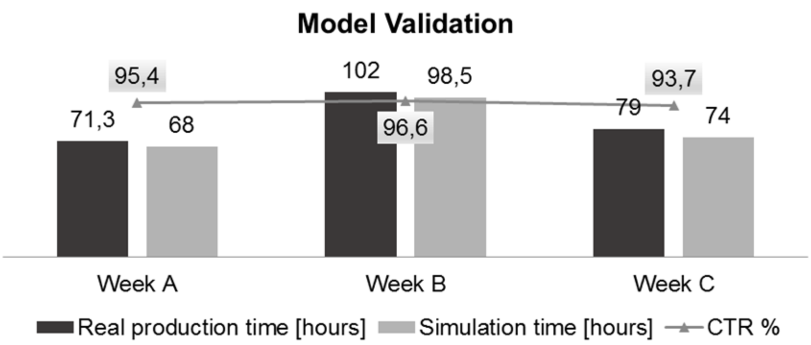


Figure 4: Validation of the model.

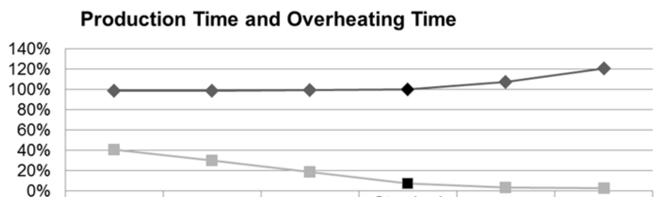
- Accumulated time on all entities for each process: heating (821.6 hours) and drawing (49.6 hours);
- Utilization of resources, defined by the ratio of the number of units that are busy to the number of units that are scheduled: time-averaged results are 0.54 for cart-gripper, 0.95 for the furnace and 0.54 for the pre-forming machine;
- Total number seized, that is the total number of times in which an entity seizes a unit of resource throughout the simulation: cart-gripper 3146, furnace 1044 and drawing machine 1058;
- Over-heating time that is the actual extra time a piece spends inside the furnace compared to its standard heating time. This is generally undesirable.

6. “What-if?” experiments and study of feasible improvements: the number of pieces inside the furnace set for each order influences both the residence time (over heating time) of the pieces at high temperatures and the production capacity of the cell, which is disconnected from the subsequent processing in the department (forging with the power hammer) because of the presence of a stock for semi-finished drawn parts. Ignoring the setup time, Figure 5 shows the simulated production time as well as overheating time by varying the number of pieces set in the furnace (adding or subtracting pieces compared to the calculated analytical number). It shows that:
   - Increasing the number of pieces in the furnace compared to those determined analytically, the capacity does not change substantially because the processing times are dictated by the subsequent pre-forming operation. That means that even if the number of pieces is increased inside, the furnace is always available to provide hot pieces. The modest reduction in simulation time (just over 1%) is attributable to the shorter waiting time that may occur during order change phases, though this means increasing the overheating phenomenon;
   - Decreasing the number of pieces in the furnace, the over-heating times will also decrease and the phenomenon can already be considered almost negligible with one piece less (3.6%). The decrease of the number of pieces in the furnace has the advantage of the reduction of heating time and, if desired, the further advantage of adaptation of the productivity from a pull perspective in the forging department.

Following the analysis both of the stages of processing and the cycle time, questions have been raised as to find which changes could improve the process. Among the different solutions to be proposed for improvement, those which would make the least possible changes to the structure of the cell were preferred, in order to consider minimizing the cost/benefit ratio. In order to reduce the processing cycle time what could change eliminating the

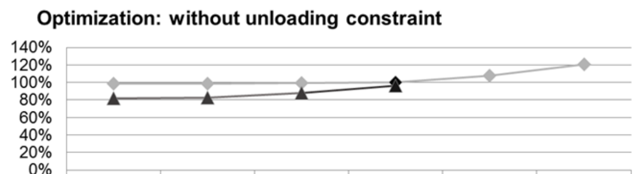
operational constraint that consists of a preforming-machine unloading before furnace discharging has been determined. The new operations by the operator would be: loading the cogging machine, waiting for the piece to be pre-formed (meanwhile loading the furnace), then calling the discharge of a new piece from the furnace when the piece is worked, load the pre-forming machine with a new workpiece and start the next cycle, only then grasping the worked part and moving it to the basket of drawn workpieces.
From the comparison between the current simulation time and those with the elimination of the operational constraint on the pre-forming machine unloading, in Figure 6 it can be seen that:

- Simulation time (cell productive capacity) is almost identical if the same number of pieces in the furnace are kept (as already outlined in Fig. 5);
- If the number of parts in the furnace are increased, simulation time drops, and reference condition is shifted to two pieces more in the furnace, compared to the configuration with the constraint;



	+3	+2	+1	Standard number of pieces in the furnace	-1	-2
Simulation Time	98,8%	99,0%	99,4%	100,0%	107,4%	120,8%
Overheating Time	41,1%	29,9%	18,8%	7,7%	3,6%	3,2%

Figure 5: Simulation times and overheating times at different number of pieces in the furnace.



	+3	+2	+1	Standard number of pieces in the furnace	-1	-2
Current simulation time	98,8%	99,0%	99,4%	100,0%	107,4%	120,8%
Optimized configuration simulation time	81,6%	82,7%	88,0%	96,4%		

Figure 6: Simulation times of the current cell configuration and those with the elimination of the operational constraint on the pre-forming machine unloading, at different number of pieces in the furnace.

- Decreasing the number of pieces, the production capacity decreases and the simulation time increases.

An increase in production capacity entails an increase in resources utilization, too.

4 IMPLEMENTATION OF THE NEW CELL

The company aims to implement an upsetting operation in the existing cell, too, which is a hot metal forging process that increases the cross section of a billet by applying a compressive force at its ends (the opposite of the drawing operation). Three are the achievable benefits: fewer cross-sections of billets to use, reduction of possible defects with a more uniform crystalline microstructure and extension of the product range. In order to implement the simulation model that includes the new operation, the orders that have already been processed in one of the validation weeks have been reconsidered. It is necessary to assume new hypotheses regarding the time intervals of future operations, assess the operational constraints for the handling and the usage of machines in the cell, and establish new standards for the operations sequence. The reference macro-operations that need to be performed in a job order can be summed up in the following:

- Seizing the billets, heating in the furnace, upsetting and storing the worked parts;
- Seizing the upset parts, reheating in the furnace, cogging and moving to storage.

The available database shows which orders need to be upset and which need not, even considering the order of operations. Some technological constraints have been identified and verified, with special regard to the maximum stroke of the hydraulic press and maximum ground clearance of the truck with the existing clamp. The following assumptions have been made on time intervals for the future state:

- New cogging times are calculated from the datasheets available, where data for current working cycles can be obtained, adjusting the values in order to take into account the different cross sections of the new billets;
- Heating and reheating times, for which already available empirical formulas are used to take into account the new cross sections;
- Handling times of the pieces to and from the press, which were chosen equal to those to and from the pre-forming machine given both that the distances from the furnace door to the two machines are almost the same and that the movement time of the hand truck pushed by the operator is independent of the shape of the load being handled;
- Upsetting times, which were obtained by filming with a camera some pilot tests carried out in the cell;
- Set up times for the pre-forming machine and the hydraulic press, which are adjusted for the new processing.

From the available data and those obtained in this manner, a model in Arena that implements the future cell configuration that includes the new operation was built.
For this new design, from the start of the simulation to the completion of all the scheduled processes of the week, the obtained simulation time is equal to 7866 minutes (about 131 hours). The comparison with the time determined for the week of validation (98,5 hours) allows to estimate that, in the future configuration of the cell, because of the introduction of the new upsetting operation, the time to process the same week of production increases by 33%. Dividing the simulation time by the average CTR (95.2%), determined during validation, it is also possible to estimate that the hours of real work (not simulated) would be 138. The resources utilization, in this case of a model that includes upsetting, are:

- Cart-gripper: 0.580;
- Press: 0.088;
- Pre-forming machine: 0.290.

In this case the pieces of the orders that undergo two machining operations are subject to two reheats: as for the logic of how the model is built, the overheating time is an average of all performed warm ups. The overheating phenomenon is linked to the furnace loading frequency. Following the results of the new model, the possibility of avoiding the second heating in the furnace has been researched.
It is known that the forgeability of metallic materials is a function of several parameters, among which the most important is the temperature that identifies three different categories of forging processes. The type of forging carried out in the cell belongs to the "Hot working" category. It is essential to process the pieces at very high temperatures (800-1100°C) both so that in these conditions the material is able to undergo substantial plastic deformation without cracking and because machines can apply smaller forces to deform the pieces. It has been determined which orders of the reference week could be processed directly, without a reheating in between the two operations (cogging and upsetting). This is researched in order to optimize the material flow, increase the cell energy efficiency, and reduce processing time. To do this, an additional constraint is set up on the minimum hot working temperature (850°C).
The time span between the unloading of a piece from the furnace and the second preforming process can be compared to the cooling time that a piece takes to reduce its temperature from 1150°C (fresh out of the furnace) to 850°C (minimum temperature constraint): if the first time frame is smaller, then the direct processing is verified and that means that the additional reheating in the furnace between the operations isn’t necessary. Cooling time has been researched through experimental analysis, for different form factors (volume/surface ratio) of the billets (Fig. 7).
To process the entire week of production in this new optimized configuration, the simulation reveals a total time of 6736 minutes (equal to

about 112 hours). In comparison with the 7866 minutes obtained from the previous model, a 14% processing time reduction is obtained. The comparison between the times of the three simulation models, in current configurations, with upsetting, and with direct operations, is:

- Current: 98.5 hours (100%);
- With new upsetting operation: 131.1 hours (133.1%);
- Optimized with direct operations when possible: 112.3 hours (114.0%).

The final optimization enables passing, compared to the week of validation, by 33.1% more to a 14% more, with a considerable saving in processing time. The pieces in this case, for the orders carried out directly, do not undergo the double heating, with further advantages in terms of both energy saved and alteration to the crystalline microstructure of the metal.
The comparison with the previous model shows an increase in the utilization rates of the hydraulic press and the pre-forming machine.

5 CONCLUSION

The construction of simulation models has enabled us to achieve our objectives: to analyze the material flow within the production cell and, on the current configuration, proceed with the implementation of the upsetting operation that will be introduced. The combination of the analysis of the situation and the simulation results showed some weaknesses and some strengths, allowing us to guide the choices of improvement and support decisions with objective data. Among other things, the importance of an improvement of the pieces handling system has emerged: automated systems, such as the use of mechanical robots or motorized trolleys equipped with special implements, are expected to be introduced in order to reduce the variability of manual handling times.

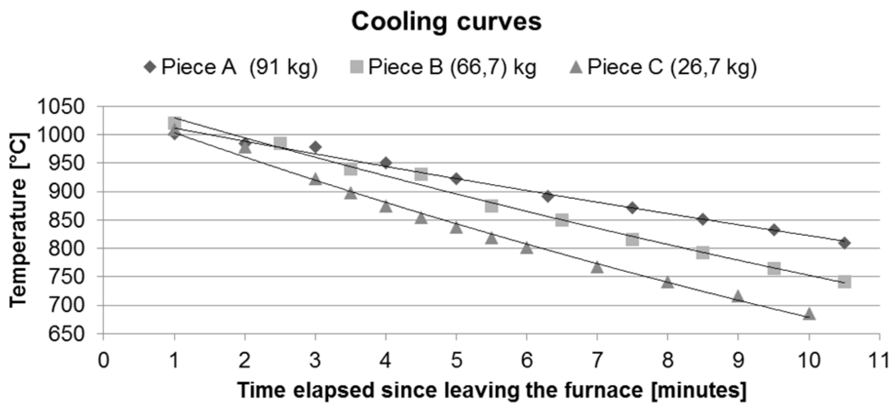


Figure 7: Cooling curves.

Simulation results have allowed us to estimate the extra residence time that workpieces experience in the furnace beyond their own right heating time.
The importance of the over-heating phenomenon suggests both the introduction of a monitoring system of this parameter and a review of right heating times. The importance of the heating parameters is revealed in the evaluation of the choice of routes with the introduction of the new operation.
In the evaluation of possible improvements, it should be added that the simulation has highlighted the benefits that could arise from the elimination of an operational constraint regarding the unloading of the pre-forming machine.

The simulation as a support to the identification of bottlenecks suggests, as a future development, the extension of the method also to other work areas present within the forging department, such as the one dedicated to the thermal treatments.

ACKNOWLEDGMENTS

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IN-PLANT MILK-RUN DISTRIBUTION FOR MATERIAL PROVISION OPTIMIZATION IN LEAN PRODUCTION

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Abstract
Under the circumstance of advanced globalization, it is increasingly difficult for production companies to remain competitiveness. Many of them are forced to restrict budget and reduce production costs. In addition, the customization of product increases continuously. This results in extension of product variation and reduction of product life cycle. Therefore, the companies need a high flexibility to respond quickly to changes in the market and to customer requirements.
Lean thinking, as a powerful tool, has been implemented by many companies in production and manufacturing. In order to avoid waste in lean manufacturing, it is necessary to manage efficiently the material flow. In this study, for a lean material handling system in the lean manufacturing of a company, an in-plant milk-run distribution system is taken into consideration. The system consists of vehicles, which move periodically in certain routes. The materials are delivered in short intervals from a central storage area to several points of use in the production. By using milk-run in plant, the material handling processes can be standardized and therefore the waste can be eliminated. One additional aim of the study with milk-run distribution for the material provision is to minimize the handling time, which determines directly the personal costs.
In order to realize the aim, the work has been divided into several steps. At first, the production processes, especially the material provision for the production have been analyzed. Secondly, the technological solutions have been analyzed in order to handle different loading units required by different machines in the production. Thirdly, the milk-run distribution for lean production is formulated as an optimization problem with the object of minimizing the number of vehicles and the distance traveled under the constraints of specific time periods, capacity of vehicle and related stations etc. Fourthly, two optimization methods are developed in order to find the optimal solution for the milk-run problem and the performance of different methods is also compared.

Keywords:
Milk-Run, Material provision, Lean production, Genetic algorithm

1 INTRODUCTION

In-plant milk-run systems are transportation systems, in which raw materials, semi-finished and finished goods are delivered from a central storage area to several points of use on defined routes and in short intervals [1]. Generally, frequent deliveries in smaller lot sizes with short lead times and low inventory at the points of use are enabled by milk-run systems. Through higher delivery frequency, a more balanced and efficient utilization of material provision can be achieved, which results in a more stable and transparent production [2]. According to Sadjadi and Amini, logistics performance can be improved by using milk-run based material provision for manufacturing and assembly stations [3]. Based on their opinion, the consequences of implementing milk-run concept are effective usage of transportation vehicles, reduction of inventories, stock out at assembly lines, maintenance costs and increase in on-time deliveries. All of these consequences are the basis for standardization. Hence, it deserves to invest the efforts in examining milk-run concept, which is the motivation of this paper.
The remainder of the paper is organized as follows. A literature review on in-plant milk-run is given in Section 2. Based on the literature, the formulation and dimensioning of in-plant milk-run are described in Section 3. Then the methods to implement and optimize milk-run are introduced in Section 4 and the paper is concluded in Section 5.

2 LITERATURE REVIEW

The literature on in-plant milk-run systems is not so extensive. Exactly speaking, there are less researches and papers in this field. The research papers in this field are categorized into three groups, each of them is presented in the following subsections.

2.1 Modeling and optimization

Most milk-run literature focuses on modeling the milk-run routing problems as vehicle route problems (VRP). Kilic and Durmusoglu presented three categories of in-plant milk-run problems [4]. The first category is named as general assignment problem, which corresponds to the problems in which the routes and time periods for milk-run are not known. When the routes are known, it is only to determine the time periods, then the milk-run problems belong to the second category of dedicated assignment problem. In the third category of determined time periods assignment problem, time periods are known, but the routes are to be determined. For this category, the authors have developed different heuristics for calculating average demand per milk-run cycle, point of use and routes. The decision of routes and time period are considered in the optimization model from Kilic et al. [5].

Emde and Boysen formulated the milk-run problem as a routing and scheduling problem with the objective of lower inventory costs and variable time periods decisions [6]. In the case study presented by Hanson and Finnsgard, the time period of the tugger train was constant and the routing and scheduling are related to each other [7]. They pointed out that the work force at the assembly lines can be reduced through milk-run concept.
Ciemnoczolowski and Bozer considered the capacity of the tow train, the cycle time on workstation starvation and the effects of the number of kanbans and determined the number of kanbans [8]. Starvation is defined as the fraction of available time a workstation is idle due to lack of parts [9].

2.2 Efficiency of milk-run

There are also a limited number of papers being published, which deal with the efficiency of material supply systems with milk-run concept. Domingo et al. reported in their research that warehouse stock can be reduced from 50% by implementing milk-run concept [9].
The predominance of combining milk-run and Kanban comparing to push system is shown in the case study from Chee et al. through discrete-event simulation [11]. The efficiency of milk-run systems has been analyzed through simulation by considering various kinds of disturbances occurring in the production environment by Korytkowski and Karkoszka [12].
Through the examination of a case study, Finnsgard et al. showed that the space requirement for materials was reduced by 67%, non-value-adding work was decreased by 20%, and travelling time was reduced by 52% when pallet sized unit loads moved by forklifts are replaced by small plastic containers transported by tugger trains [13].

2.3 Planning and designing

The planning and designing of milk-run systems was also investigated in the literature. Faccio et al. combined Kanban, fleet sizing and fleet loading problems and proposed a framework to support design and manage the milk-run systems [14]. Klenk et al. presented three strategies of exception transport, exception tour and order shifting to handle demand variation, especially over demand and they evaluated these strategies for milk-run systems [1]. The authors focused on demand peaks in milk-run operations and presented some strategies for handling the demand peaks. The strategies are then evaluated for milk-run systems with different levels of utilization and cycle time based on the data from two companies in automotive industry.
Droste and Deuse summarized three restrictive dimensions of in-plant milk-run systems, i.e. time, capacity and ergonomics and proposed an approach to model milk-run process steps in detail and to calculate resulting cycle times for one route with the objective of lowest total travelling cost [2].
Abele and Brungs proposed basic concepts to optimally design and develop milk run systems [15]. Through five major steps using milk run systems, the traditional material flow can be transited into lean material flow [16].

3 MODELING FOR IN-PLANT MILK-RUN

In this section, the concept, basic definitions, and mathematical model of in-plant milk-run especially for better understanding the case study are introduced. At first the concept of in-plant milk-run system is briefly presented. The stages of designing such kind of systems are then explained. At the end of this section, in-plant milk-run with fixed routes or fixed intervals are formulated as optimization problems.

3.1 In-plant milk-run concept

The basic structure of milk run concept for material provision is shown in Figure 1. This concept can also be used for moving finished products away from the production lines. However, it is not the concern of the research. In this paper, there is only one central source for materials, which is normally the warehouse or in some cases the supermarket in the plant. There are more than one destinations or points of use, where the material is required and should be provided. Tugger trains are the vehicles used in the milk-run system. They are driven by the operators to move simultaneously several trailers, on which the materials are loaded. The tugger trains start from the source with unit load and come back to the source with empty loading means, which are in this paper only small load containers (SLCs).

3.2 Definitions in milk-run concept

To better understand the model in the following section, it is necessary to introduce several basic definitions regarding in-plant milk-run. These are route, tour, interval, and tour cycle time.

A route describes a predefined track from the source to different destinations. For the materials at one destination, i.e. the point of use (PoU) they should be moved by a tugger train always along the same route, although the destination can be reached by different routes. In other words, if some destinations are assigned to one route, then they are only supplied by trains on this route. The tugger trains on the other routes do not stop at these destinations for material provision any more. More than one route is normally required in the milk-run system in order to reach all of the destinations.

A tour is a trip of the tugger train on one route. The tour can have a defined start time for a tacted milk-run system. The tour can also just start after the previous tour for untacted milk-run system. The number of tours along one route in one shift from eight hours depends on the capacity of the tugger trains and the requirements of the materials moved by the tours. The steps involved in a milk-run tour or cycle are loading material on means of transport, transporting material to the point of use, unloading material at PoU, loading empties on means of transport, and finally unloading empties at return location.

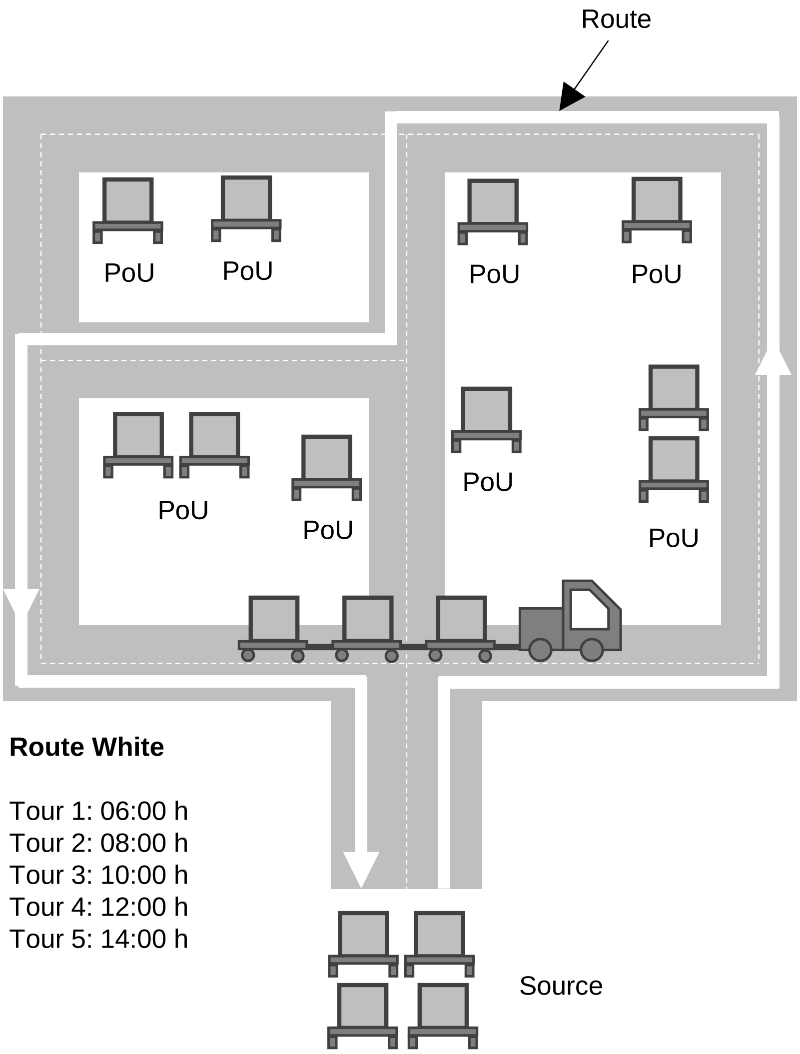

Figure 1: Basic structure of in-plant milk-run for material provision.

The interval represents the time between two planned departures of a tugger train on a route. That means, the interval is the time between the starts of two tours on the same route. The interval of the milk-run in Figure 1 equals to two hours. Every two hours, on the same route, one tugger train starts with materials for supplying the workstations on the route.

The tour cycle time is the time needed for one tour, from the beginning of loading the materials till unloading of empties. This time is influenced by the steps or activities to be done by the operators in the milk-run system. In each case, the interval must be bigger than the cycle time.

3.3 Optimization model

Generally an optimization model is composed of four important elements. They are objectives to be minimized or maximized, constraints, which represent the situations, conditions, or assumptions, and decision variables. Furthermore, some parameters as input should be carefully defined. These elements can be formulated mathematically through symbols and formulations. Here, they will be just described.

Assumptions

In order to formulate the concerted milk-run problem for the related production environment as optimization problem and establish the mathematical model, some assumptions must be made first as follows:

- Milk-run is implemented in a lean production environment.
- The layout is not to be changed.
- Material provision is pull-based.
- Every destination, i.e. PoU corresponds to a material.
- The demand of each material is considered to be constant.
- There are no traffic problems during the tours.
- The same tugger trains are used in the system.
- The speed of the tugger trains during the tours is the same and constant.

Parameters

The following parameters or given information of milk-run system should at least be included:

- Layout of the production environment.
- Required travelling distances.
- Used capacity and speed of the tugger trains.
- Locations of PoUs or destinations.
- Material demand at each PoU.
- Safety stock at every PoU.
- Time to load, unload, or reload SLCs either loaded or empty.
- Loading time at the beginning of the tour at source.
- Waiting time at each stop.

Based on the above mentioned information and the conditions or rules, such as ways for only one direction in the two physical ways are identified. Along the same physical way, two routes are defined as different routes. When it is necessary, more routes on the same way can be defined. All of these possible routes are considered in the model as predefined routes.

These predefined routes are then handled as variables. Which routes are selected, depends on the contribution of them to the objective.
Furthermore, the assumption of same intervals for all of the routes is also an input of the model. Hence, it is only necessary to define one variable to present the interval for all routes. It provides more transparency from lean production view of point. When the economical aspect is not acceptable any more in some cases, it is also recommended to have different intervals for the routes. In the model, there is then one variable for interval for each route.
In this milk-run system, one tugger train is not only used along one route. That means, it is not bounded to the route. It can also serve other routes. In other words, different routes can be assigned to the same tugger train for avoiding idle time and economic disadvantages. However, this kind of operation strategy does not influence the formulation of the objectives.

Objective
In this paper, two objectives are concerned. One objective is the number of tours in a specific time period to be minimized. The second objective is the time required for material provision in a specific time period, which should also be minimized.

Constraints
The constraints in this milk-run include:
- Each destination is only assigned to one selected route.
- A destination is not assigned to a route if it is not on the way of the route.
- The total material demand at each destination should be fulfilled.
- The capacity of the tugger train is controlled at each assignment of a destination to a route.
- Decision variables are either 0-1 binary or integer.

Variables
Decision variables in this milk-run are:
- If one route is selected or not.
- If one destination is assigned to one route or not.
- The interval for all routes

4 SIMPLIFIED CASE STUDY

Considering the page limitation and the protection of the project, in this section, only a simplified case study will be used to show the modeling, the solving methods, and the results.

4.1 Case study

The layout of the case study is the same as this one shown in Figure 1. Suppose there are driving direction limitations on some ways. After considering these limitations and the production flow, two driving ways are identified, as shown in Figure 2, which are marked in white. There are two routes one each way. Therefore, there are altogether four routes as predefined routes. Correspondingly there are four 0-1 binary variables. The destinations or PoUs with numbers under the unit load symbols and material requirement amount in small loading containers per hour are also shown in Figure 2. It can also be seen which destinations can be reached by which route. The required other parameters for the milk-run are given in Table 1. Based on the information, the transportation time for each route can be calculated. For route 1 and route 2, seven minutes are needed for the tugger train. For route 3 and route 4, five minutes are required.

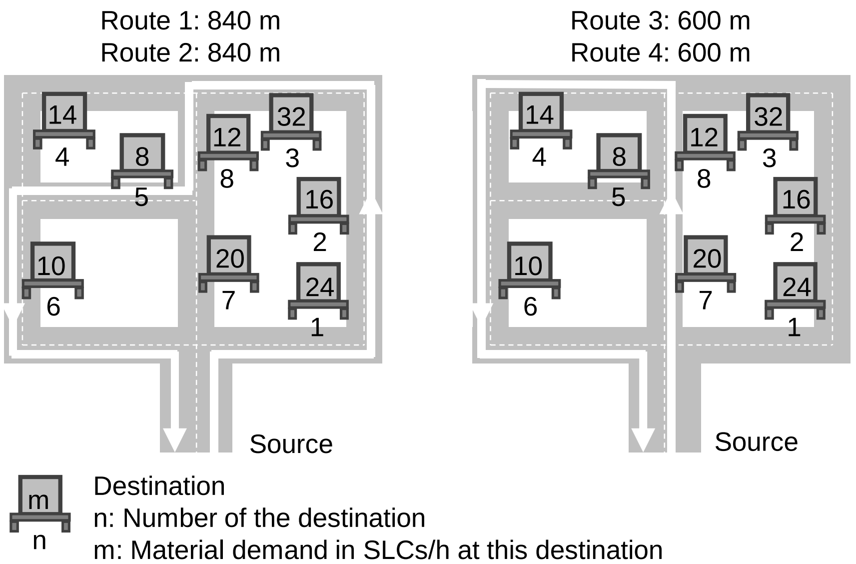

Figure 2: Predefined routes.

Table 1: Input relating to tugger train for milk-run.

Speed of tugger train: 2 m/s	Capacity of tugger train: 24 SLCs
Time to load the trailers: 2 min	Time to exchange SLCs: 0.5 min
Time to unload the empties: 0.2 min	Waiting time at each stop: 0.2 min

4.2 Optimization methods

For the optimization problem introduced in section 3, two methods have been developed. One method uses a specific heuristic “best-fit” in traduced in the paper from Klenk et al. [1]. One destination is assigned to the tugger train on one route, if the capacity of the tugger train is reached, then this destination will be assigned to the next route. If the capacity of the tugger train is not reached, then this destination is assigned to the tugger train on this route. Continuously, the next destination will be handled in the same way. With this heuristic the demand can be evenly distributed [1].
The second method being tested bases on genetic algorithm, exactly speaking, cooperative coevolutionary algorithm (CCEA). This algorithm has been successfully implemented in the research from Li et al. for the optimization [17]. In the method with CCEA for milk-run, there are two separated populations defined. One population is for the route and the other population is composed of the solutions for the assignment of destination to routes and the interval. These two populations evolve separately almost for the whole process. Only for the fitness, they both have to build the connection, because the fitness of one complete solution is influenced by all of the variables.

4.3 Results

The performance of the model for milk-run and the methods have been tested based on different examples and case studies regarding the performance. The best results for the simplified case study in the first subsection are shown in Table 2.

Table 2: Results of the example.

	Route 1	Route 2	Route 3
Destinations to be supplied	1, 2, 5	3, 8	7, 4, 6
Interval (min)	30	30	30
Cycle time of one tour (min)	26.4	24.8	23
Transport time of one tour (min)	7	7	5
SLCs exchange time of one tour (min)	12	11	11
Empty unloading time of one tour (min)	4.8	4.4	4.4
Waiting time of one tour (min)	0.6	0.4	0.4
Trailer loading time of our tour (min)	2	2	2

The results show that the method with cooperative coevolutionary algorithm is always stable comparing to the other one. It is because the decisions of route selection and destination assignment to routes are not on the same level. The cooperative coevolutionary algorithm is just proper for this kind of characteristic. There are three routes selected and the optimal interval for them equals 30 minutes. The three routes need almost the same cycle time for tours. Based on the tact time of 30 minutes, no tugger trains can be used for two routes. Hence, altogether three tugger trains are required.

5 CONCLUSION

This paper is motivated by a project of implementing in-plant milk-run system in a company for the production and assembly line. Based on the extensive literature, the milk-run concept was at first proposed, in which the basic layout is fixed, the workstations are clearly defined, the activities or steps included in the milk-run process are described. Undoubtedly, for this concept the material requirements at each workstation or point of use are already known. As for the capacity, limited by the area, it is better to tow two trailers for a better steering and higher transport speed. Based on all these preconditions, constraints and partial solution techniques, optimization methods of using specific heuristic and genetic algorithm have been developed and compared for the best solution. Although the economic aspect has not so much improved, the milk-run concept brings mainly the benefit of higher standardization and place utilization.

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SOLUTIONS FOR IMPROVING THE PATIENT FLOW IN A DAY-HOSPITAL FACILITY

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Abstract
Patients are the primary users of hospital services. Therefore, hospital managers must carefully take into consideration the effects on those subjects that can result from decisions concerning process capacity and organization. The route within the hospital facility and the overall time spent (flow time) in the process are aspects that have major impacts on the level of service from the patient's point of view. While the sequence of activities to which a patient is subjected (workflow) largely depends on medical considerations, the route and flow time are influenced by the facility's layout and the capacity and availability of resources. The study here presented was performed at the Day Hospital department of a specialized structure and was aimed at reducing the patients' flow time by identifying the system's bottlenecks, removing unnecessary waiting times and revising the patients' routings. Waiting lines methods were employed to perform the analysis and test different configurations. The results show that a revision of the process plan and the rescheduling of patients could ideally decrease their waiting time by more than 80%.

Keywords:
Logistics, Hospital, Lean management, Waiting lines

1 INTRODUCTION

The interest in the rationalization of processes in hospitals has strongly increased during the last years. Several techniques of process management and reengineering have been proposed in the health-care scientific community and applied in existing hospitals, especially for the reduction of risk, the improvement of service quality and the reduction of costs. Indeed, hospitals have become aware of the key role of the organizational change and the management of materials and information in order to improve the efficiency of all processes and, in particular, those related to the patient flow. Patients' waiting time is mainly a consequence of a hospital's limited capacity, which adversely affects the overall quality of the service as perceived by users. It is then necessary to analyze the whole process of patient management to recognize the weaknesses and produce the most effective changes in resource distribution and organization.

To this end, lean management and quantitative methods can be used to support decisions and find the correct balance between the capacity required to improve the level of service and the related costs. The study here presented was developed at a research specialist hospital compound in Italy and was aimed at the reorganization of the day-hospital service. Firstly, a thorough analysis of the existing patient flow was performed and the main problems of the process were identified by means of a survey. Some solutions were then proposed to improve the activities both from the patients' and the personnel's viewpoints. Of particular interest was the revision of the process plan, with a redistribution and rescheduling of the available capacity, which could decrease the patients' waiting time. These aspects are introduced and discussed in the following sections.

2 BACKGROUND OF THE STUDY

Recent research has underscored the need for bringing the patient at the very center of the health-care service by means of methods and tools for measuring, evaluating, changing and monitoring the activities of a facility, and, in this respect, lean thinking is considered a promising approach [1] [2] [3]. The implementation of change may have several effects on a hospital:

- A simplification in providing the care process;
- A better integration of the different involved subjects;
- A simplified and more frequent diffusion of knowledge in the organization;
- More efficient care processes using the available resources.

A hospital's key processes involve the patient; therefore, the quality of the hospital's service is directly connected to the experience of the users during their routing in the care process. This is particularly important for the health-care units with high demand and short hospitalization time, like day-hospital or emergency [4]. Consequently, the patient flow, from arrival at the facility to departure, is a critical target of any analysis and improvement action [5].
A reference routing (RR) is typically assigned to a type of patients based on their common health problem and profile (Diagnosis Related Groups – DRGs). The RR is the best temporal and spatial sequence of activities that can be devised to solve the specific health problem for that DRG; in this respect, the RR can be seen as a 'best practice' for the staff. The RR does not only define all the clinical and therapeutic activities that must be performed, but takes into consideration all the involved operators, the organizational and integration aspects [6]. The RR should be compared with the actual routing (AR) of the specific patient, that is the route that is actually followed by a specific user within the hospital because of the level of demand, availability of resources etc. Differences between AR and RR usually emerge and they should be analyzed to highlight [7]:

- If and to what extent AR is different from RR;
- Which are the main differences between the two.

On the grounds of the results of that analysis, it is possible to devise a process of continuous evolution of the patient flows: they can be updated, shared and spread among the operators, and made more adaptive. However, redesigning patient flows requires economic evaluation, reconfiguration of the organizational roles and logistic framework of the hospital. Eventually, the new RRs should be evaluated in terms of resource use, complexity and flow time, and effects on the health-care service.
It is worth remarking that the analysis and reconfiguration of such key processes demands a close integration between the information provided by the process users, the staff and the information systems [8]. This consideration was especially useful in the case-study here discussed.

3 CASE STUDY: THE NATIONAL CANCER INSTITUTE OF AVIANO

3.1 Main aspects of the 'as-is' situation

The National Cancer Institute (C.R.O.) of Aviano is an Italian research institute hospital in oncology. The day-hospital (DH) and the surgeries, which were analyzed in the study, are located on the first and second floor of the hospital building and they are part of the Medical Oncology Department (OM). Daytime care is a planned hospitalization or planned hospitalization cycles, each for a period of less than one day, which require multi-specialist skills and continuous medical or nursing assistance that cannot be provided in an outpatient setting.
The patient flow is assigned according to the OM's unit that takes charge of the patient. In order to start the DH route, patients arrive at the facility, take a number (ticket) and wait for the reception's call in a room on the first floor. When called, patients can enter the customized route and receive an electronic device that assists them throughout the route (patcaller).
Four therapeutic routes are possible:

- Route A
- Route B
- Route C
- Route H

Route A (OMA) is the most common and complete. After receiving the patcaller, the patients reach the sampling room where they receive the first nursing care and then wait for the doctor's call through the patcaller. In that event, the patient reaches one of the 12 OM's surgeries where the medical examination (VM) takes place. After that, the patient goes into the waiting room on the second floor until the DH's reception calls them. When called, the patient goes into one of the 10 rooms (with a total of 25 beds) where he/she receives the chemotherapy treatment. After that, the patient's route is concluded.

In route B (OMB) the blood sample has already been taken at patient's home and checked: results are verified by the reception and then the patient follows the same route as A. If any alterations are detected, the patient must follow the entire route A.

Route C (OMC) is assigned to patients who must receive a therapy for several days. They can go directly into the DH's waiting room until they are called for their therapy. Route D is limited to the blood sampling activity (as in the first part of A) that is performed the day before the treatment in DH.

Route H is an unplanned route to face unforeseen problems. Patients who are already on treatment can be assigned to this route when problems emerge and after an agreement with the reference doctor. The route is similar to A, but the patient is added to the admission list without appointment. This situation is frequent and negatively affects the established daily plan.

Therapies can be short (1-2 hours), medium (4 hours) and long (more than 4 hours). The adopted protocols conform to the standard of the Business Process Modeling Notation [9]. Twelve surgeries, which are mainly assigned to routes A-C (5 to OMA, 2 to OMB, 5 to OMC), and 10 rooms (25 beds in total) are available. The staff includes 18 doctors (7 OMA, 3 OMB, 8 OMC), 1 chief nursing officer, 2 head nurses and 22 nurses distributed in different shifts.

The 'as-is' situation was further analyzed by means of a Voice-of-Customer (VOC) survey. The VOC survey employed two forms: one targeted the staff and one targeted the patients' flow. The first was especially aimed at the definition of the key areas of improvement. The second was based on a paper form that was given to patients at the moment of their arrival to the DH. The staff recorded on it each activity and time to which a patient was subjected during the therapeutic route in the DH. This form was completed for 1300 patients. Particular attention was paid to the total flow time, the patients' routings, the time required for examinations and readings, and to bottlenecks or inefficiencies during the whole process. The main goal of this analysis was to monitor the time spent by patients in the facility in order to identify and remove the non-value adding activities both from the patients' and the personnel's viewpoints.

It is worth mentioning that the expected result of the overall project of improvement has been to reduce the patients' flow time, so that they spend in the hospital just the time that is needed for receiving their therapy safely and adequately. In this respect, waiting times proved to be of great concern as they affect the patients' perception of the quality of the service and the use of the resources available in the DH structure. Furthermore, it has become common practice by regional administrations to take into consideration the 'Length of Stay' (LoS) of patients in the structure as a measure of process efficiency. As mentioned in section 2, patients are subdivided into homogenous categories (Diagnosis Related Groups –

DRGs) to which a standard routing, arrival time, service time and resource consumption are associated. By comparing the standard LoS value for a DRG with the value obtained in the specific health-care structure, the administration can then judge the quality of the structure and allocate public funding accordingly.

3.2 Analysis of the 'as-is' situation

The patients' actual routings were monitored for few weeks so as to collect a sample of data that could quantitatively depict the 'as-is' situation of the DH. The analysis targeted the most critical stages of patients' routing: the arrivals at the second floor, the waiting time before reception's call and the therapy administration (service time). As previously reported, the considered system has 25 beds located in 10 rooms. There is only one key resource: the nurses, who are authorized to deliver the therapy. When DH is open (from 8.30 a.m. to 5.30 p.m.), the nurse staff is always available, even if their number changes in different days of the week. The duration of therapy administration can be different for different patients.

Two variables can be associated to a DRG:

- The time required for therapy administration (dTPT);
- The waiting time (dTACT), from arrival to therapy administration.

Three classes of duration for dTPT were identified:

- Short therapy (TB), which takes an average time of 86 minutes with a standard deviation of 48 minutes (10 min $\leq$ t $\leq$ 270 min);
- Average therapy (TM), which takes an average time of 127 minutes with a standard deviation of 54 minutes (5 min $\leq$ t $\leq$ 375 min);
- Long therapy (TL), which takes an average time of 229 minutes with a standard deviation of 77 minutes (10 min $\leq$ t $\leq$ 370 min).

In a day, an average of 5 TB, 35 TM and 10 TL are delivered. As for dTACT, after their arrival at the second floor patients spend, on average, 42 minutes waiting for the call, independently from the therapy duration. The average duration of the therapy is 146 min and the patient's average flow time in the DH (dTT = dTACT + dTPT) is 188 min: 29% of the time spent in the hospital's premises does not add value to the service received by patients. Fig. 1 shows a qualitative timeline of patients' routing. A limitation of the analysis is related to the high values of the standard deviation of the time variables. This can be partly due to the limited sample size.

In order to assess the system's performance in the 'as-is' situation, the staff availability and the number of arrivals in different time slots were evaluated, so that the service and arrival rates could be calculated.

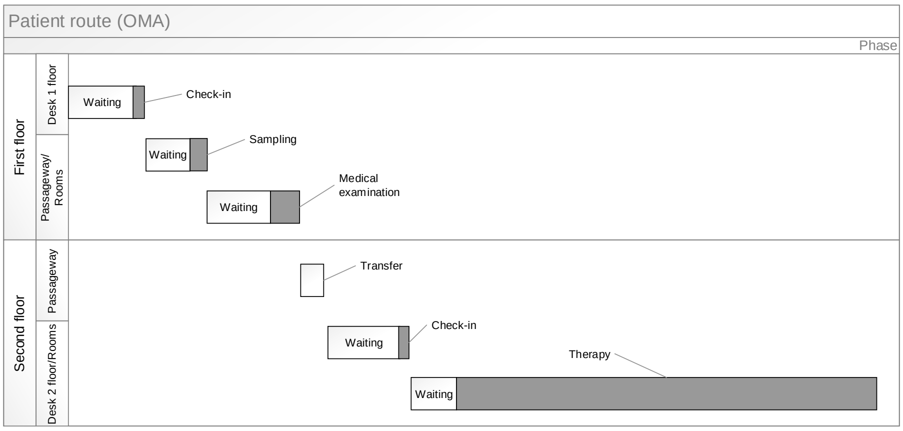

Figure 1: Simplified diagram of patients' routing.

The waiting-line model that was employed to analyze the system is based on the following assumptions, which can be considered a valid simplification of the observed process:

- The users arrive according to a Poisson process;
- Service times are exponentially distributed;
- Several servers are available;
- Users' population is infinite (or very large with respect to arrivals).

The values of the model parameters, which were obtained from the data collected in a typical day, are:
μ, service rate (0.48 patients/h);
λ, arrival rate (8.9 patients/h);
s, number of servers (20 nurses);

$\rho = \dfrac{\lambda}{\mu \cdot s} = 0.96$, utilization factor (the system is stable if $0 \le \rho < 1$)

$\Omega_p = \dfrac{\rho^2}{1-\rho} = 23.04$, congestion coefficient of the system

$L_q = \Omega_p \left[\dfrac{1}{1+\gamma_s \cdot (1-\rho)} \right] = 8$ patients; average queue length, where:

$$\gamma_s = -1 + \frac{(s-1)!}{(s\cdot\rho)^{s-1}} \cdot \sum_{h=0}^{s-1} \frac{(s\cdot\rho)^h}{h!}$$

$L = L_q + \rho = 27$ patients (average users in the system)

$W_q = \frac{L_q}{\lambda} = 0.94$ h (average time spent in queue)

$W = \frac{L}{\lambda} = 3.02$ h (average flow time)

In addition, any nurse serve 3-4 patients and the probability for a patient to wait in queue, i.e. $P(W_q>0)$, is 66%.

3.3 The improvement measures

Based on the collected data and above reported results, some improvements were planned. The value of the utilization in the 'as-is' situation was especially troublesome as it is very near 100%: a small perturbation in the process, for instance an unplanned urgent service request (Route H), could bring the system towards an unstable condition. Therefore, a key objective was to improve the stability of the process so that queue length and time spent in queue did not reach high or out of control values. Arrivals were scheduled according to a planned admissible arrival rate that was determined as a function of the service rate: the system's behavior was then evaluated for the period 8.30 a.m. – 2.30 p.m.

If the average service rate is assumed to be μ = 0.48 patients/h, the maximum arrival rate that can assure ρ = 0.80, with s = 20 nurses, is λ = 7.1 patients/h. In this situation, the process parameters have the following values:

L_q = 1.1 patients
L = 17.1 patients
W_q = 0.14 h
W = 2.2 h
$P(W_q>0)$ = 22%

It was decided to test the process behavior when the patients are scheduled according to a different precedence rule. In the 'as-is' scenario their admission to the therapy is regulated by a First Come First Served (FCFS) rule and their classification is made by the OM solely on medical grounds. A different rule, the Shortest Processing Time (SPT), was chosen considering the good results that it can provide in other contexts [10], especially in terms of the number of jobs processed in a fixed time-span. SPT was applied ranking the patients of a specific day from the shortest time required for the therapy to the longest. In the specific, firstly patients with TB are admitted to the second floor, then with TM and finally with TL. The average service rate is kept at μ = 0.48 patients/h: the maximum arrival rate that assures ρ = 0.77 and s = 20 nurses, using the SPT, is λ = 8.9 patients/h. In this situation, the process parameters have the following values:

L_q = 0.6 patients
L = 15.9 patients
W_q = 0.10 h
W = 1.8 h
$P(W_q>0)$ = 19%

This configuration improves the system stability even when some urgent cases are admitted to the process.
From a practical point of view, two changes in the process are introduced:

- At the first floor, the patients' classification is not made by the OM anymore but it is based on the type and length of therapy;
- At the second floor, the scheduling of patients is based on the SPT rule.

In face of the obtained results, the study presents some limitations. The precision of the analysis is not high and could be improved if more data were collected. In particular, a good amount of data could be obtained by the patcaller if the software was updated to trace all the activities performed by a patient. In addition, collected data are not always reliable due to the different respondents' roles in the process, who can interpret the questions differently or misjudge the importance of the change project.

4 CONCLUSIONS

The study showed the actual opportunity to improve the current health-care process, favoring both the patients' perception of service and the staff's activity. An 89% reduction of the waiting time was estimated, but the concrete results will be available only after the first transient stage of the project implementation is completed. In fact, actual processes can be subject to several disturbing factors, which are not easy to identify and model at the design stage. Nonetheless, it was evident that a simple re-organization of few key activities can bring non-negligible benefits to the quality of the service provided.
In summary, by using quantitative approaches (data analysis and models) and a process re-engineering logic, it has been possible to simplify the patients' routings and make the process leaner, with an immediate improvement of service quality and efficiency.

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EoPaMS-
EVALUATION OF PRODUCTION AND MANUFACTURING CONTROL STRATEGIES – A SIMULATION BASED APPROACH

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Abstract
Highly volatile markets combined with a constantly rising need for speed and individualization, are forcing manufacturing companies into new challenges in order to keep or strengthen their market share.
As a result of different approaches to deal with market needs, the manufacturing reality is characterized by a constantly increasing complexity of production systems.
The achievement of manufacturing objectives combined with the needed performance is highly depending on production planning and control (PPC) and its configuration. Information technologies were used as enabler to deal with the challenges that arise from the different targets. But still one major challenge is the process of finding an appropriate strategy, which is supporting the achievement and realization of logistical and company related objectives. Due to the fact that there are a very high number of possible Production and Manufacturing strategies that can be chosen, a company is faced with an important long-term decision, which is usually done without considering essential criteria. The fact that most of the production related configurations are based on specific business needs and customer requirements shows that general best practices do not exist. The different objectives and targets of a company, made them starting to adopt different manufacturing technologies and strategies to fit their specific needs.
Despite renowned research initiatives in the field of production management, the selection and combination of appropriate PMCS (Production and Manufacturing Control Strategies) is still widely unaddressed research field.
Within this paper the author will introduce an approach for finding essential criteria when it comes to the selection of a PMCS by giving a short introduction, followed by a detailed view on the examined area as well as the applicability of different PMCS based on their primary emphasis.

Keywords: Production and manufacturing control strategies, PPC, Segmented production

1 INTRODUCTION

Note*: This paper is a part of an ongoing PHD project. Therefore, the preliminary results were already published in previous conference proceedings.*

Production Planning and Control (PPC) Systems are crucial elements for a manufacturing company that has to deal with increasingly high demand uncertainties as well as different expectations resulting from the customer in a competitive and volatile manufacturing environment. [1]
The typical functions of such systems are: [2]

- Determining the amount of final products needed (primary requirements)
- Planning the requirements for the master schedule (secondary requirements)
- Inventory accounting and lot sizing
- Scheduling and sequencing jobs
- Capacity planning
- Order release
- Controlling the goal performance and taking action if discrepancies occur.

Their main purpose includes objectives like the reduction of WIP (Work in Progress), lower costs for stock, help to establish a higher agility regarding demand changes as well as minimizing lead times in a production line. All of these objectives have different interdependencies between each other [3], which leads to the lack of an “easy to use” formula, that can help to solve of the incompatibilities. (e.g. an increase of the capacity utilization is associated with an increase of inventories which in turn leads to longer cycle times.)
In order to stay competitive and to gain the needed flexibility regarding the market needs, a large number of Production and Manufacturing control strategies (PMCS) were developed. They were created on the basis of a big variety of attributes, focusing on the increase of production efficiency with respect to a targeted company goal.
However, the determination of the applicability of different PPC approaches is a very complex task, “because of the increasing number of alternative approaches and the inclination of many software producers to suggest that an approach is universally appropriate”. [1]

2 EXAMINED PRODUCTION AND MANUFACTURING CONTROL STRATEGIES (PMCS): USAGE AREAS AND THEIR APPLICABILITY

Lödding [3] accentuated that the achievement of the best possible solution of logistical objectives is dominated by the production planning. He came to the

findings, that production planning is an intellectually challenging optimization problem that can be elegantly solved by the application of different methods from scientific disciplines such as operations research.
He emphasized that a great and especially realizable production plan is one major prerequisite for the achievement of a company`s targets, but he also criticized the lack of knowledge concerning the mode of action and the parameters that help to choose “the” appropriate model. However, the company`s targets can only be realized if production and manufacturing control System is able to handle the earlier mentioned production plan.
The following section provides a brief overview of the PMCS that the author is going to examine within his research. They will be differentiated by the fact if they release or generate orders for a production system.

2.1 Order generating methods

KANBAN:
Kanban [4], which stands for a marker or a card in Japanese, is one the most common known types of pull production control systems. It was developed by the Japanese car maker Toyota, which introduced this heuristic for the decentralized control of the material flow on a multi-stage manufacturing system. Therefore, a defined number of cards is used, in order to control the work-in progress (WIP) between each pair of workstations. The systems WIP is limited by the total number of cards. Production can only be started if raw material is available and has received a card, which is authorizing the process to be started. (Material is pulled in the system) [8]

Cumulative job quantity concept (CJQ):
The CJQ concept has its origins, like many other production and manufacturing control strategies, in the automotive industry. It applies the idea of a simplistic in- and output control (without capacity restrictions) for controlling multi-level productions.
Therefore, the different stages of manufacturing are separated in so called control blocks, which are passed by the material flow. With the help of the CJQ the quantity of the output is co-written and compared to a cumulative set point, which provides the possibility to clearly identify bottlenecks and help to determine production capacity. [3]

2.2 Order release methods

CONWIP:
CONWIP has some similarities to KANBAN, but beside the fact that each workstation defines the amount of cards in the system, CONWIP is using a single global set of cards (also if different product types hit the production line) to control the WIP in the whole system. The card will only be detached if the product leaves the production process. So, to give a better understanding on the principle, we could say that once raw material is authorized to enter the line, the material flow can be seen as the one of a push system. Due to the fact that WIP is a constant (thus the name) in the whole system and is not controlled at the individual workstation, CONWIP is a much easier to manage system than KANBAN. [4]

Load-oriented order release:
The main aim of load-oriented order release is the reduction of process-related waiting times by releasing just orders, that are urgent and need to be processed and are not exceeding a certain limit of bottleneck workstations. Therefore, the upcoming production orders are released each as a function of the momentary capacity load of a workshop according to the load values of the different work and manufacturing locations. Criteria for the dispatching a production order is the load barrier, which is regulated by a percentage that defines the maximum load of a workstation. [5]

2.3 Usage areas

Most of the mentioned production and manufacturing control strategies were first implemented in the automotive industry. Some more or less successful implementations found their way in other industrial sections by considering obviously facts, like the one that KANBAN is not appropriate for high variety and/or custom product environments. The facts that there is still a huge gap, concerning relevant criteria for those strategies, show that there is a high potential in developing an appropriate selection method.

2.4 Applicability of selected PMCS based on the primary focus

For further research activities it is necessary to classify the examined PMCS according to their primary emphasis. The author is focusing in this paper a classification, published by Graves et.al. [6], who classified PMCS based on their mechanism focus.

They introduced an approach in where they examined the mechanisms that tend to just keep enough inventory downstream of a machine to meet projected demand over time, called Infinite capacity based systems, mechanisms that are focusing on a smooth material flow, called production based mechanisms and a combination of the above mentioned.

The infinite capacity based PMCS assume that the manufacturing line can deliver products within a given and mostly constant lead time, where the line will have sufficient capacity to meet changes in demand within the given lead

time, e.g. MRP. The production based mechanism recognizes the limited capacity of a manufacturing line, where the focus of those PMCS is clearly on smooth material flow. Their main aim is to keep just enough material at the upstream side of (critical) machines to keep them busy.
Table 1 shows their classification approach pointing out examples for different PMCS based upon their mechanism focus as well as the properties that are explicitly considered by each PMCS.

Table 3: Adapted from Graves et.al [6], Characterization of different PMCS.

Mechanism focus	**Explicitly considers**			**Examples**
	Demand	*Lead time*	*Workload*	
Infinite capacity	Yes	Yes	No	**MRP** Base Stock
Production based	No	No	Yes	**CONWIP** **KANBAN** **BOA** Workload Control QMRP*
Combination	Yes	Yes	Yes	**MRP/KANBAN** Hybrid PAC*

*QMRP → queue management release policy / *PAC → Product Authorization cards

2.5 Definition of the examined area

The choice of an appropriate strategy is often an ill-informed decision based on shallow features of the software system instead of the selection of features that are designed for a specific industry. [1] He highlighted the fact that the "right" choice is particularly important, because the implementation can be a very expensive and timely process, with respect to changes regarding to culture, philosophy and working practices. Making a wrong selection could lead in some cases to an expensive mistake, that could ruin businesses.
One of his insights was that this issue is particularly acute for the MTO production, as the MTS sector is more predictable and comes up with higher levels of repeating business. He explained his assumption by highlighting the fact that the MTO sector is one with increasing importance, due to higher demand for specialized products in most industries.
A classification was created, where a special focus was placed on the field of the "highly customized" industry, better known as the MTO (Make-to-order) industry. He divided it into the following two types:

- Repeat Business Customisers (RBC): Industry, that produces customized products on a continuous basis over the length of a contract. So the production line is dealing with customized products which are may be produced more than once, permitting a small degree of predictability.

- Versatile Manufacturing Companies (VMC):
  Very complex industry type, that requires sophisticated solutions. Each order is competed for individually and a high variety of products with variable demands that are manufactured in small batches with little repetition.

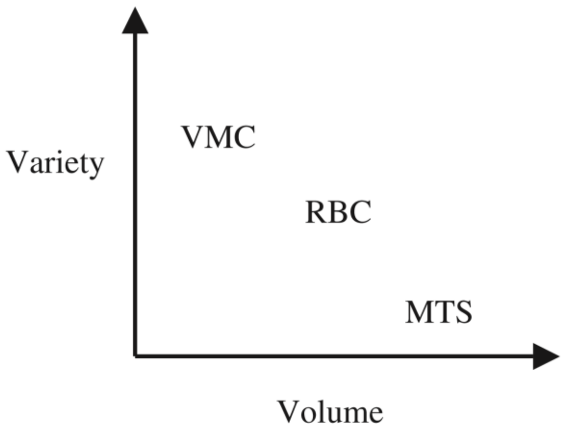

Figure 1: Positioning of RBC, VMC and MTS with respect to Variety and Volume [7].

Figure 1 shows the position of RBC, VMC and MTS environments on the traditional volume/variety spectrum. In this study the author is concentrating on the PMCS mentioned earlier in 2.1 and 2.2 that are primarily used in such RBC environments. The clear focus is on the combination and simultaneous usage of multiple strategies and their influences on each other to find fundamental criteria that support the selection of an appropriate PMCS.

3 MULTI-DIMENSIONAL CLASSIFICATION APPROACH FOR PRODUCTION SEGMENTS BASED ON SPECIFIC PRODUCTION PROPERTIES

To validate and improve the selection of an appropriate PMCS, it is necessary to clearly classify the production system and the strategies themselves. Fernandes [8] clarified that a primary requirement for the improved understanding of production systems and their management is an appropriate classification of such systems. Therefore, the author is going to try an approach in which he classifies the examined production segments regarding the four following properties by giving examples from renowned literature.

3.1 Object-related production properties

This category focusses on the material itself, or according to a simplified model of a production system, on the operand that is going through a transformation process to get from an initial state to a desired one. [9]

The most common classification concerning the object was made by Wild [10] in the early seventies. He classified the production system into a process manufacture and divided Mallick`s and Gaureau`s intermittent process definition into a batch production and a jobbing manufacture, which lead to a higher degree of differentiation possibilities concerning the examined area. This definition is used in many textbooks and is adapted in a wide range of fields.

Another approach was made by Woodward [11] who conducted research on 92 manufacturing companies. He derived 11 categories from the information collected that were based on specific properties regarding the produced product. E.g. process production of crystalline substances.

Franke [12] proposed an approach where he divided different manufacturing systems by the variety range of the manufactured products. He identified two types of variety. The external useful variants that describes the range of different products, contributing to meet customer needs and the internal malicious variety, which is related to the diversity of production flows within a production line.

3.2 Structure-related production properties

The structure related production properties are focusing on the flow type of different transformation processes to describe the examined environment. Johnson and Montgomery [13] classified production systems with respect to the needed processes. They defined a continuous, an intermittent, a large project and a pure stock system. Those categories differ due to the number of produced variants as well as the produced volume. They differentiated these categories by analyzing the flow pattern that the product has to go through. Frizelle [14] on the other hand presented an approach by the means of the three letters V, A, T. Where the "V" stands for a plant which is represented through a small amount of raw materials that are assembled into many finished products, whereas the “A” symbolizes a plant that represents many raw materials that are used to produce few finished goods. The “T” plant has a specified number of input elements, that is/can be assembled into a wide range of finished products.

3.3 Complexity-related production properties

The complexity related point of view is made with respect to uncertainties, that exist within a manufacturing environment. According to ElMaraghy [15], who described a complex system as one, where uncertainty exists, this classification is done with respect to uncertainty aspects, resulting from the behavior of Customers and Suppliers as well as from the workers within a production line. Those factors can be examined using information resulting from Service Level Agreements (SLA), as well as over- and underdelivery quotes. The workers within the production line can be analyzed by their frequency of errors during the manufacturing process.

3.4 Automation-related production properties

Automation related properties describe the degree of automation used in production. [16] According to this approach, production systems can be classified, by dividing the manufacturing line elements into three categories, the non-changeable automation (e.g. conveyor belt production), that is focusing on high volumes of finished products with a low amount of variants, the flexible automation (e.g. industrial robots), which is used when a high amount of different variants is produced and the programmable automation that is focusing on a range of finished goods that lies between a high and a low volume as it is mostly used in batch production environments.

4 RESEARCH METHODOLOGY AND FURTHER RESEARCH OBJECTIVES

To validate the criteria for differentiating PMCS based upon their area of application, different qualitative and quantitative research approaches have been tested. For this specific project, a combination of a desk research and a discrete-event simulation (DES) model, using Plant Simulation by Siemens PLM Software has been chosen.

“Plant Simulation is a computer application developed by Siemens PLM Software for modeling, simulating, analyzing, visualizing and optimizing production systems and processes, the flow of materials and logistic operations.” [17]

The model shown in Figure 2 enables the author to select segments of a production line and combine different manufacturing strategies, (e.g. a CONWIP system followed by a KANBAN, etc.) for an arbitrarily chosen size of machines. The production line model has customizable input parameters, in order to evaluate the effect of this combination onto important target values, like cycle time, inventory, etc. (red rectangle in Figure 2)

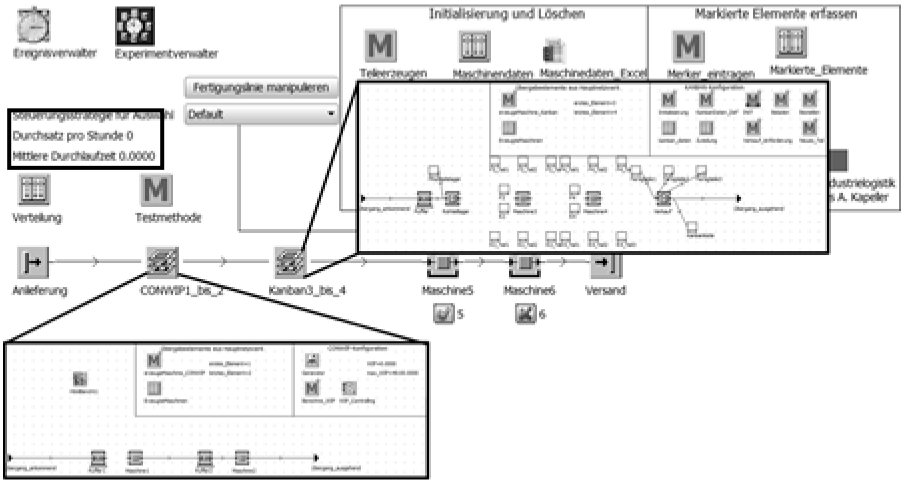

Figure 2: EoPaMS Simulation Prototype.

The DES Simulation model will then be tested by using captured production data from a project partner, to validate and answer the following research questions:

- Which criteria are needed to differentiate PMCS based upon their area of application?
- How does the deliberate combination of different PMCS influence different characteristics (e.g. inventory, lead time, utilization, etc.) of a manufacturing line in the field of RBC environments?

The main aim of this work is the establishment of a generic and objective classification approach that will be used to evaluate different Production and Manufacturing Control strategies. EoPaMS should enable decision makers in manufacturing companies to select the appropriate PMCS for their environment, but also offer them the possibility to evaluate the strategies that can be compared within their company or supply chain by the usage of a segmented viewing perspective.

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SESSION C
Management Techniques and Methodologies

RELIABLE INPUT FOR STRATEGIC PLANNING: THE INTEGRATED SCENARIO DATA MODEL

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Abstract
Strategic planning of products and production systems is the key to create business opportunities utilizing the full potential of evolving technologies, to adapt to changing markets and to enhance time-to-market. As a prerequisite, methods and tools like Scenario Technique approaches need to be more intuitive and efficient. To increase the availability, timeliness, data security and forecast reliability, the Integrated Scenario Data Model (ISDM) has been designed as an instrument to extend evidence-based influences on strategic planning and engineering. The approach is based on a model-based integration of existing complementary data resources, formats and standards (e.g., STEP, SCOR, ISCL and ISA-95). The main contribution is based on an analysis and semantic mapping of available information resources and the required inputs for scenario based engineering. It facilitates the aggregation of trend data representing especially economic and political impact factors, data acquired from product lifecycle management tools (including, e.g., ERP, MES and PDM systems) as well as constraints, for instance determined by ethics and legislation. While models exist in all relevant fields, there is no transparent and integrative approach for the creation of future scenarios available so far. Thus, the ISDM increases the reliability of scenario creation and of business model development and reduces the efforts for iterative or even agile application in product development processes.

Keywords:
Scenario technique, Strategic planning, Product development, Data management, Semantic modeling

1 INTRODUCTION

Strategic planning of products and production systems nowadays means to create business opportunities utilizing the full potential of evolving technologies and interconnected, global markets [1]. New business models [2] are essential taking into account the highly dynamic innovations from all relevant disciplines [3]. Targeting an enhanced time-to-market in general, strategic planning needs to speed up significantly [4]. However, contemporary Scenario Technique approaches are characterized by manual provision with required input information (such as environmental, social, political and technological trends) and meta-information (like probability and interdependencies of trends); trend estimation, assessment of risks and experience with previous products are collected by manual estimation and time consuming interviews, literature research and discussion with strategic planners and CEO's [5]. Depending on low quality of input information, it is rather unrealistic to forecast reliable scenarios for the future.

To increase the availability, timeliness, data security and forecast reliability, an Integrated Scenario Data Model (ISDM) has been developed and will be described in this contribution. The ISDM represents an instrument to extend evidence-based influences on strategic planning and engineering. The approach is based on a model-based integration of existing data resources, formats and standards. The ISDM maps the semantics of available information resources and the required inputs for scenario based engineering. It facilitates the aggregation of:

- Trend data representing especially economic and political impact factors
- Data acquired from product lifecycle management tools (including, e.g., Manufacturing Execution and Product Data Management Systems)
- Constraints, for instance implied in terms of data quality or determined by ethics and legislation.

While models and tools are established in all relevant fields and partially used for commercial applications, there is no transparent and integrative approach for the creation of future scenarios available so far.

The paper is structured along this line: Chapter 2 provides an analysis of a) Scenario Technique for strategic planning and b) integrated data management approaches. The research approach presented in chapter 3 highlights key research questions addressing the requirements for the ISDM structure with regard to input data and traceability of Scenario Technique. Chapter 4 introduces the ISDM focusing on its core elements. Finally, chapter 5 provides a summary and an outlook to future research directions.

2 STATE OF THE ART

Data integration for Scenario Technique needs to be based on a twofold approach: Demands are determined from a methodological perspective, while available data can be identified by analyzing prevailing IT systems and management tools. In the following, the state of the art will be investigated in these two areas. First, the principles of Scenario Technique are amplified and resulting information flows are deduced (chapter 2.1). Second, existing data management approaches to provide necessary input information are analyzed (chapter 2.2).

2.1 Scenario Technique

The Scenario Technique with original military roots has meanwhile found various applications in social and economic issues [6, 7, 8]. Origin of the consistency-based approach is formed by Reibnitz [9]. Reibnitz was the first a) to provide a comprehensive method and process model, which contains all the necessary steps and b) to apply a funnel with a positive and negative extreme scenario of the future. Reibnitz mentions explicitly that the real future development will only adjust between the two extreme scenarios, but not that one of the extreme scenarios will be achieved in the same manner. Therefore the process model by Reibnitz is often cited and taken as a basis for further advancements (as examples, cp. [7, 10]). Hence, in the following it will be taken as a reference in order to analyze activities and identify relevant information flows within Scenario Technique. Thus demands for the ISDM are deduced from a methodological perspective.

The goal of future scenario analysis is set by the client and taken as input for the "**task analysis**"(step 1, see Figure 1). Input from other data sources are characteristics of concerned branch of industry, strategic business unit and product group (S1-Ext). This input can be retrieved from official statistics, company-internal knowledge of business unit and product group, e.g. benchmark analyses and self-evaluation. As a result of step 1, the subject of investigation and the as-is status of the company is specified (S1-Int). The as-is status is described by stakeholder (including priorities and interests), technology portfolio, strengths and weaknesses, threat of competitors and substitutes, and bargaining power of buyers and suppliers.

In the following "**influence analysis**" (step 2), external areas of influence affecting the company or strategic business unit are identified (e.g., procurement and buyer markets, competition, policy and legislation, technology, economy as well as the company). Corresponding influence factors are derived, evaluated and cross-linked to each other (S2-Ext). According to their position in the system grid, influence factors can be active, passive, ambivalent or buffering. On this basis, the most relevant influence factors are selected and entitled as "key factors" (S2-Int).

Trend analyses are taken as external input for step 3 "**trend projections**" (S3-Ext). Key factors (S2-Int) are formulated neutrally as "descriptors". For example, a value-neutral formulation of the key factor 'market growth' would be 'market development'. On the basis of such descriptors, their current and future statuses are described. In the course of this, unique and alternative descriptors are distincted from each other. Unique descriptors describe a future status by one value, which is often represented by a linear relationship with time. Alternative descriptors however may take different values in the future [9]. As a result of step 3, trend projection of unique (S3b-Int) and alternative descriptors (S3a-Int) is created.

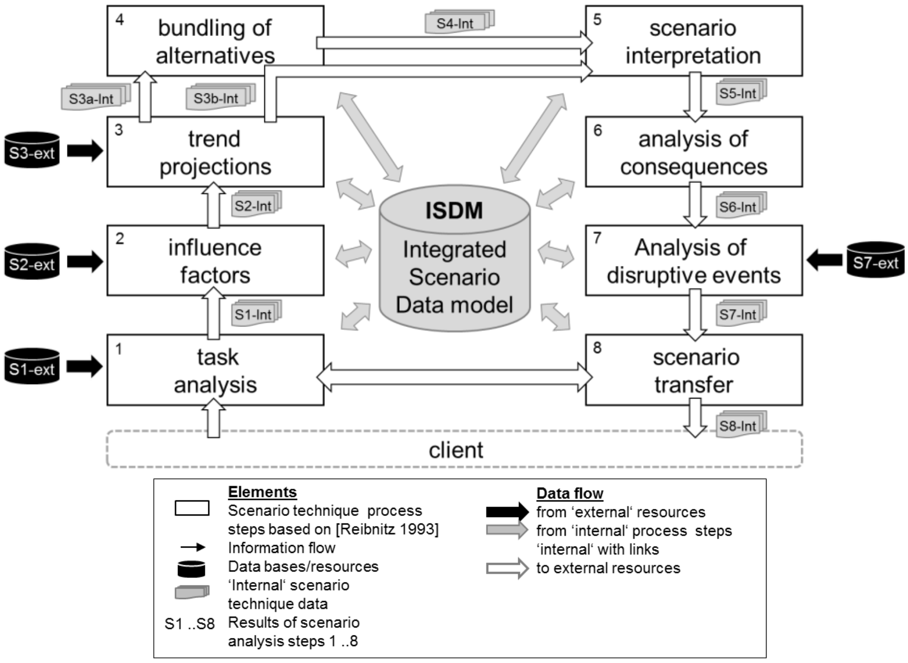

Figure 1: Information flow analysis diagram.

Only trend projections of alternative descriptors are taken as input for step 4 "**bundling of alternatives**" (S3a-Int). The aim of this step is to review the various alternative developments that have been identified in step 3 with one another for consistency or compatibility and logic. Consistent descriptors are bundled to raw scenarios and evaluated intuitively with regard to their stability and difference. Alternative development opportunities of cross-linked descriptors can also be bundled by mathematical models, such as cluster analysis, branch-and-bound or evolutionary algorithms. Results of step 4 are consistent, stable and very different scenarios (S4-Int).

Together with trend projection of unique descriptors (S3b-Int), such selected raw scenarios (S4-Int) form input data for step 5 "**scenario interpretation**". Raw scenarios are detailed, completed and interpreted verbally.

These completed scenarios form input data for step 6 "**analysis of consequences**" (S5-Int). Opportunities and risks arising from the completed scenarios are identified individually for each scenario. Corresponding measures are also derived separately for each scenario. As interim result, a preliminary strategy is formed by intersection of the measures (S6-Int).

In step 7 "**analysis of disruptive events**", possible external and internal fault events (S7-Ext) are collected and analyzed regarding their relevance

for the specified subject of investigation. A fault event represents an event which is unlikely to occur, but significantly in its effects for the company [9]. Relevant disruptive events are identified and their significance is evaluated. Further, preventive and reactive actions (crisis plan) are determined (S7-Int).
Goal of step 8 "**scenario transfer**" is to formulate a guiding strategy on the basis of preliminary strategy (S6-Int), preventive and reactive actions against disruptive events (S7-Int). In addition, alternative strategies are defined and an environment monitoring system is established (S8-Int).
In summary, the following demands result from this analysis of activities and relevant information flows on the database for the ISDM. They form the basis for reliable and traceable scenario creation and analysis:

- Links to external data sources (S1-Ext, S2-Ext, S3-Ext, S7-Ext in Figure 1) have to be provided persistently. This is a prerequisite to access such data sources automatically and facilitate traceability of created scenarios.
- Internally generated interim results (S1-Int, S2-Int, S3a-Int, S3b-Int, S4-Int, S5-Int, S6-Int, S7-Int) as well as results (S8-Int) have to be stored.

2.2 Integrated Data Management

Scenario Technique requires reliable input information subsuming, for instance, data describing the actual situation including product programs, key technologies, competitors, results from trend analysis, needs and potentials. Data management approaches and systems are available to act as 'external resources'. They need to be assessed with regard to relevance for different phases of the Scenario Technique, level of detail and corresponding value to influence the scenario definition and availability with regard to prevailing IT systems, communication networks and data formats.
The digitization of processes in production chains changes the role of human factors [11]. It extends the opportunity to derive relevant data based on concepts like agile manufacturing, knowledge-driven and virtual enterprise and autonomous control [12]. The conceptual information basis is built by tools along the product lifecycle and the automation pyramid [3, 13]:

- Enterprise Resource Planning (ERP) systems subsume data about resources, customers, offers and orders including economic and technical information, acceptance rates and actual projects.
- Product Lifecycle Management (PLM) carries information from requirements specifications to lessons learned from after sales services.
- Product Data Management (PDM), often included in PLM tools and concepts, provide centralized access to all relevant technical documents based on integrated product data models.
- Manufacturing Execution Systems (MES) support decision taking within production systems. MES rely on actual and real-time production data, subsuming data from manufacturing and quality management processes combining and utilizing functionality of Computer Aided Manufacturing (CAM) and Computer Aided Quality assurance (CAQ) software systems.

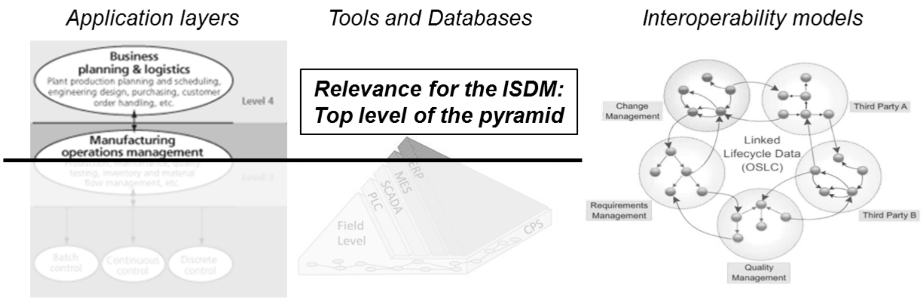

Figure 2: Existing data and prevailing IT systems for an Integrated Scenario Data Model (examples based on ISA-95, OSCL and [16]).

These systems support the management of data to be used especially for scenario input parameters characterized as ‘certain’ data. Certainty often correlates with objective and retrospectively retrieved data; ‘uncertain’ data which is essential to be incorporated in the foresight phase needs to be derived and incorporated utilizing specific approaches [14] and modeling probabilities [15, 16]. Additionally, aggregated views based on these systems and related tools (e.g. for requirements engineering and engineering change management [3]) help to identify relevant information for the task analysis phase.

Various sets of data are available in different data management tools (see figure 2). Boundaries between these systems are kind of vague, holistic architectures very different [13]: ERP systems often subsume PPS functionality due to their overarching functionality while companies still run specific PPS systems. Similarly, PDM is an essential part of PLM contributing the technical basis for product data management. Architectural concepts and reference models exist in standardized form, e.g., regarding processes (cp. SCOR reference model), automation level (cp. ISA-95 model) and data exchange (cp. OSLC for linked lifecycle data).

The differentiation among the different system categories is mainly driven by different perspectives instead of altering technical capabilities. Therefore common data formats and shared terminologies are needed to enable interoperability and flexibility. They define a framework to represent the semantic structure of a) specific data sets and b) their interrelationships.

The most widely used standard is the Standard for the Exchange of Product Model Data (ISO 10303 STEP). STEP is extended for various application domains. For the ISDM approach the most relevant applications are targeting Product Life Cycle Support (PCLSlib), product data management via the PDM schema and consequently "Managed model based 3D engineering" represented by the application protocol STEP AP 242 (ISO

10303-242). Besides these structural views to data integration, several approaches address the organizational level of PDM/ERP integration (cp. [18]). Acquiring data from these tools and especially their interfacing elements is a key challenge for the scenario analysis (e.g., combining analyses on the acceptance of product configurations and the closing ratio). Therefore it is essential that organizational aspects like global company internal networks and supply chains are taken into account [19].

3 RESEARCH APPROACH

The research approach is based on the analysis with respect to information flows within Scenario Technique (chapter 2.1) and prevailing IT systems and data management (chapter 2.2).

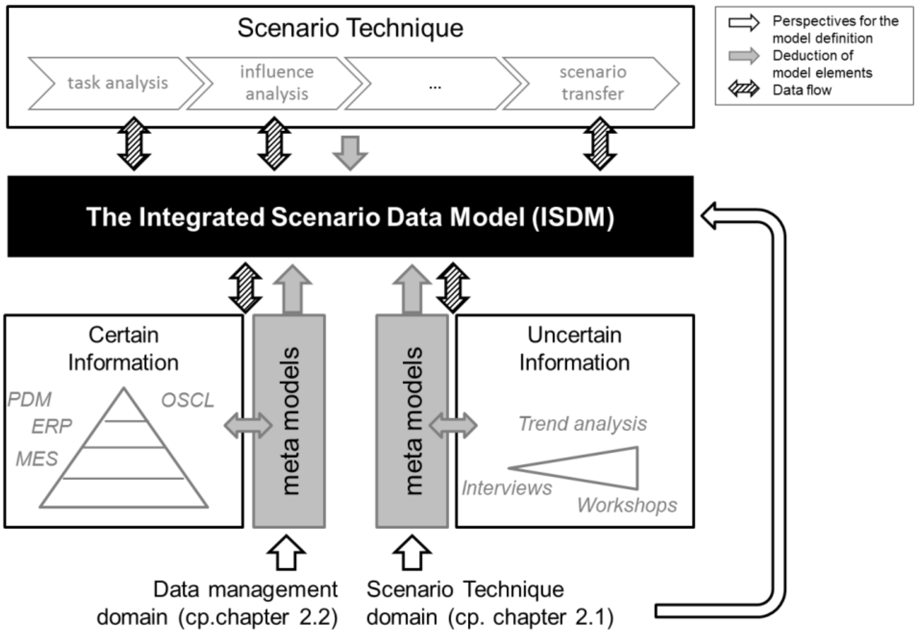

Figure 3: The Integrated Scenario Data Model:
Mapping meta-models for technology and scenario domains.

The approach addresses following research questions:

- How will the input information needed for the application of Scenario Technique be provided reliable, consistently and efficiently?

- How can these inputs be continuously updated with little effort, keeping track of changes and their effects for the scenario analysis?
- How will the interim and final results generated in each step of Scenario Technique be stored for the actual procedure and as a basis for future application of Scenario Technique?
- How are the intermediate and final results classified with regard to information maturity and certainty? How can uncertainty be included in the documentation?
- How can the accuracy and incidence rate of anticipated future scenarios be increased through reflection and validation of prior results and comparison with the real development?
- How is the foundation for premises controlling in parallel with the application of the selected guiding strategy laid?

The pursued research approach is illustrated by the coarse structure of the Integrated Scenario Data Model (ISDM) presented in figure 3. The ISDM serves as connecting element between the application of Scenario Technique (top of figure 3), already existing IT systems and data management approaches (left bottom of figure 3) and data acquisition from the Scenario Technique domain (right bottom). Following this coarse structure, the concept will be amplified using meta-models in chapter 4.

4 INTEGRATED SCENARIO DATA MODEL (ISDM)

The integration of data which is used or generated by the Scenario Technique is driven by the process itself (cp. chapter 2.1). Therefore, the core of the model is dedicated to the representation of scenario data. It is complemented by a semantic model mapping this data model with external data resources (cp. chapter 2.2). The mapping layer benefits from existing integrative schemas and approaches incorporating them into a holistic model. These two building blocks form the Integrated Scenario Data Model (ISDM) representing the internal Scenario Technique perspective and including references to external data resources (see Figure 4).

Based on the analysis of process steps of the Scenario Technique, five different clusters of information are identified that need to be integrated and maintained through the ISDM. These clusters determine partial models subsumed by the ISDM. Each partial model is related to one or more steps of Scenario Technique. At the same time, they determine the structure of the internal database of the ISDM (see upper part of Figure 4). This structure is complemented by the semantic meta-model adopting existing ontologies and links to external databases. External databases are integrated either following semantic standards (e.g., STEP) or need to be annotated explicitly based on the ISDM's semantics. Mapping technology driven meta-models based on a formal representation of the semantics of scenario driven data types is the key to retrieve relevant data from a company's data base.

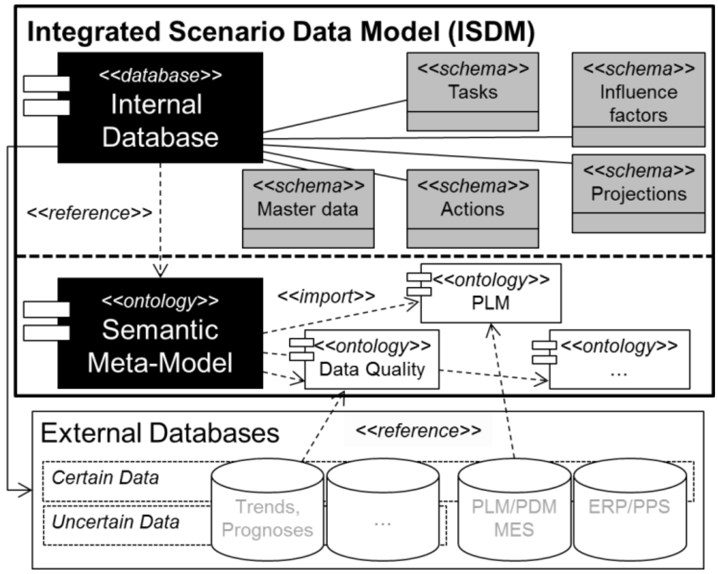

Figure 4: The Integrated Scenario Data Model (ISDM) structure.

Semantic technologies are used to implement, maintain and analyze such models and use them as a basis for inference and reasoning (cp. [20]): Assuming that a 'thing' like a company, a task or a scenario has certain characteristics, inference allows to understand different categorizations of the 'thing' (i.e., assignment to concepts in an ontology) while reasoning adds conclusions based on logical axioms defined in an ontology (e.g., using description logics; cp. [21]). The core ontology for the Scenario Technique is implemented using standard data formats:

- The Resource Description Framework (RDF) builds an XML based foundation which is enabling linked data approaches. For the ISDM, it allows, for instance, inclusion of results in the Open Linked Data cloud.
- The Web Ontology Language (OWL) with its specific dialects extends the capabilities by concepts to express relationships and constraints.

The Open Services for Lifecycle Collaboration (OSLC) is treated as a reference example in this paper (cp. chapter 2.2 and figure 2). The concept includes three core elements: a) a community sharing the ambition to interlink lifecycle data, b) the definition of a data exchange language as well as c) reference implementations and pilots that can be adapted to explore the potentials and setup new interlinked models [22, 23].

Both the structure of the internal database and the semantic meta-model are implemented applying the five clusters of the ISDM. Relations are specified by imports of sub-ontologies and references to semantic concepts. **Master data** comprises an identifier for the analysis, information about the history of the analysis and goals of the analysis. The Scenario Technique is initialized by a profound analysis of **tasks** (implementing goals and strategies) of the subject of investigation. Being an enterprise or a specific department within an enterprise, the as-is status is described formally. The status is encapsulating information about the characteristics of the relevant branch of industry, strategic business (or organizational framework in general) and product group (if applicable). These data sets are provided by a client; they are certain and need to be updated continuously. In contrast to existing Scenario Technique approaches, this is covered by accessing master data documentations. The second step of the Scenario Technique is dedicated to an analysis of **influence factors**. Influence factors are partially specific for the goals of a scenario analysis; partially they are generic and transferrable to other cases. They represent areas of relevance; details about and results of investigations (from sensitivity analysis, probabilistic models etc.) need to be archived to facilitate traceability and future iterations altering input variables according to new or changed assumptions. The Scenario Technique highlights a subset of influence factors as key factors determining the projections. **Projections** are created through trend analyses for the key factors. This might subsume technological foresights as well as market development studies. While the input data is stored as part of the influence factors, details about the execution of simulations as well as results are stored in a dedicated partial model. Additionally, scenarios are specific instances in the 'projections' model being treated (in terms of sorting, ranking, interlinking) throughout further steps of the Scenario Technique. The **actions** derived from the scenarios are handled separately. They represent conclusions being oriented towards the enterprise. Actions subsume strategies, environment monitoring systems and specifications regarding iterations of Scenario Technique execution.

5 SUMMARY AND OUTLOOK

Enterprises heading towards economically successful product innovations proactively anticipate future scenarios. In order to keep pace with the increasingly dynamic and unpredictable nature of the markets, shorter planning cycles become necessary. One of the most common approaches of systematically generating future scenarios is Scenario Technique. However, its application is associated with considerable effort, inaccuracy and lack of reproducibility. For more frequent but reliable use of Scenario Technique, the contemporary effort required for data acquisition would be too high.
For these reasons, the Integrated Scenario Data Model (ISDM) has been developed as a data-management-based approach. The ISDM allows

retrieving and aggregating data from already existing IT systems and data management approaches. The model is used to structure databases for storing interim and final results of the iterative steps of Scenario Technique. Thus the ISDM serves as a bridging element between the applications of Scenario Technique on the one hand and partially automated data provision from prevailing IT systems on the other hand. This concept is realized using and interlinking meta-models. The degree of novelty lies in partially automating collection and consistent representation of all scenario input data. Thus, quality of input data rises and companies are enabled to anticipate transparent and comprehensible future developments in their business area at any time. Short-term availability allows continuous and more frequent updates of scenarios and derived actions.
Future research topics will be detailing partial models and meta-models of the ISDM, defining interfaces in between the partial models and the meta-models, as well as their implementation in an IT prototype.

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FIVE INSIGHTS IN EFFECTIVELY MANAGING PRODUCT DEVELOPMENT

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Abstract
Development engineers are most valued for their excellence in physical product development, but on the flipside, project managers face problems when trying to fit them into effectively running development processes. Because of the advantages of Lean Management in production (Lean Production), process managers often try to transfer lean principles directly to development processes, not considering that major differences exist between well-described production processes and new product development processes which include much more uncertainty and risk. Nevertheless, several lean principals are applicable in product development. This paper describes five lean development insights (LDIs) which were found when optimizing an entire product realization process. Lean principles have been examined and then translated to collaboration between product development and tool manufacturing at a globally operating German family-run company. These LDIs are meant to help project and process managers, consultants and developers to rethink their ways of organizing product development. The application of these insights will result in increased transparency, intensified collaboration, improved processes and quality, shortened lead times, and also eliminate waste.

Keywords:
Lean development, Collaboration, Agile, PLM, Frontloading, Simultaneous engineering

1 INTRODUCTION

Product development in companies is currently facing other challenges than several decades before. They are part of a widened business environment with an increasing number of competitors in a globalized, interconnected world, in which at the same time customers tend to increasingly asserting their individual needs. Technology is progressing fast and products are becoming more complex. Conventional new product development (NPD) processes are overwhelmed by these influences. If companies do not adapt to such changing circumstances, they will not be able to cope with them and will eventually disappear.

Since the development of Taiichi Ōno's Toyota Production System (TPS) and Womack and Jones's lean concepts, companies have been able to achieve great improvements in production efficiency, but to date not in R&D. The question is whether it is possible to obtain similar results in R&D, and whether companies will forfeit engineering ability and effectiveness by trying to make the development process more lean and efficient.
This paper presumes that the ideas of lean manufacturing can and should be adapted to development processes. After a brief introduction of lean concepts and conventional new product development processes, a case study is outlined. The potentials for collaboration between product development and tool manufacturing at a globally operating German family-run company have been identified. On this basis, five lean development insights will be described that help to rethink the conventional ways of organizing product development and to make it more efficient. From this, actions and measures for the proper translation of lean principles to the development processes will be recommended.

2 LEAN THINKING

According to a survey the term 'lean' is used synonymously for efficient operation and less waste. Schuh [1] states that 'lean' is an approach which helps companies to add value without generating waste. Womack and Jones [2] describe the purpose of 'lean' as being to reach the goal of fulfilling the customer's exact requirements while consuming fewer resources – less human work power, less equipment, less time. They studied Taiichi Ono's works [3] regarding the Toyota Production System and visited many companies all over the world to create the key principles of lean thinking: to specify value, to identify the value stream, to make the value flow continuous, to let customers pull value and to pursue perfection [3]. The individual principles are described as follows.
Specify the value: Sometimes engineers tend to get lost in detail. Fascinated by the complexity and functionality involved, they dissipate their efforts without adding value for the customer. Instead, the value must be defined from the customer's point of view, because the customer is the one who decides whether to pay for the product or not. Therefore, functionality, design, usability and brand image must be aligned to the customer's requirements. Any activity that creates no value for the customer is waste and must be eliminated. Ono [4] has identified seven types of 'muda' (Japanese for waste): "over-production, inventory, waiting, motion, transportation, reworking, and over-processing." Womack and Jones added an eighth waste type: products and services that do not meet the customer's requirements [3].
Identify the value stream: The value stream describes the entirety of the activities that add value to the product or service. Material value creation takes place throughout the entire manufacturing process, from raw materials

to the finished product. Effective processes and actions must be identified and every kind of waste eliminated. A further goal is to optimize the entire value chain by involving customers and suppliers into this process. [2]

Make value flow continuous: When the value-generating process steps are defined and separated from unnecessary ones, the next goal is to achieve continuous flow. Like Ford's innovative assembly line, the processed products run through the whole value chain at a steady pace and result in a continuous and reliable stream of finished products. [2] Thus, no large storage facility is needed any longer, and the opportunity to improve coordination and processes is created.

Let customers pull value: Since the customer creates the demand, he should be the initiator of these processes. Manufacturing should start at his order. Thus, material flows against the flow of information. The customer pulls the product through the value chain, something that is called the pull principle.

Pursue perfection: All these lean principles interact with another. Thus, it is important to put them into practice, on an ongoing and iterative basis. Every worker should follow a continuous (ongoing) improvement process.

3 NEW PRODUCT DEVELOPMENT

3.1 Stage Gate Process

New product development is the process of producing a product from the initial idea or order placement to delivery to the user [5]. Therefore, every company should develop its own approach which adapts best to the given conditions. Most companies use a variation of the Stage Gate Process [6]. Cooper established the Stage Gate Process and divided the new product development process into a series of activities (stages) and decision points or milestones (gates). Each stage contains several cross-functional and parallel activities in which technical, market and process data and information are collected, analyzed and interpreted. This newly found knowledge forms the basis for the decision whether to enter the next gate (go), go back to the stage before (loop) or stop the project (kill). The process begins with a first check (Stage1). The scope, ideas, potentials and technologies of projects are roughly examined and defined (preliminary investigation). In the second stage, the product concept is generated, and a business use case is built (detailed investigation). Then, in stage three, the core development process is carried out, the technical issues are overcome, the interaction with the customer is planned, and key deliverables such as the pricing model, capacity plan and test plan are defined (development). Subsequently, the project is validated in stage four in terms of the product itself, the production process, customer acceptance, and the economics of the project (testing and validation). Finally, in stage five, the product is produced and launched (full production & market launch) [6].

3.2 Case Study

To get an idea to what extent the application of lean can optimize the new product development process, typical potentials were worked out in a case study at a worldwide operating German company. The focus has been placed here on the collaboration between manufacturing and development processes. More than 20 potentials have been compiled in several workshops with staff from different departments affected. The most important potentials will be exemplified below.

It turned out that development processes suffer from **insufficient definition of the project**. Without clarification of the challenges, goals and tasks of the project, all work and data will remain volatile. Sometimes new product development **lacks good collaboration**. Results are forwarded only when completed. Such **sequential engineering** leads to **longer waiting times** and **poor quality** and is often due to a **lack of communication,** which originates from lack of time or other problems. Another major potential lies in the exchange of data and information. Media and system discontinuity result in unnecessary transfer problems and poor data quality.

4 LEAN DEVELOPMENT INSIGHTS

The lean principles described above should be transferred to new product development. The question should be answered to what extent the application of lean can improve collaboration in new product development. Based on the potentials just developed, five practically oriented insights will then be formulated, the lean development insights (LDI).

The definition of the value, the value stream and the introduction of lean standards in stiff assembly lines are relatively uncomplicated. The value of physical products is clearly visible. Modern design, valuable raw materials, useful function, or the brand image conveyed are reasons why a customer is willing to spend money. In product development, it is more difficult, more abstract. The results of the development are not physical, but intellectual. They are created in the form of information and should be made visible through a digital validated visualization of product and manufacturing processes. [7] Knowledge must be generated and transferred to co-workers. Thus, the value stream in product development consists of a **flow of information**. A good way to visualize value and waste is a value stream analysis. Its goal is to identify the individual processing steps, activities and their sequence and duration, lying and waiting times, grinding and other process data. Schuh explains how this analysis can be applied in product development. He states that the formulation of guidelines and target statuses are the basis for identifying the value in product development. Defining a huge, far-away goal, a management policy, and deriving smaller objectives from it will help to identify waste and value in product development. [2] He stresses the need for detailed descriptions of customer value and its clear and transparent communication across the company. The real contribution to the fulfillment must be made readily accessible and understood by every single employee throughout the process, so that they can do their work. Knowledge about waste and value is the foundation for lean development. Any other following insight is based on the first LDI.

> **LDI1: Customer value in product development is generated in the flow of information and must be made transparent throughout the entire process.**

According to ISO 9000, a process is a set of interrelated or interacting activities which transforms inputs into outputs [8]. The goal of lean development is to create standardized, recurring workflows. They should ensure good collaboration in complex projects through lean processes. But to create them, a clear definition of the project must be achieved first.

“If there is no consensus on the fundamentals, it is pointless to forge together plans.” [9] In order to carry out a project with maximum efficiency, it is important to provide clarity on the entire project. As is already practiced in the automotive industry, all crucial decisions should be set at the beginning of the product development process. Such **frontloading** should be performed in organizational aspects such as tasks, competencies, responsibilities, targets, milestones, project structure, scheduling, cost planning, risk analysis and technical content issues, e.g. design and functionalities. Agile methods like the war-room can help here by intensively creating the product concept in a short time.

This is a special, intense method of **simultaneous engineering**. This term describes the goal-oriented, interdisciplinary, collaborative and parallel work of development, production and sales [5]. Organizationally different teams should work simultaneously on one and the same issue. This requires an explicit task and concept definition, good communication and exchange of data. This means that independent tasks should be executed in parallel and should be seen as a general concept at the process level. In contrast, dependent tasks cannot be executed simultaneously. Co-workers should bide their time aggressively and start with total commitment once the preceding step is completed. This leads to a major reduction in processing time and a significant increase in productivity and should be applied at the operative engineering level. So frontloading and simultaneous engineering can be performed, it is important that sufficient capacities are held in reserve for this early stage. Thus, it is possible to clarify uncertainties and thus avoid changes early on.

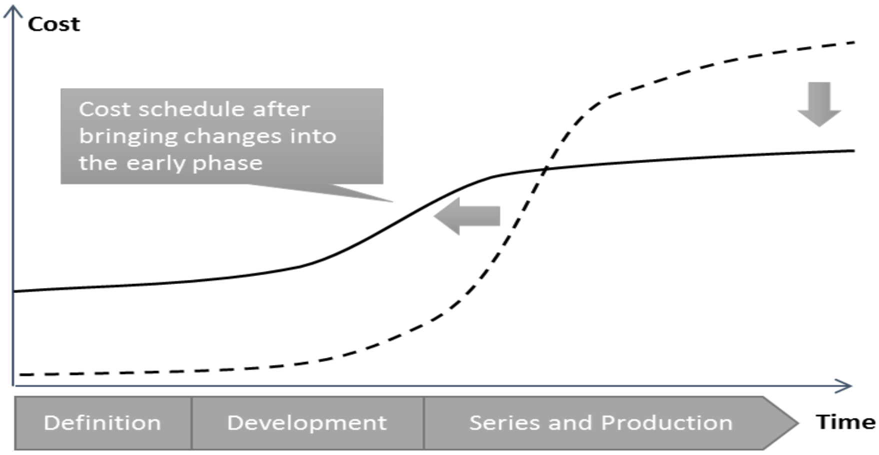

Figure 3: Frontloading and pro-active culture of change.

This results in the next insight:

> **LDI2: An explicit task definition at an early stage and interdisciplinary, simultaneous work minimize errors, changes and iteration loops and eventually shorten the cycle time.**

As described, new product development is very complex and requires collaboration between different persons, and therefore clear processes. However, the single developer needs as much leeway as possible in his daily activities to work out the best solution, powered by his creativity. This conflict of aims, clear processes and leeway for creativity can be solved by dissecting the problem. Where is flexibility, and where is standardization of the processes helpful?

As identified earlier, the individual product designer needs leeway in his engineering work. In daily work (engineering level) he should be given all the space and tools he needs to deliver the best result. Since he works in a highly complex environment with many different people, collaboration (process level) should be standardized to facilitate coordination and maximize transparency and clarity in processes.

The Stage Gate Process is predestined to meet this demand of organizational structure in development processes and helps to create a company-wide common understanding of the new product development process that strengthens collaboration. In issues about rights and responsibilities, the accepted Stage Gate Process provides an objective appraisal function and allows binding and consistent decisions.

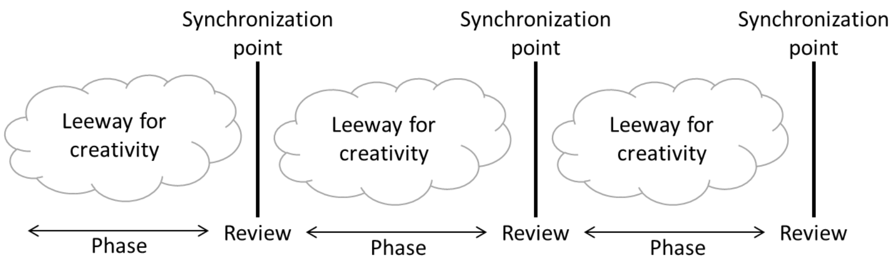

Figure 4: Leeway and standardization.

In detail, project-wide synchronization points should be inserted to ensure proper interaction in time and content issues between different departments and people. At these points, the results and information should be synchronized and exchanged. The focus should lie here on standardization, collaboration, reconcilement and discussion about problems and new ideas. Thereby phases are generated that organize the complete development into a timely consistent rhythm. During the individual phase the developer should be given maximum leeway for creativity to generate the best solutions. It is very important that he can unfold his personal skills and creativity without being blocked by organizational constraints. Non-innovative, repeated actions of the engineer should be standardized and simplified or automated. It will then become possible to synchronize the individual developing actions of a cross-functional team at the end of each phase. The conflict of aims, standardization and collaboration versus individual leeway in an interdisciplinary product development, is resolved in this manner. For this reason, standardization can create space for creativity and therefore help to create a setting to come up with innovations. Thus, the best practice in new product development is to develop appropriate approaches and methods for both levels, engineering and process, that interwine and act symbiotically. [2] The corresponding insight is:

LDI3: A consistent rhythm with synchronization points at the end of each phase and maximum leeway in between simplifies collaboration and generates space for creative inventions.

To set the synchronization points properly, it is important to perform value stream analysis and establish a continuous value-adding development process. However, in most cases the project members do not work just on one project. Companies are looking for many projects to maximize revenue. If staffing levels do not increase as well, the individual employee has to work on many projects at the same time. This gives rise to substantial problems.

Employees often have to switch between tasks, e.g. stop following up the last workshop through having to attend meetings for another project.

Figure 5: Reduction of workload leads to higher project throughput.

Constantly switching between activities causes the lead times of the individual projects to accumulate and so results in more lead times. Furthermore, “mental lead time” is generated. The engineer needs time to become acquainted with the action previously started. Multitasking evokes harm. Thus switching between projects must be minimized, either by reducing the number of projects or increasing staffing levels. Concentrating on a single project will accelerate its execution. Techt states that, in multi-project companies, a reduction of 25% in workload can increase project output by 20% and lower project lead times by 35%. [10] If fewer projects are running at once, the individual employee has fewer tasks to manage at once and can exercise his functions more intensively, so ensuring better quality work. In addition, fewer projects are then pending and are accumulating lead time. In practice, this might allow one engineer to manage two projects that are in a polar project state to overcome unpreventable waiting times. This leads to following insight:

> **LDI4: A reduction of simultaneously processed projects leads to a shorter lead time and greater project throughput and allows for more flexible resource allocation for each project.**

It was previously assumed that the data exchange process works well when the process is properly defined. However, reality proves that the exchange of information can yield problems. New product development generates and exchanges large volumes of data and information between the participants involved in the process and has to cope with reciprocal dependencies and several interests. There is often special software that disrupts the flow of information, and consistent data management is lacking. Collaboration, release management, version handling and the multiple use of single objects lead to major problems. Only when all data is supplied from one source the accuracy of data is preserved, so allowing exchange to be simplified. The process of product lifecycle management (PLM) and its contribution to solving this problem is thus described below.

PLM aims to manage data, documents, processes, functions and applications over the entire lifecycle of the product in a holistic, enterprise-wide approach. The different types of data are stored and made available in one system, which integrates all software components throughout the whole lifecycle. The core data management process collects all product-defining data, which are not fixed in documents or a file structure but simply stored in a database. Structure is provided by relations of metadata and characteristics of the object. This way each department can create its own dynamic view to view only individual key data and documents. The classification of materials can facilitate the search for data as well as its reusability. Existing solutions can thus be adapted to new problems, and equivalent parts can be used in several different articles. Furthermore, it is possible to assign the relevant status to components and articles and to make them visible to interested parties. These principles follow the **Single Source of Truth** concept, which ensures that the same information only ever exists once, and all references are fed by it [2].

An implementation project must be started in order to use the PLM system. Matt & Partner found out that 41% of these projects fail, and 43% of them exceeded the budget [11]. Companies often skip the analysis of the current state and fail to create processes that meet the company’s needs and the user’s acceptance. A jointly executed value stream analysis and the formulation of a PLM strategy that is derived from the corporate strategy can put things right. Media discontinuity and island systems must give way to transparency and data consistency. It is critical to gain user acceptance by including them in the implementation process and selecting a user-friendly system. Well-organized training and communication of the benefits of the system are requirements for a successful implementation. Thus, the fifth insight is:

> **LDI5: The implementation of a user-friendly, accepted and integrated PLM system provides for continuous value creation in new product development by means of a consistent flow of information.**

5 LEAN DEVELOPMENT OUTCOMES

Henry Ford's strength was his relentless will to become better. He stated that most people waste more power in talking about problems, rather than resolving them [2]. Therefore, after developing lean development concepts, they were applied to existing problems and individual solutions for the single potentials were presented. Now, from this, recommended actions will be

formulated regarding how to implement lean development in the collaboration process of a company.
Management has to define and advertise the company-wide policy, i.e. the major goal they are heading for. Then, lean thinking should be implemented in the corporate culture, just like a cooperative, non-egoistic way of thinking. To do this correctly, a sophisticated strategy has to be established. This should start at the top management level. Acceptance and support of the most important decision-maker is the basis for a successful implementation of lean. They should be given the right training to set an example in living ‘working lean’ on a daily basis, and then supporting and demanding lean thinking from their employees. In parallel every single employee should receive ‘lean training’ to get to know lean and its opportunities, and to also encourage acceptance of this concept. This results in the first lean development outcome (LDO):

> **LDO1: Change corporate culture gradually top-down through training and example.**

Meanwhile, a complete analysis of the current state can then be carried out. By means of value stream analysis every single process should be recorded and rethought by experienced employees and consultants, who are not company-blind, but conversant with processes and lean thinking. Every single action should be analyzed in terms of its needed input and required output. When all wastage and values are identified, new processes should be defined, taught and made transparent in a suitable new lean product development process guide.

> **LDO2: Analyze together every activity and create a new lean-appropriate development guide based on the following LDOs.**

This guide should be mainly driven by the frontloading principle so that decisions can be made on a well-informed basis. Often work at this early stage is not assigned to a cost unit. To solve the problem, project budgeting should be implemented. The project manager then can use frontloading and enjoy all its benefits. This is the third LDO:

> **LDO3: Shift the maximum work to the early phase and introduce project budgeting.**

To this end, the individual employee must not be allocated in several different projects, i.e. the number of his or her projects should be minimized. This effect could be intensified by implementing mature simultaneous engineering. The new processes should be defined in such a way that parallel interdisciplinary working is possible with regular meetings.

LDO4: Minimize multi-project management for the individual and create collaborative simultaneous engineering.

A new guideline for the product development process should act as a framework for development. Independent gatekeepers should ensure that staff proceeds and gates are passed correctly. Moreover, the engineer should acquire leeway through agile methods while needing regular synchronization points.

LDO5: Combine the Stage Gate Process as the organizational framework with agile product development for daily work.

Data-based PLM software should support the development processes. Its task is to supply all data over the product lifecycle at the right time and at the right place, and to replace all other software programs or integrate them in the PLM system. Thus, the last LDO is:

LDO6: Implementation of data-based PLM software and elimination of all other island solutions.

6 CONCLUSION

The aim to improve collaboration between new product development and manufacturing by transferring lean principles to the development field leads to five principles: to specify value, to identify the value stream, to make the flow continuous, to let the customer pull value and to pursue perfection.
While transferring these principles to the new product development, five fundamental insights were developed that led to recommended actions. All other insights are based on the first one, which states that in product development value is not tangible, but abstract in the form of information, and this value stream should be made visible for all people within the process (LDI1). To handle all the problems that occur during new product development, knowledge about the product and project should be collected and generated early on. In connection with interdisciplinary simultaneous engineering, lead times can be shortened (LDI2). In order to improve collaboration, repeated non-creative tasks should be standardized. Furthermore, higher-level interdisciplinary synchronization points should be harmonized through a stage gate-process. In between these points the engineer should be given maximum leeway through an agile environment (LDI3). Project multitasking can hinder engineers in completing tasks. The variety of projects means that they often have to switch between them. A minimized number of projects can help to shorten lead times and increase project throughput (LDI4). Finally, the implementation of a user-friendly PLM system helps to apply the Single Source of Truth principle to improve

processes and data management, if it is eventually accepted and implemented in its entirety (LDI5).

Overall, this paper has shown that the transfer of lean principles to new product development can improve collaboration and communication, shorten lead times and eliminate waste. Furthermore, it provides recommended actions that will support realization.

To take a look into the future, globalization and individualization of demand will continue, so companies have to prepare for versatile single part production: Industrie 4.0. Thus, development costs have to be minimized and in the meantime, the variation of developed products has to be increased. Lean development is the proper approach to handle this situation. 'Lean' must be well trained and gain acceptance among engineers. A holistic concept has to be developed, and sufficient time and money provided.

Despite all the positive aspects of lean, there is a certain danger. If a company just lets the customer pull value, no disruptive technology-changing innovations can emerge. So they have to generate space where waste can occur, and people can research into future products and technologies. Only if they actively face these challenges, adapt Industrie 4.0, give leeway to researchers, lateral thinkers and innovators they will master the future and find their way to the perfect company.

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HOW ELASTICITY INDICATORS SUPPORT COST MANAGEMENT

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Abstract
Against the background of rising overhead costs in manufacturing companies the application of methods of overhead cost management is of increasing importance. Within this article existing approaches of cost management are explained in principle. Based on these approaches a new complementary approach of managing costs with the help of costs elasticity ratios is described by a case study. The method is based on the hypothesis that there are no fixed personnel costs, but personnel costs with different elasticity with respect to the volume of orders. Personnel costs elasticity (ε) is derived from the quotient of the relative change in personnel costs (k) and the relative change of the order volume (q) of a billing month (i). The method aims to increase the flexibility of overhead costs, but can also be applied with respect to so-called direct costs. In this case, the question arises as to what extent the direct costs actually develop proportional elastic over time.

Keywords:
Cost management, Overhead costs, Direct costs, Labor costs, Elasticity

1 RISING OVERHEAD COSTS – CAUSES AND EFFECTS OF THIS TREND

The trend toward shorter product and innovation life cycles along with decreasing development and time-to-market periods is continuing [1]. At the same time, complexity and variant variety in production are also increasing as a result of global competition. This has led to increased volatility in the incoming order situation in many industries and companies. At the same time, there is also a trend toward rising overhead costs – also caused by increasing complexity and dynamism – in manufacturing and administrative departments in western industrialized nations [2] [3] [4] [5]. These additional overhead costs in areas such as procurement, logistics, maintenance, quality management or work preparation are also referred to as complexity costs [6]. According to Fischbach and Sommer [7], overhead costs make up over two-thirds of total costs in most industrial enterprises.

Direct costs are viewed as completely variable. Assuming productivity is constant, they change in a linear relationship to the output quantity. In contrast, the overhead costs of a company are largely considered to be fixed, at least with respect to a specific period. According to this premise, if overhead costs constitute a large portion of overhead costs, a high capacity utilization rate is necessary for a factory to reach the break-even point [8]. Companies that operate in volatile markets and have a high percentage of overhead or fixed costs face the problem of not operating profitably in periods of low demand and not reaching their financial goals [9]. In addition, cost analyses of companies that operate in volatile markets show that personnel costs classified as direct costs do not always change in a linear relationship to the output quantity. There can be many reasons for this. For example, productivity may decrease during peak order periods because of the added training time required when temporary workers are hired or because of bottlenecks that can occur in production and distribution.

2 OBJECTIVE OF THIS ARTICLE

Methods of cost management are becoming increasingly important because of the trend toward rising overhead costs in manufacturing and administrative departments. The purpose of this article is to present a new, complementary approach to managing the direct personnel costs and overhead costs of manufacturing departments and areas closely related to manufacturing. The method is based on the hypothesis that there are no fixed personnel costs, only personnel costs with different elasticity with respect to the volume of orders [9]. The aim of the method is to make managers and employees aware that a model that strictly separates direct and overhead personnel costs as well as variable and fixed personnel costs does not nearly reflect reality in a variety of ways. A much more useful cost management practice is to differentiate costs by their level of elasticity with respect to order volume and to leverage the potential flexibility of costs through resources such as flexible time recording systems. This method should be viewed as a supplementary method of cost management. It can be useful for the overall budgeting process as well as for target costs management [9].

3 FUNDAMENTALS OF COST MANAGEMENT

Cost management involves planning, controlling and monitoring costs. Cost management focuses on changes in the level, progression and structure of costs [10] [6]. The level of costs is determined using the quantity and value structure of the costs. The cost progression shows changes in costs over time. The progression of costs is often compared to the progression of a corresponding value such as revenue or sales volume. This comparison shows that costs often do not respond immediately to changes in cost drivers, such as a drop in sales volume or revenue. Another phenomenon that may occur is a change in costs in anticipation of increased sales, for example if new personnel is recruited or machines and materials are purchased in advance. In this case, a cost progression diagram would show a change in costs prior to a change in a cost driver such as sales volume [10] [6]. Cost structure analyses can be used to classify overall costs according to fixed and variable costs as well as direct and overhead costs. Costs can also be categorized by cost type, cost center and cost object. These cost structure analyses are often combined with cost progression analyses in order to reveal trends in cost structures, initiate cost reduction activities in advance and assess their effectiveness. Additionally, individual cost management methods can be used throughout the entire product creation process – from product development to production planning to production and distribution. Budgeting and target costing are the most well-known methods of cost management.

4 COST MANAGEMENT USING ELASTICITY INDICATORS

The purpose of the developed method is to provide a simple but effective tool for cost management in the company (for method, see [9]). The method and the case example below focus on personnel costs, which are especially important in many of Germany's manufacturing industries [1] [11].

The method is based on the hypothesis that there are no fixed personnel costs, only personnel costs with different elasticity with respect to the volume of orders. However, the order volume does not necessarily have to be the same as the quantity of manufactured goods or the number of production orders. For example, in a consignment warehouse, the number of picks can be a benchmark for the volume of orders. For a manual assembly department, it can be useful to calculate the order volume as the sum of the order times of the period using standard time management methods, since these target times are usually used for estimating manufacturing costs and the sales price. In this way, the manual assembly department will increase profitability by extensively adjusting personnel costs to the changes in order times [9].

The minimum requirement for using the method is the ability to differentiate between vacation and undertime/overtime in costing for month-based time sheets. In other words, according to the definition of costs, only the hours worked in a month will be applicable to costing [9].

The central parameter of the method is elasticity, which is used primarily in macroeconomics [12]. This parameter is used to examine how the value of a dependent variable varies if the value of an independent variable is changed. The method not only considers the absolute changes to dependent and independent variables, it also takes into account the relative changes in relation to a base level [13].

Personnel cost elasticity (ε) is calculated using this method. The percentage change in personnel costs (k) of the period (i) compared to the personal costs of the reference period (R) is used as an independent variable. The independent variable is the percentage change in order volume (q) per period (i) compared to the order volume of the reference period (R). The personnel cost elasticity (ε) is the quotient of the dependent and independent variable:

$$\varepsilon = \frac{\frac{k_i - k_R}{k_R}}{\frac{q_i - q_R}{q_R}} = \frac{(k_i - k_R)\ q_R}{k_R\ (q_i - q_R)}\ mit\ i = \{1; 2; 3; ...\} \quad (1)$$

Personnel costs elasticity (ε) can be used to determine the extent to which personnel costs follow the order volume: The reference period is usually the accounting month with largest actual or expected order volume, or the accounting month with the lowest total personnel costs per unit or per production order. Reference values for costs and order volumes are based on a month in which the personnel cost structure in relation to the order volume is considered especially favorable.

Assuming that the reference values for personnel costs and order volumes are greater than the comparison values from other periods, the following three distinct cases emerge: A personnel cost elasticity with the value 1 means that the personnel costs have developed proportionally and elastically in relation to the order volume in comparison with the reference month, meaning the personnel costs are completely variable. If the value for personnel cost elasticity is greater than 0 and less than 1, the personnel costs have decreased to a lesser extent than the order volume. If the value for the personnel cost elasticity is greater than 1, the personnel costs have decreased to a greater extent than the order volume.

5 PROCEDURE AND EXAMPLE

The method was tested in a manufacturing department. The department manufactures products that are structurally very similar. The results of the method test were published in a simplified case study [9]. The basic procedure for using the method is described below using a simple case example. In this fictitious example, the manufacturing department has only two cost centers. The personnel costs of direct employees are recorded in cost center A and the personnel costs of the indirect employees are recorded in cost center B. The method is applied in five stages, as shown in Figure 1.

1. Plan and implement data acquisition
2. Determine cost percentage of individual cost centers
3. Determine percentage changes in order volume and personnel costs of individual accounting months compared to corresponding values in the reference period
4. Determine personnel cost elasticities
5. Interpret data and initiate actions

Figure 1: Procedure for using the method.

Data acquisition is planned and implemented in the first stage. This stage consists of four steps. In the first step, the area to be examined is delineated from a costing perspective by determining which cost centers and types will be included in the analysis. The assessment period is determined in the second step. The periods in the assessment period are usually months. The parameter that significantly influences costs is determined in the third step. Data are collected in the fourth step. The result is table 1, which is shown in Figure 2. As shown in table 1, demand for products is subject to seasonal fluctuations. The personnel costs for individual accounting months are listed for each cost center (CC). Cost center A contains the direct personnel costs. Cost center B includes the indirect personnel of the production department (e.g., management personnel, maintenance, quality assurance). The second column of the table lists the order volume and the fifth column lists the total personnel costs. The sixth column shows the total personnel costs per unit as the quotient of the total personnel costs and the order volume.

In the second stage of the process model, the cost percentages of the individual cost centers in the overall costs of the production department are shown. This data is useful for interpreting the cost structure. The example (see table 2 of Figure 2) shows that the percentage of direct personnel costs varies between 74% (May) and 80.4% (February). This means that direct personnel costs comprise by far the largest portion of the total personnel costs of the production department in all accounting months.

Table 1: Changes in order volume and personnel costs					
CC		A	B	Σ (A-B)	
Months	Order volume [in thousands]	Direct personnel costs [K €]	Indirect personnel costs [K €]	Total personnel costs [K €]	Total personnel costs per unit [€ / unit]
Jan	200	400	100	500	2,50
Feb	220	430	105	535	2,43
Mar	180	360	100	460	2,56
Apr	140	300	95	395	2,82
May	120	270	95	365	3,04
Jun	120	270	90	360	3,00
Jul	110	260	85	345	3,14

Table 3: Relative change in order volume and personnel costs compared to reference month			
	A	B	A B
Relative change in order volume [%]	Relative change in direct personnel costs [%]	Relative change in indirect personnel costs [%]	Relative change in total personnel costs [%]
-9,1%	-7,0%	-4,8%	-6,5%
-18,2%	-16,3%	-4,8%	-14,0%
-36,4%	-30,2%	-9,5%	-26,2%
-45,5%	-37,2%	-9,5%	-31,8%
-45,5%	-37,2%	-14,3%	-32,7%
-50,0%	-39,5%	-19,0%	-35,5%

Table 2: Percentage of monthly costs in total costs of month				
CC		A	B	Σ (A-B)
Months	Relative change in order volume	Percentage of direct personnel costs	Percentage of indirect personnel costs	Percentage of total personnel costs
Jan	91%	80,0%	20,0%	100%
Feb	100%	80,4%	19,6%	100%
Mar	82%	78,3%	21,7%	100%
Apr	64%	75,9%	24,1%	100%
May	55%	74,0%	26,0%	100%
Jun	55%	75,0%	25,0%	100%
Jul	50%	75,4%	24,6%	100%

Table 4: Elasticity of personnel costs in relation to order volume			
CC	A	B	A B
Months	Elasticity of direct personnel costs	Elasticity of indirect personnel costs	Elasticity of sum of total personnel costs
Jan	0,77	0,52	0,72
Feb			
Mar	0,90	0,26	0,77
Apr	0,83	0,26	0,72
May	0,82	0,21	0,70
Jun	0,82	0,31	0,72
Jul	0,79	0,38	0,71

Figure 2: Example of method in use.

The third stage of the process model involves defining the reference period and calculating the percentage changes in the order volume (q) (independent variable) and personnel costs (k) (dependent variable) of individual accounting months compared to the corresponding values of the reference period. The period with the largest order volume is usually selected as the reference period. February is selected as the reference period in this example. With 220 thousand units, this month has the largest order volume. At the same time, this month had the lowest personnel costs, which where €2.43 per unit. Based on the data shown in table 1 (see Figure 2), the next step involves calculating the changes in the order volume (q) (independent variable) and personnel costs (k) (dependent variable) of

individual accounting months compared to the corresponding values of the reference period of February. Table 3 in Figure 2 shows the calculation results for the percentage changes in order volume (q) (independent variable) and the personnel costs (k) (dependent variable) in comparison with the corresponding values of the reference period. For example, order volume decreased by 36.4% in April compared to February. At the same time, total personnel costs during this period decreased by only 26.2%.
In the fourth stage, personnel cost elasticities (ε) are calculated based on the results in table 3. These are obtained by dividing the relative change in personnel costs (k) by the relative change in order volume (q) in an accounting month. For example, in April, the elasticity of personnel costs for the entire manufacturing department (Figure 2, table 4) has the value 0.72, obtained by dividing -26.2% by -36.4% (see table 3). Since the value for personnel cost elasticity, which is 0.72, is less than 1, this parameter indicates that order volume has decreased somewhat more significantly than personnel costs during the same period.
In stage 5 of the process model, the data is interpreted and actions are developed based on it. Target values and specification limits for the personnel cost elasticity of individual accounting months can be defined by planning the sales volume and therefore the order volume on a monthly basis. Past values for the personnel cost elasticity of individual cost centers can be used as a basis for defining target values and specification limits. Additionally, individual cost centers can be compared so that identical conditions in individual cost centers will lead to the same requirements with regard to cost elasticity. Furthermore, the potential elasticity of personnel costs can be estimated using work and time studies in order to obtain challenging but realistic target values and specification limits for the personnel cost elasticity of individual cost centers.
The results of the case example show that managers of this manufacturing department are not sufficiently able to adjust the personnel costs recorded by cost center A to the volatile order situation. In addition, the elasticity of the costs of indirect personnel can be classified as minimal.

6 CRITICAL EVALUATION OF THE METHOD AND CONCLUSIONS

The method of managing personnel costs using elasticity indicators aims to make managers and employees aware that a model that strictly separates direct and overhead (personnel) costs as well as variable and fixed costs does not nearly reflect reality in a variety of ways. A much more useful cost management practice is to differentiate costs by their level of elasticity with respect to order volume and leverage the potential flexibility of costs [9].
The method presented here should be viewed as a supplementary method of cost management. It can be useful for the overall budgeting process as well as for target costs management because knowledge about the elasticity of individual costs is important, especially for planning purposes. During the

budgeting process, the method can help to objectify this process because comparable conditions in individual cost centers lead to identical requirements with respect to cost elasticity [9].

The goal of the method is to make overhead or fixed costs more flexible, but it can also be applied to costs that are typically defined as direct costs. In this case, it necessary to determine the extent to which costs that are classified as direct costs actually develop proportionally and elastically over time.

The method presented here is similar to activity-based costing because the indicator for order volume is also used to identify cost drivers. Unlike activity-based costing, the method presented here requires less work because it is based on existing cost center structures. Similar to activity-based costing, identifying the correct cost drivers is not always easy. Ideally, drivers should correlate strongly to revenue as well as costs. In summary, the proposed method can be a good compromise between the expensive activity-based costing method and existing methods with their assumptions of fixed overheads.

Another challenge of cost management with elasticity indicators is choosing the correct reference period or the correct reference values because these values have a crucial effect on the overall calculation of elasticities.

Similarly, elasticity indicators should not be considered in isolation because an isolated view of the values of these indicators can result in incorrect interpretations for three reasons: First, small changes in the two initial values (e.g., a 1% decrease in order volume, a 2% decrease in personnel costs) can have a significant effect on the value of the indicator. Second, an elasticity value of 0.5 can mean that personnel costs have decreased by 20% and order volume by 40%, resulting in two negative initial values. Another reason for an elasticity value of 0.5 is that personnel costs increased by only 20% while work volume increased by 40%. Third, it is always necessary to consider the percentage of the personnel costs of a cost center in the total costs. Therefore, when this method is used, the elasticities as well as the initial values and the weights of individual cost centers must be analyzed (see Figure 2) [9].

In the future, information about the elasticity of costs in relationship to cost drivers could also be helpful in developing better dynamic cost models for pricing, since cost-plus pricing rarely allows for a balanced allocation of costs to cost objects because of frequently high overhead rates.

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APPLICATION OF SWARM INTELLIGENCE FOR AUTOMATED GUIDED VEHICLE SYSTEMS

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Abstract
Due to the increased individualization of customer demands in the last 20 years, the production systems are required to be more flexible and scalable. It is the same for the material flow system with automated guided vehicles (AGVs). To realize the flexibility and scalability, it is recommended to decentralized control the vehicles. As an attempt, a concept of swarm intelligence with Radio Frequency Identification (RFID) is proposed and introduced in this article. The concept is supposed to be used for automated guided vehicle systems in which objects have to be transported from place to place. Therefore the object has to be self-organized and has to manage its own transport. In this context the vehicles have to choose the most optimal transportation. Swarm intelligence is a topic which deserves a high level of attention as a method to realize high flexibility and scalability.

Keywords
Swarm intelligence, Automated guided vehicle system, RFID, Internet of things, Multi-agent system

1 INTRODUCTION

Growing and changing performance requirements imply decentral and flexible routing systems [1]. In this regard the communication and controlling of objects, vehicles and persons has to be autonomous. Decentral, flexible and self-organized systems are implemented in the context of Industry 4.0 as a part of Internet of things [2] [3]. The importance of this topic was made clear when the Federal Ministry of Education and Research of Germany nominated Industry 4.0 as an important object of research [4].
This article aims at showing one possibility of decentral, flexible and scalable application. Swarm intelligence will be used in the context of an implementation with an automated guided vehicle system. The use of RFID is in this context and article a way to implement the idea of swarm intelligence.
The research on swarm intelligence and RFID is presented in section two. Section three defines swarm intelligence and gives an overview about methods of how automated guided vehicles can be controlled by software-agents, which model the entities in the cloud. Section four involves the actual concept. In order to do this, the agents are characterized, the

workflow and the logical and physical challenges for implementation are outlined. In the next section the advances for companies are named. Finally a conclusion in section six and prospects in chapter seven are presented.

2 LITERARY REVIEW

The themes swarm intelligence and RFID have attracted increasing interest in the last 20 years [5]. Research in this context focuses on a theoretical or practical base, as it becomes visible by looking at the promotion of research in countries like Korea, USA and Germany.

Swarm intelligence in nature is a very important starting point for many researchers. Bonabeau, Dorigo and Theraulaz point out how perfectly ants or bees solve problems concerning the search of food where swarm members give each other information about food places. Furthermore the swarm uses a kind of collaboration for example for crossing a ravine [6].

Application Research mostly deals with logistical themes like production or transportation, which show examples of implementation of swarm intelligence and automation [7]. Michael ten Hompel, the head of the Fraunhofer-Institut für Materialfluss und Logistik (IML), where important research about swarm intelligence and RFID takes place plays a predominant role in this field [7] [8]. The benefits of swarm intelligence can also be seen among other things in life science or commercial contexts as researchers point out [8].

Finally it has to be pointed out that there are theoretical reflections in the field of informatics, in which the question is elucidated about what artificial intelligence is. Based upon this, the basic architecture of multi-agent systems is discussed. Fundamental research in this field is collected in the „Handbuch der Künstlichen Intelligenz“ [9].

There is a large quantity of different informatics applications that can be abstracted in books or online on websites like JADEX [10]. Articles which present programs, for example the methodology Tropos implemented on the platform JACK can be found. It is an agent-oriented software development methodology [11].

3 CONTROLLING OF AUTOMATED GUIDED VEHICLES THROUGH AGENTS

Swarm intelligence means low complex entities work together to solve a complex task [12]. This is the aim of automated guided vehicles in a physical cyber system. The benefits are the flexible reaction to changing external circumstances and the robustness concerning failures of individuals [6]. Communicating vehicles can also be called automated system or smart-object-system [13] [14]. The self-organized communication between the vehicles can work, for example, as distributed automation, service-oriented architecture or multi-agent system [15].
In distributed automation the functional modules work with events [16]. In comparison, the service-oriented architecture can be seen as a loose connection between service provider and service user [17]. The communication works yellow pages online where services are offered [17].
Multi-agent systems model swarm intelligence in form of software-agents [12]. Each agent represents an object or vehicle in the cloud, where they can communicate directly with each other [18]. That is the reason that a multi-agent system is very flexible and scalable [19].This kind of system is used in the following concept.
RFID-Systems are information carriers and can be transported by the object [3]. Therefore RFID provides a possibility to decentralize information and identification which is important for an intelligent logistic system. RFID-Systems are at least one tag as information carrier and one reader to read out the information from the tag and if possible (and necessary) to re-write the tag again [20].

4 DEVELOPMENT OF THE CONCEPT

The aim of this article is to create a theoretical concept of the communication between agents in a multi-agent system in order to simulate swarm intelligence. It is required that an object comes into the transportation area where it organizes its further transportation autonomously. The organization of transportation includes the communication between the object and the vehicles to pick the fastest transportation. The control of the route is not part of this article and concept.

4.1 Characteristics of agents in this concept

The agent traits can be described as targeted, self-organized and rational [21]. There are a few possibilities to solve the problem of figuring agents. The three-tier architecture with working tiers for fast reaction, planning and modeling [22]. An agent with belief-desire-intention (BDI) architecture is segmented in his beliefs, which involve the status of his environment and his own, his desires, which influence the agent manner, and intentions to implement goals [23].

In order to generate decentralization and therefore flexibility, the communication between the agents has to be direct. This form of communication is called message-passing [24]. Another way, but not a highly decentralized one, would be the communication over a blackboard, where agents put information on this board and every other agent can read them [24].
There are different ways to find out the agent with the fastest transportation. Two types should be presented: auction and negotiation. For an auction, agents submit tenders between them and a specific way can be chosen [25]. In negotiations, on the other hand, an agent gives another quotation which he can accept or decline [22].

4.2 Workflow of the concept

The concept is realized with two types of agents: agents who represent vehicles and agents who represent objects. The object agent can just solve the task to get his designated position, if he works together with a vehicle agent.
Figure 1 presents the concept of this application. For a better overview there are just three vehicle agents. It is viewable that the swarm intelligence lies with the vehicle agents. They communicate with each other to transport the object in the best way and solve the tasks together.

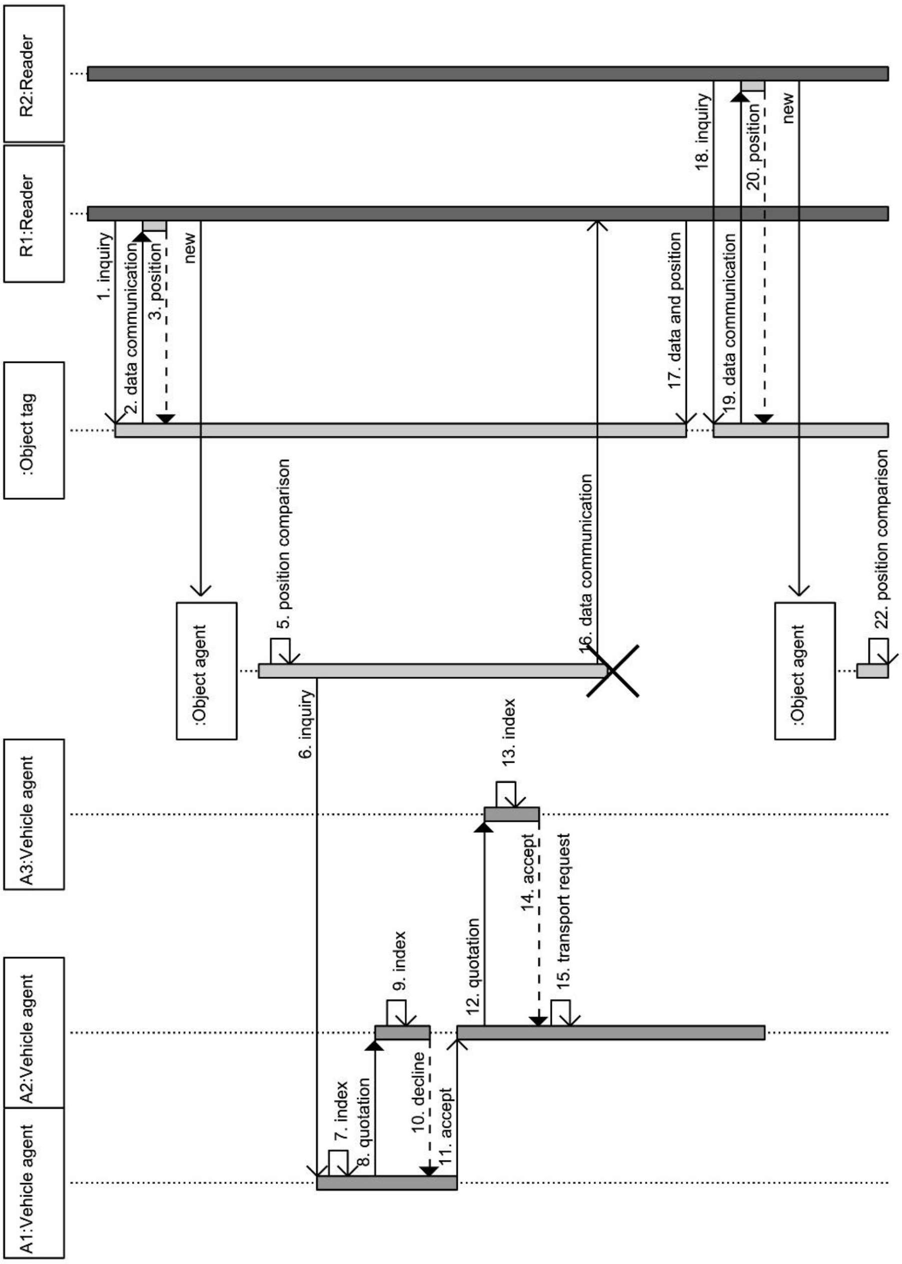

Figure 1: Workflow.

In the following part the sequence diagram is explained with its individual steps:

1. Inquiry: At the beginning the reader sends an inquiry on his frequency field.
2. Data communication: Given that there is an object with a tag in this field, the tag answers and begins with data communication to the reader [26]. Just due to the reader's frequency field, the passive tag is able to send an answer [27].
3. Position: After that, the reader writes the cutrrent position on the tag.
4. New: During the data communication the agent will be transferred from the tag to the reader (agent-on-tag) [28]. The reader sends the agent to the agent-platform where it can run on [29]. The platform is responsible for the management and technical design of the agents [30].
5. Position comparison: The object agent will check if the current position is his designated position.
6. Inquiry: The positions aren't equal. So the object agent has to ask the first vehicle agent A1 for transportation.
7. Index: In order to compare the different transportation times the vehicle agent A1 has to create an index.
8. The task of the index is to confirm the transportation effort for each vehicle. To succeed, the criteria driving time and energy status have to be included in the index.
9. The driving time means, on the one hand, the time the vehicle needs to reach the object. On the other hand, there might be the case that the vehicle is already transporting an object. In this case the driving time includes the time to finish this task and the time to reach the designated position. The energy status is important for the index, if it is so low that transportation is not possible.
10. An important requirement in this setting is that every vehicle can transport every object in the field and every vehicle has the same maximum speed. Otherwise these points have to be calculated in the index.
11. Quotation: The vehicle agent A1 starts a quotation with its calculated index to the agent with the next higher number A2.
12. Index: Agent A2 starts to create its own index and compares it with the index of the quotation.
13. Decline: The index of Agent A2 is better, so it declines the quotation.
14. Accept: Agent A1 accepts and gives the responsibility of the transportation to agent A2.
15. Quotation: Agent A2 starts a quotation with its index to the next higher agent.
16. Index: Agent A3 creates its own index.
17. Accept: Its index isn't better so it accepts the quotation of agent A2.
18. If there were more agents, A2 would have to ask them.
19. Transportation request: The vehicle starts the transportation of the object.

20. Data communication: Before the tag is out of the field of the reader the agent is transferred from the platform to the reader.
21. Data and position: The reader transfers the agent and information back to the tag and changes the current position to a driving position.
22. Inquiry: At the end of the transport the reader at the final destination gathers the tag in its field.
23. Data communication: The tag answers the reader's inquiry of the reader similar to point 2.
24. Position: The reader writes the current position on the tag.
25. New: The reader sends the information and the agent to the platform.
26. Position comparison: The agent compares the current position with its designation position. Because of the equality the object agent will not start an inquiry.

Another method to achieve the best transportation is the auction. In this case there are two possibilities; first a vehicle agent heads the auction and second, a collective agent works as representative of the swarm, while heading the auction.

4.3 Logical and physical challenges for concept implementation

There are different logical and physical challenges for implementation of this concept. The protocols of communication, the ontology and the speech have to fit with the requirements of the software architecture [31].

The software-agent-platform has to manage and control the agent and has to give agents information about other existing agents in the system.

In order to reach a very decentral concept, the automated guided vehicles should be equipped with small computers on which their agent can run. This requires a platform where agents on other hardware can communicate with each other.

The data inside the object tags should give information about the identification number, the loaded items, the agent and his data, the current and the designated position. The benefit of agent-on-tag is de-centrality but the high memory size required, brings the disadvantage that the time needed for reading and writing by the reader gets very large [28]. With a weak migration, where the status of execution isn't transferred, this disadvantage can be diked [32].

Another physical challenge is the linkup between the hardware (reader, vehicles and the computer with software-agent-platform) e.g. this can be implemented with WLAN. The object tags also have some challenges: they have to be passive and they have to have a relatively large memory capacity. Next to this it has to be ensured that the tags have the same frequency as the reader. Subsequently, it is important that the frequency fields of the reader do not overlap.

5 BENEFITS FOR COMPANIES BY USING SWARM INTELLIGENCE

Automation in companies involves the possibility of controlling the complexity of systems. In this context swarm intelligence is implemented as a multi-agent system and enables modular and flexible use of the system [33]. A changing number of agents or a change of the environment doesn't necessarily force a change to the architecture of the system. This is a useful option to reply to the accelerated efforts of adaptation which enterprises face nowadays.

For larger companies another benefit of a multi-agent system is the usage of the same multi-agent and RFID technology along the whole supply chain. Information can't be lost because they are saved directly on the object. Therefore they are transported with the object from enterprise to enterprise.

6 CONCLUSION

In this article, a de-central control of automated guided vehicles by using swarm intelligence for a selection process for transportation was presented. . The capabilities of multi-agent system were also demonstrated.

An object agent can reach out a transport for himself to the vehicle agents in the system. In order to find the best transportation they each generate an index to compare the transportation offers. The benefits of swarm intelligence can be seen by the communication between the agents. An object agent will not succeed if no vehicle can transport the object. It has been shown that the selection process can be managed like an auction or trial. Because of the very de-central communication of the vehicle agents, in this case the negotiation was presented.

Capabilities of this concept are noticeable in the flexibility of the system concerning changes and the possibility of usage throughout the whole supply chain.

7 PROSPECTS

Reconsidering this article it must be admitted that only a small part of swarm intelligence usage was shown. Another interesting part is the transportation process in detail. More research in this field seems to be necessary but it can't be done in this article. Apart from this there are many other application areas, which view is of importance.
The benefit of swarm intelligence for automated guided vehicles is the de-central communication. While transporting an object it is possible for each vehicle to communicate with other vehicles. Information about non passable parts of the route or about the fastest route are parts which are shared.
To conclude, the interest of research is increasing because of the rising challenges in the area of logistics and the requirements due to more flexibility and de-centrality.

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PRODUCTION FLOW MANAGEMENT: MULTI-OBJECTIVE OPTIMIZATION AND SCHEDULING THROUGH THEORY OF CONSTRAINTS

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Abstract
In recent years small medium enterprises (SME) have to manage an increasing number of products, while trying to improve effectiveness of the system to achieve the imposed objectives. The high complexity of the production system and the difficulty to manage the system lead to a low effectiveness regarding the objectives, high inventory and low throughput rate. This paper considers an approach to solve these problems, based on the concept of theory of constraints (*TOC*). Every organization has at least one constraint. A constraint is any cause that limits the organization's goals. When focusing on the constraints, *TOC* gives a substantial improvement without the need for excessive resources. The main goal of this paper is the redesign and control of a production flow that achieves specific performances. This is a typical problem SMEs have. To overcome the constraints, a discrete event simulation (*DES*) software simulates the production and optimises through optimization software. It includes the analysis, simulation and then subsequently the creation of a new production layout and a potential weekly optimization. For maximizing the desiderated performances a rescheduling of the weekly production period is done using the drum-buffer-rope (*DBR*) method.

Keywords: Theory of Constraints, Optimization, Simulation

1 INTRODUCTION

Staying in the market for a company is mandatory. Therefore an effective and an accurate development of the manufacturing system is required. For this reason, several techniques to support the decision making have been developed in the last 20 years in order to evaluate the manufacturing production strategies and the system itself [1].

This case study will follow the logical steps to reach the objectives as shown in Figure 1.

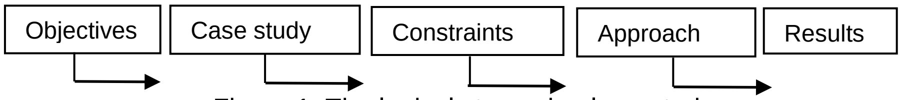

Figure 1: The logical stages implemented.

First of all the definition of the objectives has to be done. Next is the evaluation of the current situation, in order to find the problems that arise while trying to reach the objective. Because the production system is unbalanced and contains bottlenecks, the *Theory of Constraints (TOC)* is considered. The *TOC* is a managerial change method that focuses on profit. Every organization has at least one constraint. A constraint is any cause that limits the organization's goals, which is usually profit, although in this case the goal is the control and management of a production flow. *TOC* focuses on constraints, first on normal bottleneck processes in job-shop manufacturing organizations, but also in non-manufacturing areas such as sales, supply chain, etc. In this case, the constraint is considered only from a manufacturing point of view. A manufacturing plant is a connected set of processes that transform inputs into sellable outputs. *TOC* considers this system as a chain and the strength of the system is as strong as its weakest link. Goldratt [2] defines a five-stage approach that focuses on finding and strengthening the weakest link, so that the whole system improves immediately. As the focus is on constraints, the use of *TOC* can result in a substantial improvement without the need for excessive resources.
The Five Stages of the Theory of Constraints

- *Identify the System Constraint*
- *Decide How to Exploit the Constraint*
- *Subordinate Everything Else*
- *Elevate the Constraint (strengthening the weakest link)*
- *Return to Stage One, but Beware of "Inertia"*

TOC is an on-going process of continuous improvement. If improvement stops, the system is the constraint.
The flow line in question is a *Hybrid Flow Shop (HFS*). There are many definitions of *HFS* [2]. In general, *HFS* is as a set of n jobs to be processed in m stages. In our definition of *HFS*, the following assumptions are made:

- The number of processing stages m is at least 2,
- Each stage has $k \geq 1$ machines in parallel and in at least one is $k>1$,
- All jobs are processed following the same production flow: stage 1, stage 2,. . . , stage m. A job might skip any number of stages, assumed it is processed in at least one of them.

- Some jobs can have loops in the production system.

The *HFS* problem is considerably more complex and intractable than conventional flow shop; it belongs to an N-P hard case. Due to these difficulties a precise method has not been found that solves every case in a reasonable time [3]. Similar cases of *HFS* have been reviewed in the literature. Considering the due date the authors [3] conclude the following as objectives: minimize *Earliness* and maximize *Tardiness*. On the other hand Armbruster and Kempf [4] consider various methods and objectives that are used for *HFS*: not only max Earliness and min Tardiness, but also minimize *makespan*, flow time, inventory cost, etc. Even if 60% of the cases consider minimizing the *makespan*, other objectives may be more important depending on the situation. Production scheduling problems are multi-objective by nature, and in most of the cases, these objectives are in conflict among themselves. The authors [5] solve two *HFS* scheduling problem by minimizing or maximizing the objective functions with constraints, through a multi-objective optimization approach, which combines a simulation model and an optimization software. They declare that the approach gives a solution that is robust, fast and accurate.

A typical approach to define a production system has usually three phases:

- Defining the desired performances of the production system;
- Setting the general features of the production system;
- Verifying the performance level of the production system.

Repeat phase 2 and phase 3 until the production system achieves the established performance avoiding undesired behaviours in the production system such as bottlenecks. The second phase uses Discrete Event Simulation (*DES*) tools to understand the behaviour of the production system. The here discussed method focuses directly on the performances. In this case, the purpose of the optimization is to find out the optimal general features: the right set of input variables so that the output achieves our goals. Thus, implying the idea that the performances are objectives and using optimization as a research tool. The processing production plant *HFS* is described with the objectives, constraints and problems in chapter 2. The approach to achieve its objectives is described in chapter 3 with the Drum-Buffer-Rope (*DBR*) method that reschedules a week time period to maximize the desiderated performances. The results are shown in chapter 4. Finally, a conclusion is made in chapter 5.

2 PROCESS FLOW TEST CASE

The production line can handle the process of twenty different product typologies; the final products differ in size and in customization. Numerous product typologies add complexity to the system and for this reason only the most important flow routes shall be studied. In fact, the most products are grouped into part families that have a standardized process. A brief description of process-flow is shown in Figure 2. The letters A, B, C, D represent each a product family. Letters E, F and H are components and each block in the diagram represents a machine group. The company fails in managing the production system that comes in part from supply chain and from system complexity. It is difficult to have a precise forecast of raw material supply for reasons that will not be discussed here. Due to the fact that the sales differ every year, this work will consider quantity and type of products that are produced in the first four month of 2014. That means 5 days a week for 16 weeks. The production works in batch. There is a buffer between each stage, with the task to regulate the production flow due to different throughput between machine-groups.

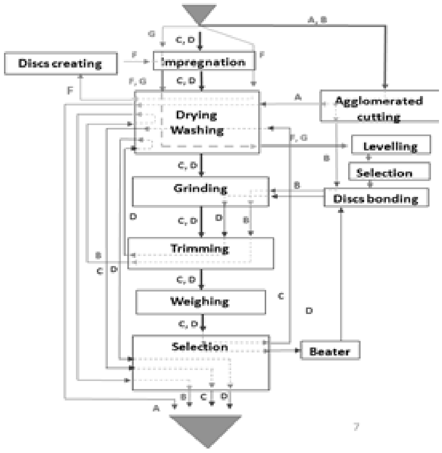

Figure 2: Processing line flow diagram.

The most critical machine groups are Selection and Drying/Washing. They are considered the bottlenecks of the system. Due to the great sales variation, the company does a weekly production launch. Referring to *TOC* [2], if the number of machines, shifts and operators increases at the bottleneck and the production line is kept balanced, the throughput increases and the time to market decreases. In present case the company doesn't have problems of *due date* or *deadline*, so it doesn't make sense to consider them as objectives. So, what is the main problem of the company? The main difficulty is to control the complexity of the products and their process flow. The best objective is to minimize the *makespan* (dominant objective), because it reduces the products' process flow time. Instead of *makespan*, the *Index Flow* (*IF*) is introduced: *IF=Process Time / Lead Time*. Since the goal is to minimize the *makespan*, *IF* should tend to 1 as much as possible. The number of products in each buffer must not exceed a limit, due to insufficient space. The Saturation index for a machine group is the ratio of idle time and on-shift time. It measures the occupation of the machines. To control the balance or imbalance of the workload in the various machine-groups and its economic value, the minimum percentage of the machine groups, Saturation is introduced as a constraint. For this case the number of products in each buffer must not exceed a limit, due to insufficient space. Summarising, the constraints are:

- Limiting the capacity of each buffer.
- Limiting percentage of minimum Saturation, of each machine group.

The objective functions are:

- Maximizing the total Throughput rate of the system.
- Maximizing IF of the products.

The number of machines and operators per machine group are considered. The model has the ability to vary this number between a minimum value and a maximum value. The same principle also applies to the number of shifts per day for each group-machine.

The priority is the variable that dictates the precedence of one product in respect to another in the production system (1= lowest priority; 4=highest priority), giving more control on flow and scheduling. Managing the number of shifts, machines and operators, it allows the user to control unwanted behaviours of the production line, like bottlenecks and working load unbalances among the different machine groups.

Summarising, the variable are:

- Number of machines and operators for each machine group.
- Number of shifts for each machine group.
- Priority of each part family.

3 APPROACH

The approach is to connect an optimization cycle to a model that simulates the production using a discrete event simulation (*DES*) of WITNESS 14. The concept of the approach used to solve the problem is inserting variable inputs into a *DES* model that simulates the process flow. The *DES* model produces an output, which is compared to the main objective. This information is sent to the Genetic Algorithm (Esteco MODE-FRONTIER). Then, through the genetic algorithm, the inputs are changed accordingly (trying to improve the output) and inserted back into the model. The model will give another output and the loop is repeated. The number of iterations (loops) is defined at the beginning by the user. It is important to define the right number of iterations having a sufficient number (although not too many) of optimal solution sets (Fig. 3). The task of GA is changing inputs producing an output from *DES* that will converge to the objectives by a set of optimal solutions [6].

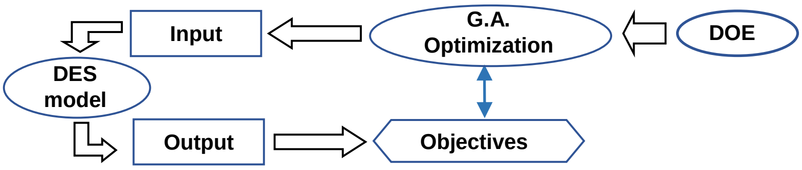

Figure 3: Optimization cycle.

To increase the robustness of the GA, it needs information on how the system works, for example, most critical variables and regions of optimal solution. To overcome this, the first cycles are lunched with the variables given by Design of Experiment (*DOE*). The number and feature of variables determines the method used to create the *DOE*. After the loops are finished, with the help of the Pareto Front a set of optimal solutions are given.
Each of these solutions are characterized by the fact that one objective cannot improve without worsening other objectives [7]. Pareto Front is rearranged in clusters through a clustering method. For each cluster a second round of optimization by a mono-objective Simplex algorithm (greater accuracy) maximizes the main objective (Fig. 4) [8].
Hence, the clusters' target is to get greater precision from a non-robust algorithm. In addition, the results from the second cycle are compared with the results from other two methods: Self-Organizing Map (*SOM*) and *MCDM* (Multi Criteria Decision Making). *MCDM* is a tool that is part of a family of decision making methods. The family of *MCDM* algorithms chooses the best solution considering the attributes and their preferences [9]. The Self-Organizing Map (*SOM*) is an unsupervised neural network algorithm that projects high-dimensional data onto a two-dimensional map [10]. In our

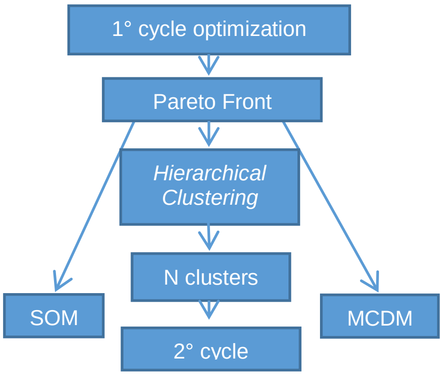

Figure 4: Optimization steps.

particular case Johnson's rule cannot apply for scheduling, because the assumptions are broken due to loops in the process [11]. So a method from *TOC* is considered. One of the basic rules of *TOC* is to make sure that the bottleneck is working at 100% capacity, all the time. Protect the bottleneck in the system (that means the whole system) against the variations within the processes by eliminating the inefficiencies and letting only well-trained operators to work on the bottleneck. To guarantee that the bottleneck is not starved or choked, parts must be available when needed and moved out when processing is completed. This may mean altering scheduling at other work stations so that parts are available at the bottleneck when needed. This is the basic idea of the *Drum Buffer Rope* (*DBR*) system [12]. *TOC* considers Work in Progress (*WIP)* every part that is in the system before being picked by the bottleneck (Fig. 5). The drum (bottleneck) is the weakest link in the system. The buffer defines when to launch a product into the system (avoiding excess *WIP*); rope defines when to release work into the system (avoids excess *WIP* and its associated costs). When the production is launched in the simulator, the *DES* model gives the absolute time of parts and its attributes (name, process time, transportation time, etc) that were taken by the bottleneck.

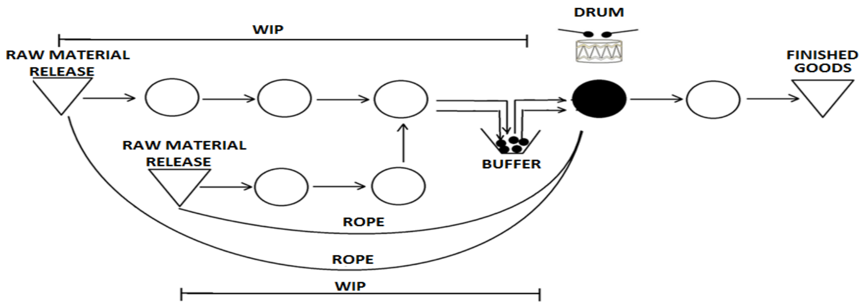

Figure 5: Drum-Buffer-Rope.

With this information a rescheduling of the arrival time (released into the system) of each part is done using the formula:

$$T_{arrival} = T_{absolute} - T_{process} - T_{tranport} - \Delta C \qquad (1)$$

$T_{absolute}$: the absolute time (the moment when the part is picked for processing by the bottleneck).
$T_{process}$: *the* process time of the part until it is picked by the bottleneck.
$T_{transport}$: the transportation time until it is picked by the bottleneck.
ΔC : a constant (4 hours), so part arrives at the bottleneck with some margin. This improves and makes the system more reliable by creating less *WIP* and minimizing the *Makespan* [13]. The optimization of a simulated 4 month forecast is done using the same approach as shown in Fig. 4. In the second cycle of optimization the only objective function is *IF*. The same objectives are taken when using the *MCDM* and *SOM* post-processing tools. The results are compared amongst these methods and the preferred solution is chosen. With the number of machines, priority of the products and the process flows stated, the new layout can be created. To demonstrate the complete control of the process flow (the main problem of case study), the optimal number of shifts and product priority for each weekly production launch is found, thus showing the potential of becoming able to solve dynamic scheduling problems. The most critical week of the 4 months period (macro cycle) is considered for the weekly launch. The objectives function, GA and constraints are the same for the first cycle of optimization in the macro cycle. To save time the number of machines, operators and priority of products are constant. The only variables are the daily shift for each machine group and product priority. The number of available machines and operators are given by the optimization solution of the 4 months period. The objectives are identical to previous launch. To find the optimal weekly scheduling (shifts, number of available machines and operators and priority) the *MCDM* is used because it is the fastest tool. Finally to maximize the *IF* and lower the inventory, the rescheduling of the part launch is done using the *DBR* method.

4 RESULTS

GA uses input variables: priority, number of active machines, operators and shifts for each machine group. The run stopped with the 12507th design; GA gives 68% feasible designs and 32% unfeasible designs. Fig. 5 shows the total mean saturation and *IF* Saturation levels of the sub-clusters with confidence ellipse. One can notice that the clusters are very close, implying that each cluster with the mono-objective optimization will give similar results. Figure 6 (a) shows distribution of different components on *SOM* hexagonal grid. Similar component maps are placed in adjacent positions in order to spot correlations. Figure 6 (b) shows a *SOM* of *IF* component. The variation between maximum and minimum of each component value is shown by colour variation. The highest values are in red (upper left corner) and the lowest in blue (the darkest spots). The results from the second optimization cycle of the clusters and from the methods *SOM* and *MCDM* are shown in table 1. The preferred solution is from cluster 0 since it has the highest *IF* and throughput rate.

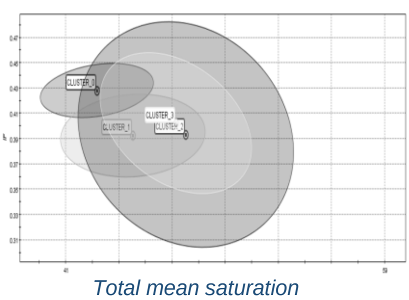

Figure 5: Clusters groups.

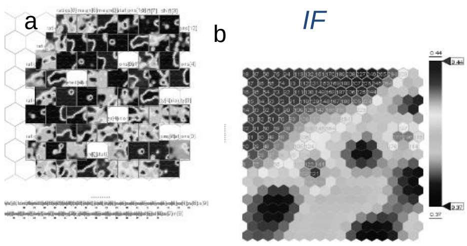

Figure 6: (a) *SOM* components (b) *SOM* of *IF* component.

The results from the weekly scheduling (the daily shift of trimming machine group is taken as an example) are shown in table 2. Even if the Selection machine group has the highest saturation level and *WIP*, the Washing machine group is the bottleneck of the entire system because it also has a high Saturation and because all the products are processed there, differently from the Selection machine group. The results from the simulator are compared to the actual times of the company. Tab. 3 shows the results, with T1 as the product lead time in the production system. The huge difference in time is because the product flows are not controlled by the company. Since the product flows are not controlled it is expected that the production system has a high *WIP*.

Table 1: Production flow test case results.

	Simplex algorithm						
	Unit	**Clu_0**	**Clu_1**	**Clu_2**	**Clu_3**	**MCDM**	**SOM**
Completed A	pieces	1755	1755	1755	1755	1749	1719
Completed B	pieces	184	184	182	182	182	198
Completed C	pieces	558	558	558	558	558	558
Completed D	pieces	537	537	537	537	537	537
Saturation Select	%	53	53	53	53	53	53,02
Saturation Wash	%	66	66	66	66	66	65,86
Total IF	/	0.513	0.513	0.509	0.505	0,44	0,42
IF Standard dev.	/	0.25	0.25	0.25	0.25	0,22	0,21

Table 2: Trimming machine weekly scheduling results.

	Unit	**MCDM**
Trimming Monday-Shift	n° shifts/day	1
Trimming Tuesday-Shift	n° shifts/day	1
Trimming Wednesday-Shift	n° shifts/day	1
Trimming Thursday-Shift	n° shifts/day	2
Trimming Friday-Shift	n° shifts/day	1
Completed product A	pieces	131
Completed product B	pieces	10
Completed product C	pieces	22
Completed product D	pieces	68
Saturation Selection	%	68
Saturation Washing	%	56
Total IF	/	0.52
Total stand. Dev. IF	/	0.22

Table 3: Lead time comparison between *DES* model and actual situation.

	Unit	**Standard process**	**Actual process**
T1 Product A	days	2.54	36
T1 Product B	days	0.63	16
T1 Product C	days	7.30	59
T1 Product D	days	2.82	24

In fact, in the last week of June, when the production is low, the *WIP* in each actual machine group was checked. The results are shown in table 4.
From table 4 one can notice that out of the total 253 batches, 180 are in the selection machine group (71%). This demonstrates that the product flows are not controlled and the actual production system is very unbalanced with the Selection machine-groups the main bottleneck. The new layout cannot manage this quantity of *WIP* due to insufficient space.

Table 4: WIP in actual machine groups.

Machine group	**Batches**
Selection	180
Grinding and Trimming	19
Washing	54
Total	**253**

Table 5 shows the results of implementing the *DBR* in the weekly scheduling with the Washing machine group as the Drum (bottleneck). The saturation level with *DBR* of the machine groups are the same as before. This is due to the fact that production system processes always have the same quantity, only the part arrival is changed with the *DBR* method, decreasing the *WIP*. By decreasing the *WIP* the *IF* obviously increases, because the time that the products spend in the buffers is decreased. Theoretically, managing the flow is also simplified by decreasing the *WIP*. That means the transportation time is also simplified and decreased (this was not simulated in the *DES* model), that includes: searching the batch, extracting the batch, transporting, stocking.

Table 5: Comparison actual weekly scheduling and *DBR* weekly scheduling.

	One week forecast				
		Unit	Old scheduling	*DBR* scheduling	Diff.
	IF[0] (Total)	/	0.5	0.66	0.16
	IF[1] (Tot. S.D.)		0.22	0.22	0
	IF[2] (Product A)	/	0.54	0.69	0.15
	IF[3] (Product B)	/	0.31	0.64	0.33
	IF[4] (Product C)	/	0.71	0.74	0.03
	IF[5] (Product D)	/	0.56	0.56	0
	T1 Product A	hours	69.7	55.52	-
	T1 Product B	hours	41.5	39.43	-2.07
	T1 Product C	hours	71.63	64.76	-6.87
	T1 Product D	hours	87.26	82.26	-5
BUFFER AVERAGE	….	….	….	….	….
	Buffer - Selection	hours	1.8	0.6	-1.2
	Buffer - Selection	hours	6.9	5.3	-1.6
	Buffer - Selection	hours	4	5.7	1.7
	Buffer – Washing	hours	0.7	0.5	-0.2
	….	….	….	….	….
	Buffer - Selection	batches	0.3	0.1	-0.2
	Buffer - Selection	batches	3.8	1.7	-2.1
	Buffer - Selection	batches	1.8	1.5	-0.3
	Buffer - Washing	batches	0.5	0.3	-0.2

Because the weekly scheduling is done considering the new layout, the selection machine group is divided into 3 parts in the new layout. This is done to balance the flow and minimize the transportation time with the standardized process. Even if the selection machine group still have the highest *WIP*, the bottleneck is always the washing machine group because of its high saturation level and all products are processed there. The total *IF* increased by 24%, underlining that the *DBR* method decreases lead time.

The total average time in the buffers decreased by 14% and the average number of batches by 42%, a significant amount.

The buffers don't go to zero with the *DBR* method because the production system isn't linear; there are many intersections in the process flow (Fig. 6) and the system is still unbalanced. It would be interesting to introduce new selection machines as the whole system will benefit by increasing the throughput rate and decreasing the *WIP*. But, unfortunately the company is in dire state. In any case the average number of batches in the buffers is much more balanced with the DRB method. The average time of the *WIP* in the buffers is still unbalanced but it has improved with the *DBR* method. The drum (Washing) decreases the average number in the buffer by 40% and average time by 30% with the *DBR*.

5 CONCLUSION

The results of the system are substantially better than before. With the help of *TOC* the bottleneck of the system is underlined. At the same time it shows where to tackle the issues so that the whole system improves dramatically. It strengthens the idea that the method with *TOC* has great potential in enhancing a production system, decision making by using “what if” situations and solving the main problem that is managing the production system. The cycle time for each optimization launch varies. The first cycle of optimization including the post-processing time lasted 3-5 days depending on the case study. The second cycle of optimization lasted only 2-3 hours. This underlines the fast speed of convergence of the simplex algorithm. Instead, for the production case study, the weekly scheduling optimization and *MCDM* lasted, together, less than 24 hours. With such a short time, this method can be used not only as decision making but also for managing a manufacturing flow. It would simplify and make production launch dynamic scheduling, created in a short time, possible. The applied methods reached the goal of the article. With *DBR* method the objectives are improved even more. Lowering and balancing the *WIP*; increasing the total *IF* by 24%.
The approach has the following advantages:

- Accurate: the model can give very precise results if the model is done properly. The accuracy of the system is given by how detailed the DES model is made with respect to reality.
- Robust: The input commands the simulation model and the objectives are strictly correlated to the output of the DES model so, to have a robust system, the input and output must be correct. The model gives the user complete control over the system, solving the main problems and reaching the objectives and, thus, making the system effective.
- Speed of convergence: the genetic algorithm will converge quickly to an optimal solution.
- Flexible: once the model is well defined, making variations is easy.

And the following disadvantages:

- Time consuming: The critical part of the work is preparing the Witness model: it takes from three to four days.
- Deep knowledge: the model creation and use of the approach requires profound knowledge of both the software and the factory production flow.

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SESSION D

Wood Processing Technologies and Furniture Production 1

MACHINE ACCEPTANCE PROCEDURES IN THE WOOD AND FURNITURE INDUSTRY

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Abstract
The traditional way to test woodworking machinery before acceptance is nowadays not appropriate to the statistical needs of modern quality assurance methods like statistical process control (SPC) [1]. A working group of the German Association of Engineers (VDI) is working on that topic and editing a guideline VDI 3415-1 and VDI 3415-2. An introducing paper was given on the last conference.
Scientifically accompanied machine run off procedures show that beside statistical problems also the measurement capability plays a great role in this context. As own experiments show the reworked DIN ISO 22514 [2] has a certain potential to be applied but there is also a need for an adapted procedure. The guideline VDMA 8669 [3] can help. The contexts and constraints will be shown.
A run off procedure for a workcell center was made in accordance with DIN ISO 22514-2 [2]. As a tolerance level DIN 68100 HT 15 was taken for the whole workpiece. The datasets consist out of measurements of 44 characteristics of one workpiece. In total 200 workpieces were used to determine on different ways the machine and process capability indexes. The measurements were taken on an automatic noncontact measuring table. A similar test was made for a molder, also with 200 parts with a custom made measurement device. In both cases the measurement capability was determined in accordance with used automotive and other standards.
The given standards can be applied but need to be adapted to the special needs for workpieces made out of wood and wood based materials. In the last conference in the context of methodological sensoric testing, the RV-factor was introduced. The RV-factor – the relation between the range of the characteristic values and the width of tolerance - has, beside mathematical weaknesses, also a potential for variable characteristics like length measurements.

Keywords:
Machine acceptance procedures, Machine capability, Measurement capability

1 INTRODUCTION

Process qualifications are used in large-scale production in order to demonstrate the capability of machines and processes for statistical process control (SPC). When building new production lines, they are therefore used especially in the automotive industry for machine run off tests. For this purpose, different evaluation methods have been developed that are based on values of quality characteristics which are produced under production conditions (50 or 200 parts) (see also ISO 22514 [2]). To perform the analysis with the necessary statistical confirmation, the used measuring methods must be specified in its accuracy and in relation to the required tolerances (see also VDA 5 [4]). If the focus of the investigation is only on the machine acceptance and not on the preparation for an SPC, the requirements set in the standards and working standards of the automotive industry are often too high (Hanrath 1997 [5]). The VDMA 8669 [3] therefore gives since 1999 a different, simplified procedure for machine acceptance.
But often a SPC has to be introduced after the machine acceptance not only in the automotive industry, the standard, which mainly hosted on machine acceptance, is rather less used.
At the last, 5th International Conference Production Engineering and Management in Trieste a development of a method based on VDMA 8669 was presented [6]. The focus of the method is on machine acceptance and run off tests in the wood and furniture industry and is therefore in accordance with Technical Committee FA 102 of the Association of German Engineers VDI, to establish a useful standard with guideline 3415. Because of the variety of attributive quality characteristics for typical workpieces of the mentioned branches and industries, the method must also be suitable for sensory analysis (see also [7]). The evaluation according to the range factor was therefore identified as useful.

2 CAPABILITY STUDIES

2.1 Process capability

Capability studies, such as those used in the context of process qualifications, set the tolerance (upper specification limit (USL) – lower specification limit (LSL)) of one or more quality characteristics of a workpiece in relation to the moments of the respective frequency distribution of the values of quality characteristics of a small series. Under the assumption of a normal distribution, the standard deviation σ and the arithmetic average μ of the frequency distribution of values of a quality feature of 50 (for C_m and C_{mk} as shown below) or 200 (for C_p and C_{pk}) workpieces are used.

$$C_m(6\sigma) = \frac{Tolerance}{6 \cdot \sigma} = \frac{USL - LSL}{6 \cdot \sigma} \qquad C_{mk}(6\sigma) = \min\left[\frac{USL - \mu}{3 \cdot \sigma}, \frac{\mu - LSL}{3 \cdot \sigma}\right]$$

C_p and C_{pk} is defined the same but only for a sample of 200 parts. Thus C_m and C_{mk} equals 1, if 99.73% of occurrences in the sample are situated centered within the defined tolerance. If a normal distribution cannot be assumed or been proved, more or less large deviations and inaccuracies will arise. The ISO 22514- [2] therefore defines time-dependent process models (A1, A2, B, C1-C4, D), which frequency distributions differ from the normal distribution and / or where time is a subject to variations. Thus, tool wear, as a trend, transfers a normal distribution under short-term conditions in an approximate trapezoidal distribution. Here, the calculation formulas using the variance and standard deviation in the relation of tolerance and 6σ, lead to different quantiles. ISO 22514-3 [2] therefore suggests following assessment:

$$C_m(quantile) = \frac{USL - LSL}{\hat{X}_{99,865\%} - \hat{X}_{0,135\%}}$$

$$C_{mk}(quantile) = \min\left[\frac{USL - \hat{X}_{50\%}}{\hat{X}_{99,865\%} - \hat{X}_{50\%}}, \frac{\hat{X}_{50\%} - LSL}{\hat{X}_{50\%} - \hat{X}_{0,135\%}}\right]$$

The VDMA 8669 [3] defines the RV-factor in the reverse direction and uses the range instead of the quantiles.

$$RV = \frac{x_{\max} - x_{\min}}{USL - LSL} \qquad RV_k = \min\left[\frac{x_{\max} - \bar{x}}{USL - \bar{x}}, \frac{\bar{x} - x_{\min}}{\bar{x} - LSL}\right]$$

RV, thus, indicates the percentage to which the tolerance range is exploited by the values of the quality characteristics. That seems plausible and easy to understand, but cannot be compared with the other capability indices. For a better understanding in the following tests, the reciprocal value of *RV* and RV_k is used. This is defined analogous to ISO 22514 [2].

$$C_m(range) = \frac{USL - LSL}{x_{\max} - x_{\min}} \qquad C_{mk}(range) = \min\left[\frac{USL - \bar{x}}{x_{\max} - \bar{x}}, \frac{\bar{x} - LSL}{\bar{x} - x_{\min}}\right]$$

From the original list of the characteristic values, the median, the range, the quantiles and the quantiles distance can be seen and the standard deviation can be estimated. To select the distribution form, and thus, reliably to select the method of calculating capability indices tests on distribution forms or classifications and further evaluations must be made.

2.2 Measurement capability

Not only here the repeatability of used testing devices generating the values plays a role. The standards ISO 22514-7 [2], VDA 5 [4] as well as VDMA 8669 take as an estimate for this purpose, the standard deviation of

measured values generated by the multiple measurements (VDA 5 and ISO 22514-7 ≥ 25; VDMA 8669 = 50) of a quality characteristic of the same master workpiece. These are then often put in relation to the tolerance or to the process variation of the characteristic and are called measurement capability indices. The procedure for analyzing the measured values is determined by the standards, this results to different calculation formulas for the measurement capability indices.
In relation to the process standard deviation $\sigma_{process}$ formulas for measurement capability indices C_g and C_{gk} are defined as following:

$$C_g = \frac{n\% \cdot \sigma_{process}}{\sigma_m} \qquad C_{gk} = \frac{0{,}5 \cdot n\% \cdot 6 \cdot \sigma_{process} - \left|\bar{x}_m - x_r\right|}{3 \cdot \sigma_m}$$

In relation to the process tolerance of the characteristic T_c the formulas are defined as:

$$C_g = \frac{n\% \cdot T_c}{6 \cdot \sigma_m} \qquad C_{gk} = \frac{0{,}5 \cdot n\% \cdot T_c - \left|\bar{x}_m - x_r\right|}{3 \cdot \sigma_m}$$

σ_m = measurement standard deviation
x_r = correct value of the characteristic
$\bar{x}_m$ = arithmetic average of the measurements

The percentage of tolerance *n%* depends on the use of the evaluation method. In the metalworking industry, the methods according to working standards of Bosch (n% = 20%) or Ford (n% = 15%) [8] are often used. Thus, different acceptance limits results for C_g and C_{gk}.
The proof of the capability of the measurement or testing systems must be carried out by means of a measurement capability analysis. This must also analyze the process in terms of stability, outliers, trends and special process situations, in addition to the statistical analysis and calculation of measurement capability indices.
The guideline VDA 5 in the second edition from 2010 is identical in content to the ISO 22514-7 "Capability of measurement processes" of 2014 [2]. For the capability study in VDA 5, typical influencing factors that can affect the measurement process are listed, and the user is obliged to take into account situational factors additionally. With the capability analysis first flow combined standard uncertainties u_{MS} (MS = measurement device) into the expanded uncertainty U_{MS}. It is a measurement series of 25 or more repeated measurements. The subsequent comparison of the expanded uncertainty with the tolerances of the characteristic leads to the suitability or fitness quotient characteristic Q_{MS} to review the suitability and capability of the measuring system for the specific application. The calculation formulas are defined as following:

$$U_{MS} = k \cdot u_{MS} \quad ; \quad Q_{MS} = \frac{2 \cdot U_{MS}}{TOL} \cdot 100\%$$

$$k - factor \ (level \ of \ confidence) : 1 = 68{,}27\% \ ; \ 2 = 95{,}45\% \ ; \ 3 = 99{,}73\%$$

According to VDA 5 is Q_{MS} ≤ 15% recommended. Neglecting the systematic failure Q_{MS} is similar to the capability indices C_g and C_{gk} and can be calculated as following:

$$C_g = \frac{0{,}2 \cdot TOL}{4 \cdot s_g}$$

A C_g-value of 1.33 is then comparable to a Q_{MS_max} value of 15%.

3 EXEMPLARY CAPABILITY TESTS

3.1 Experimental design

To estimate whether capability analysis can be used and how they behave on the different ways calculated capability indices, investigations were carried out on a machining center (Fig. 1 [10]) and a moulding machine (Fig. 2 [11]). The applied methods were similar according to ISO 22514 [2]. 200 parts made out of MDF with different quality characteristics were produced and measured.

Figure 1: Machining center.

Figure 2: Molder.

As tolerance class DIN 68100 HT 15 was chosen in both cases. DIN 68100: 2010-07 can now be applied as a suitable definition for capability studies. HT 15 provides as an average accuracy demand / process difficulty for both woodworking machinery.

Accompanying the capability tests in both cases the temperature profile were measured at selected locations to assess the heat transfer. The cutting knife conditions were taken before and after the whole tests as a digital image by the machining center also in spaces there between.
For the parts produced on the moulding machine a special measuring device was designed and built, which allows a fast measurement of many measuring points semi-automatically and immediately after the production (Fig. 3). The parts produced on the machining center were measured on a fully automatic measurement table (Fig. 4) at the facility of the manufacturer of the measuring table. However, this measuring table scans most geometrical quality characteristics by camera without direct contact, depth measurements with a probe.

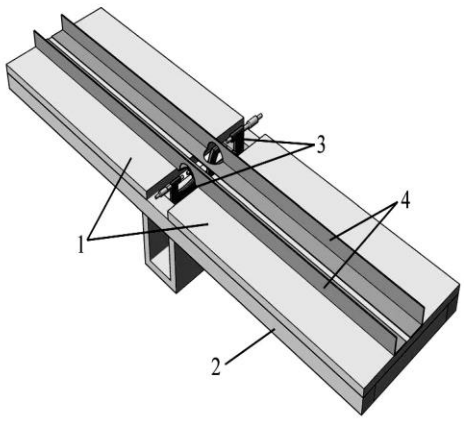

Figure 3: Measuring device molder.

Figure 4: Measurement table.

3.2 Measurement capability tests

In both cases measurement capability tests were carried out. The specific problem was the wooden workpiece because it is a relatively soft workpiece material. In opposite to metal materials, wood and wood based materials wear out during tactile measurement with the same master workpiece. Values of quality characteristics measured with tactile methods, showed a trend, due to wear and the variance, in the case of the moulder was relatively high. The optical measurements with the automatic measurement table did not show this behavior. Here the reflecting properties played a role due to the used high gloss lamination. Also deformations in the third dimension (buckles at the bore holes) could not be detected with the optical method.

An acceptable C_g could be generated in both cases for the selected tolerance HT 15. But the procedure was due to the mentioned problems not fully satisfying and is at the moment an objective of further investigations.

3.3 Process capability

The workpiece of the molder was milled at four sides with four spindles. The width of the workpiece was measured at 5 points (Fig. 5), the thickness of each 5 points on the right and the left side.

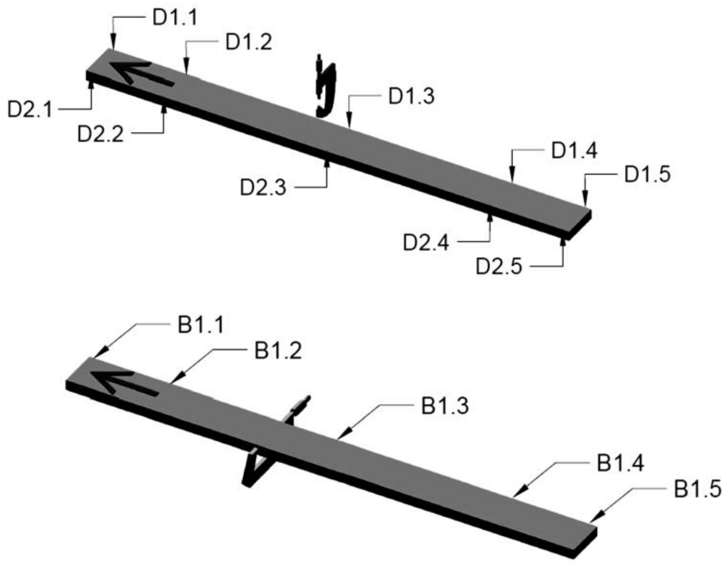

Figure 5: Workpiece molder.

The measured values were shown in an original value chart and a histogram (Fig. 6). The 200 pieces were manufactured in two blocks a 100; an offset between the two blocks with 100 parts can be seen. Next an emergency stop occurred, this influence is partly to recognize as a minimal offset of one axis.

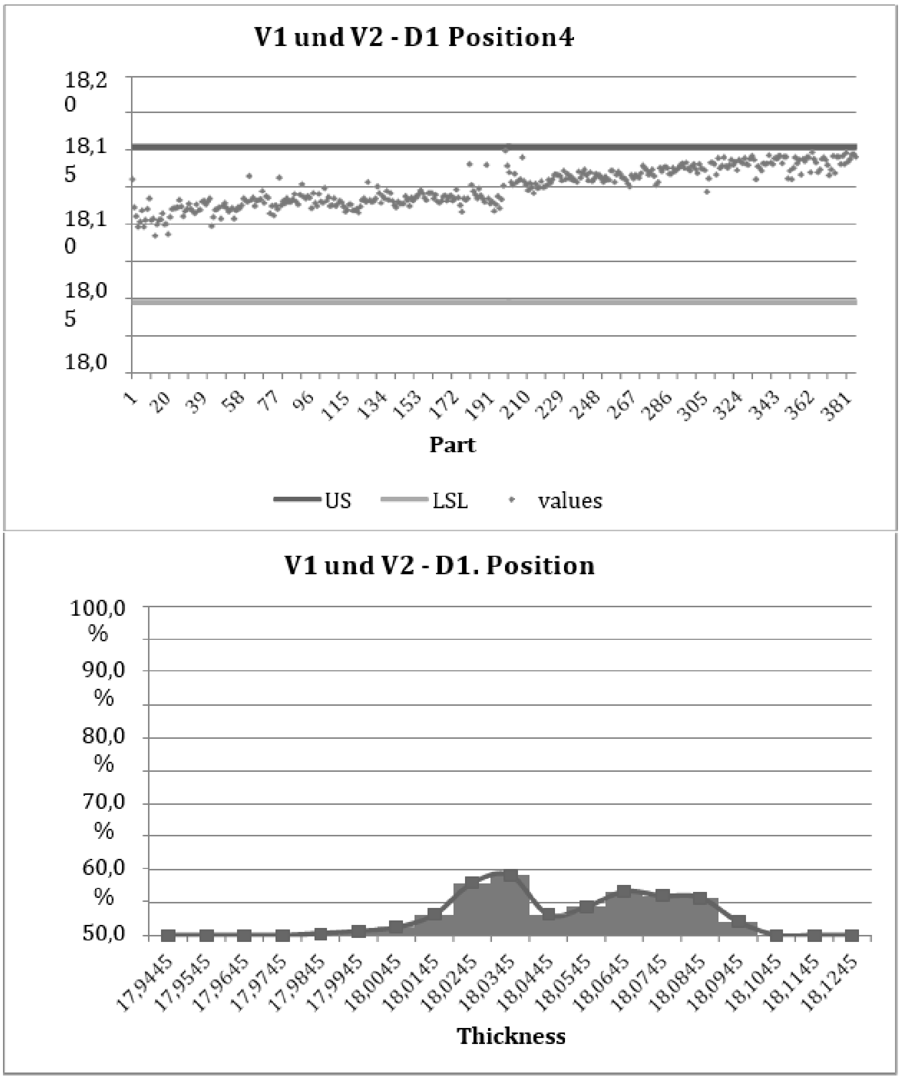

Figure 6: Original value chart and histogram of a machined board thickness.

Here, the capability indices were calculated according to the methods, which are described above. As expected, the capability indices calculated with the range, were mostly smaller than those of the factor of 6 σ, but not always. The distributions were normally distributed under no circumstances, partly bimodal and skewed; the calculation by 6 σ should therefore not be used. Calculated with the range capability indices were as expected always smaller than those determined by the quantile (Fig. 7). However, the differences were small and added up to average 4.8% and maximal 18.6% based on the correct calculation using the quantiles.

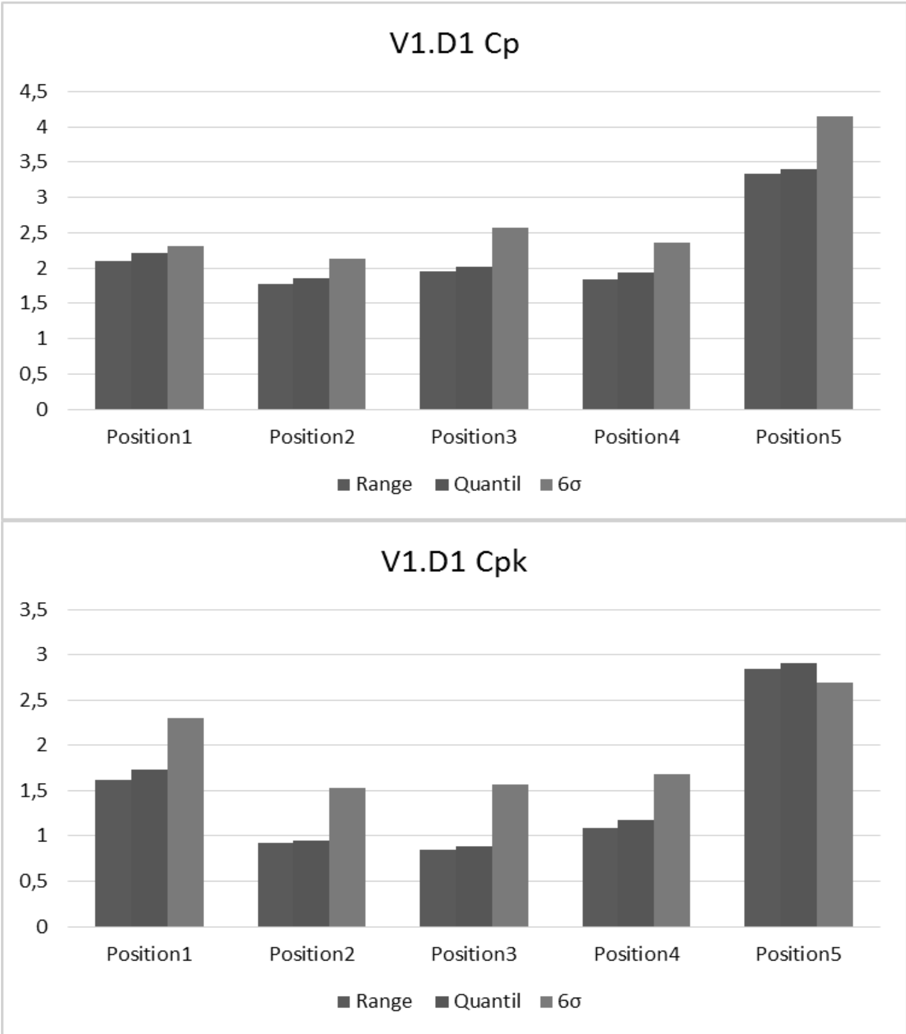

Figure 7: Capability indices for a machined board thickness.

For the characteristics of the workpieces produced by the machining center the results were similar. The evaluations were partly more complex. In addition to pure distance measures also squareness, parallelism and position tolerances of various holes were analyzed (Fig. 8). Positional tolerances are not defined by DIN 68100. Alternatively a factory specification of the machine manufacturer was used, the tolerance range is smaller than HT 15. The distributions were rarely approximately normally distributed, mainly towards trapezoidal distribution shaped and sometimes skewed. The validity of the capability indices calculated with a factor of 6 σ is therefore low and the values were both larger as well as smaller than the values obtained with the two other methods. With the exception of one value the capability indices calculated using the range were also smaller than that obtained with the quantile (Fig. 9). The differences here were in the average 4.0% and a maximum of 16.9% based on the correct calculation using the quantile.

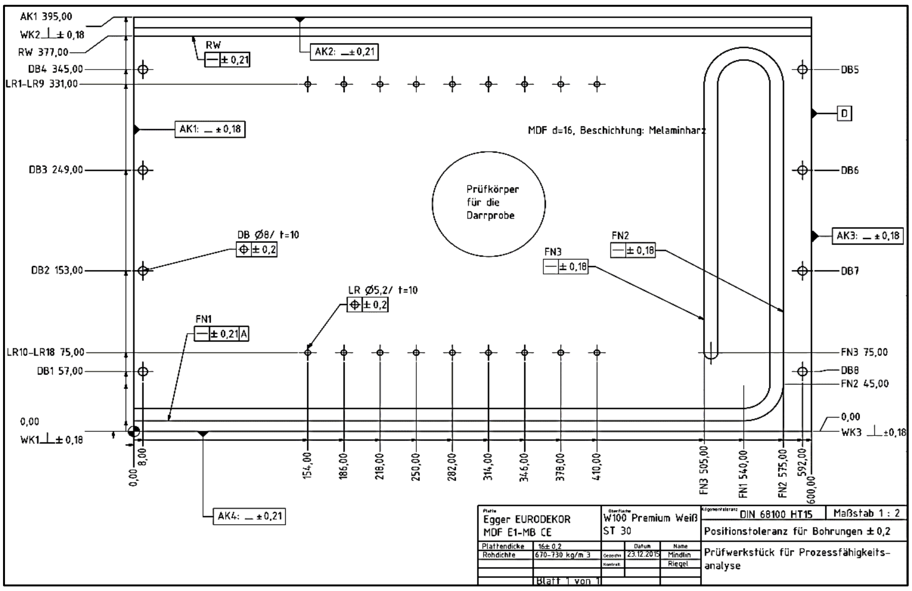

Figure 8: Workpiece machining center.

In both cases of the capability analysis no outlier tests were made, even if they had been authorized in part by the current standards. The focus of the investigations was clearly on the suitability of capability tests for machine acceptance procedures. For no machine buyer, it would be understandable in this context that single measured values of produced workpieces are not statistically taken into account.

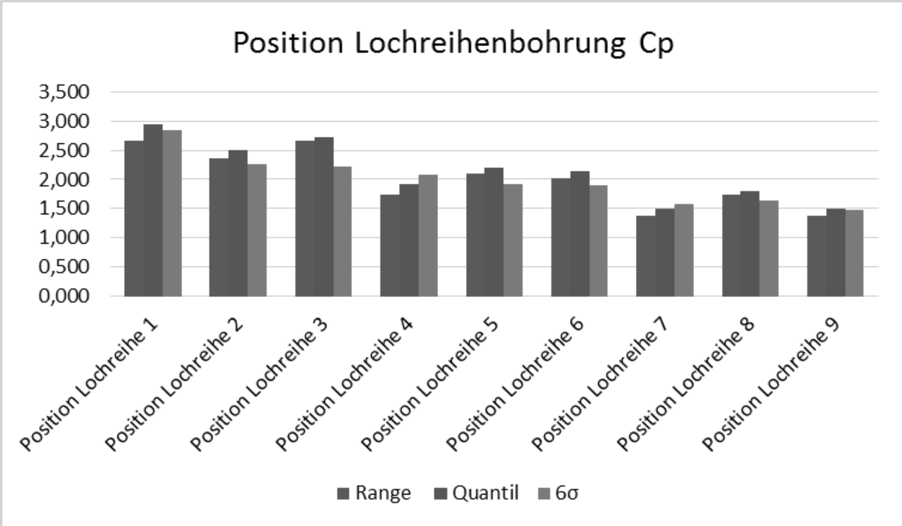

Figure 9: Capability indices for a position of a serial bore hole.

4 CONCLUSIONS

The limits of the capability indices are normally established in steps of a third. This is because of the correlation to 6 σ or 3 σ. Usually a value of 1.33 for normal and 1.67 for most relevant features are fixed in contracts as limits for process capability indices. Values for short-term skills (machine capabilities C_m, C_{mk}) can be raised to one level to have a reserve during the final inspection. Higher values are rarely sought, since the cost of the machine and the process would rise. The resolution required for the capability indices is therefore regarded as relatively low. As already explained in the last conference, the RV-factor or its inverse gives significant advantages over other methods in its suitability for attributive characteristics. The measurement capability of sensory tests, despite methodological procedures, special equipment and intensive training (see VDI 3414-2 [9]), cannot be significantly improved so that requirements such as the ISO 22514 would met. From a lot of 50 workpieces, the search out each best and worst and assign a grade on a scale with respect to tolerances is possible. For 200 parts the evidence should be shown. However, the effort and costs would probably increase significantly or it would lead to an overwhelming of the auditors.

Statistically, the difference in the calculation using the range or the quantiles is given and it turns out - as evidenced by the tests - in practice. It is depending on the form of distribution but it often has a low dependence. This raises the legitimate question whether the acceptance procedures of woodworking machines analogous to VDMA 8669 using the RV-factor or its inverse should be raised to a standard. Because of the high importance of the attributive, only sensory testable characteristics would allow an equal treatment for measuring and testing. Their determination and of the indexes itself would be simple and comprehensible but the use of them in capability analysis determined parameters in a subsequent SPC is currently rather rare. Because of possible outliers and other reasons, the method may not be 100% mathematically correct but practical.

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DRAFT DYNAMIC SEAT WITH A USE OF UNCONVENTIONAL TECHNOLOGY

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Abstract
The main goal of this study is to prove and demonstrate two experimental chair constructions together with their manufacturing. Both chairs for dynamic sitting are designed to be manufactured on CNC machines. The material used for this experimental sitting is plywood, which allowed to test new joint designs. Especially the flexibility of the plywood was the main factor for its usage. The first presented design is fabricated with laser CNC and the second one with classic CNC router. The results of this contribution are two shown chair prototypes, functional and esthetic, meeting ergonomic and safety demands.

Keywords:
Chair design, CNC technology, Flat pack, Experimental construction

1 INTRODUCTION

Laser beam machining of wood belongs to the unconventional methods used to machine wood and wood-composite materials. When cutting wood with laser, chemical degradation occurs. It results from the influence of high temperature and the inhomogeneity of material composition. Some phases of the material show chemical changes. After cutting, the edges are straight and the surface is smooth but covered by a layer of residual carbon dust [1]. Singed cut areas can increase esthetics of every machined part to a certain extent, if the natural appearance of the material remains in existence after surface finish. On top of that, the singed areas provide some level of wood preservation.

When using classic tools or laser to machine wood, it is important to take into account some factors which can influence the cutting quality. These factors include density, thickness, humidity and type of material, but also the type of glue used when producing wood-composite materials [2]. The higher the thickness and humidity are, the lower the cutting speed is, which results in deeper carbonization of machined areas. Due to this fact, it is applicable to machine wooden material not thicker than 50 mm [3]. The cutting speed is influenced by the density of wood, too. Compared to wood with low density (pine, poplar), the cutting speed of high density wood (oak, walnut) reaches lower values.

Laser cutting technology used to mill wood and wood based composites does not produce sawdust, the cut is thin and precise. Using more-axis CNC machining centers increases machining productivity and enables cutting in different directions and under different angles. Additionally, it is possible to start and stop the cut anytime, the cut is smooth and sharp angles can be produced [4].

2 DESIGN OF THE CHAIRS

2.1 Manta chair

The goal was to produce a chair using a joint which is rigid and stable enough when the final product is completed. Functionality, esthetics and simplicity were considered as well. It was decided to create a knock-down joint which can be used to fold the furniture without glue or other joining parts (metal fitting), and easily disassemble it back. There was also another demand: The final joint should not have any visible apertures after inserting and securing all parts, i.e. it should look compact and undivided. A working model was made from paper and cardboard. However such a model is suitable for checking tightness and composition of the joint only. To verify the toughness, load capacity, the joint was manufactured from oriented strand board as well as a working model. The result is shown in Figure 1.

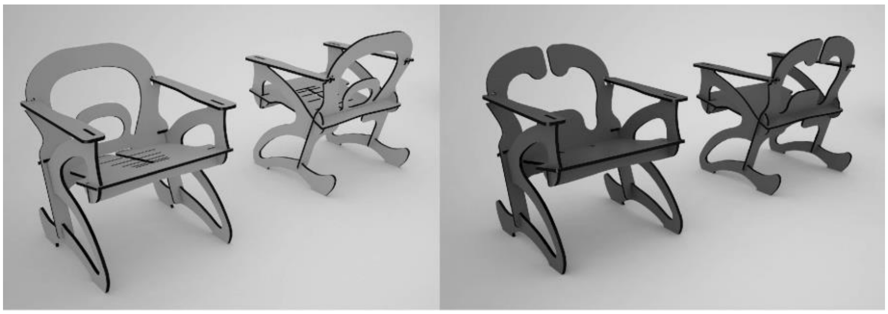

Figure 1: Visualization of Manta armchair.

2.2 MAA chair

Chair is made of thirteen plywood panels. This chair features a modernized classics return to the rural rustic style. To increase the comfort of the chair, it is additionally comprised of flexible parts, which are the seat and backrest. This chair is the only one with glue joints and thus it is difficult to disassemble. There were two versions of the backrest of the chair. The designed chair has great strength. A final prototype is shown in Figure 2.

Figure 2: Prototype of Manta armchair.

3 DEVELOPMENT

3.1 Manta chair

The development of the armchair resulted in two models. To make the final product as simple as possible, only one construction joint was applied to the second model. In both cases the armchair is composed of two legs, two aprons, two armrests, one backrest part, one seat part and dowels. To provide a potential customer with product variability, several versions of the seat and the back were prepared (Fig. 3). The customer can choose a component which suits his/her preferences, taste, mood and esthetic feelings best**.**

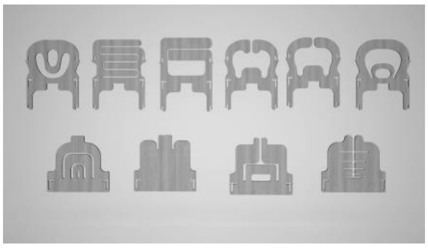

Figure 3: Variability several versions of the seat and the back.

3.2 MAA chair

Manufacturing joints on a regular CNC router is not easy. Paths for the tool were generated according to the defined parameters of a shape. During the development, various designs were tested on one detail sample to achieve the best properties. Joints require precise manufacturing and they are highly dependent on flat surfaces that fit together. The quality of plywood and the setting of the final milling process are the most important issues in achieving the best possible result.

Figure 4: Chair has great strength.

4 MANUFACTURING AND ASSEMBLY PROCESS

4.1 Manta chair

The lower and upper part of the aperture are cut off under a certain angle, to secure that the basic part fits in as good as possible after it is inserted. In the upper part of the apron there is a carved joint. The third part of the puzzle fits into this joint. The seat and the back consist of the third part of the final construction joint. In the edge part of this third component there is a T-shaped aperture. Vertical cuts are straight, horizontal cuts are skewed to fit in the apron part properly. It is very fast and easy to fold and dismantle the whole joint. The part of the joint with the T-shaped aperture is taken and the apron component is inserted into its upper vertical part. Afterwards both joined parts are slipped into the basic part and turned slightly (resp. a free area of the third part). Both parts are tightened and after they fit in indent sites of the part in the shape of a disrupted logarithmic spiral, the whole structure of the final construction joint is finished. It is necessary to secure free areas from accidental dismantling when using this type of joint to make an armchair. In Figure 5 the variation of the Manta armchair is shown.

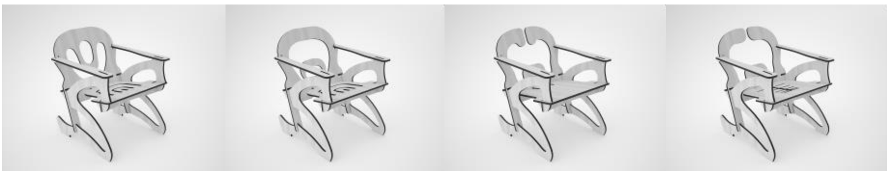

Figure 5: Variation of Manta armchair.

4.1 MAA chair

Before manufacturing, it was necessary to create a model and program for the CNC router. The development of the construction was done in DXF file in TurboCAD and BricsCAD and connected with OptimCabinetV2. For the CNC machine the SCM program was translated using TaskCAD and for the CNC Homag WoodWOP DXF import was used. Simulations were done by AlphaCAM. The manufacturing was performed on a 5-axis CNC router Homag Venture.

5 NUMERICAL MODEL DEVELOPED FOR VERIFICATION SEATING

In order to describe how the Manta chair responses to stress (displacement - deflections, relative deformation and stress), a numerical model of the part and the whole chair in different load cases was compiled. The model was built in an environment of ANSYS Mechanical APDL version 14.5. The analysis included the chair in its different types of shell finite elements. It also includes a description of the deflection of the seat at different loads. Then the structure of the different types was analyzed with focus on the different contact pairs in the joint part of the chair. The outputs of numerical models of the mechanical response of chairs served as a basis for adjusting and optimizing the structure, e.g. a change of dimensions in high tension areas (Fig. 6).

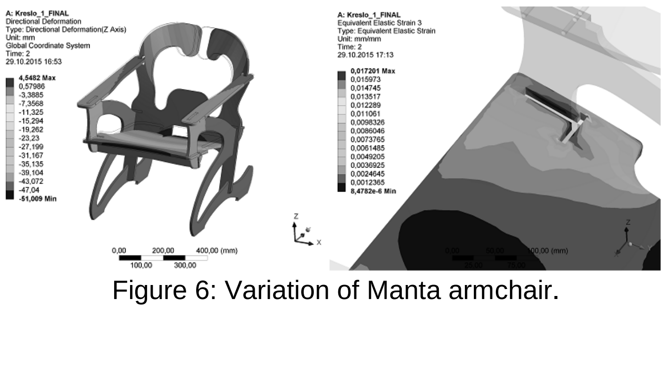

Figure 6: Variation of Manta armchair.

6 CONCLUSION

In this study two similar approaches for chair design were presented. The goal was to design chairs with basic joints and easy to assemble without using glue or metal fittings. Both presented prototypes fit well into the flat pack category and they are innovative in design and also used technology. For the Manta chair, there are several types of seats and backrests fitting together. This allows the user to choose the best color and shape. The chair MAA has glued joints, but retains the main idea of the project and dynamic sitting. It has a flexible seat and back, making it very ergonomic. The project outputs are prepared in such a way that no major adjustments are necessary to begin mass production in the furniture industry.

ACKNOWLEDGMENTS

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STRENGTH GRADING OF OIL PALM LUMBER BY MEANS OF ULTRASOUND AND NATURAL FREQUENCY

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Abstract
Monocotyledonous oil palm wood exhibits variations in density and distribution of vascular bundles and properties across and along the trunk. Therefore, appropriate strength grading procedures are necessary to ensure adequate usage and the correct kiln drying process. The application of non-destructive methods, such as measurements of ultrasonic velocity and natural frequency to determine elasto-mechanical properties, is common for dicotyledonous wood species. The purpose of this study was to examine the applicability of these methods on monocotyledonous oil palm wood. Furthermore, various influences on the wood's elasto-mechanical properties, such as the span-to-depth ratio, based on a three-point-bending test, and moisture content in the grading process were evaluated.

Keywords:
Oil palm, Grading, Ultrasonic velocity, Natural frequency

1 INTRODUCTION

Oil palm trees (*Elaeis guineensis* Jacq.) are mainly cultivated in large plantations for food production and as an industrial raw material. Their productivity decreases markedly at around 25 - 30 years of age, at which time the trees are commonly replaced. Each year, large quantities of oil palm trunks are obtained which traditionally are considered waste product. Recent research, however, has explored the potential commercial uses for oil palm wood. In various cases, the wood can substitute for tropical hardwoods, e. g. as construction timber. Using the wood as a load-bearing product requires defined elasto-mechanical properties – and therefore strength grading of the lumber.
The anatomic wood structure of monocotyledonous palms differs from deciduous and coniferous trees. Palms have no secondary growth due to the absence of a cambium layer. Palm wood consists of high density vascular bundles embedded in soft (lower density) parenchymatous ground tissue (without knots). Bulk density of palm wood depends on size, number, and anatomical structure of vascular bundles. Thus, palm trunks show a significant bulk density gradient over both trunk height and cross section. The number of vascular bundles decreases logarithmically from cortex to

the center of the trunk [1]. According to [2], the amount of vascular bundles increases along with stem height. Because the anatomical structure of the vascular bundles vary as the stem height increase, the bulk density and mechanical properties decrease accordingly. Knots, probably the most important grading criteria for deciduous and coniferous lumber, are not present in palm lumber. Hence, palm wood is more homogeneous compared to dicotyledonous wood. Elasto-mechanical properties of oil palm wood, especially the modulus of elasticity (MOE) and modulus of rupture (MOR), correlate with bulk density [3]. Presumably, bulk density, respectively the size and number of vascular bundles per area, is the most important grading criteria for oil palm lumber. In an exploratory study, the applicability of ultrasonic and natural frequency measurements for grading purposes of oil palm wood were evaluated by comparing the dynamic MOE from ultrasound (MOE_{US}) and longitudinal ($MOE_{NF,\ long}$) as well as flexural vibration ($MOE_{NF,\ flex}$) with static MOE (MOE_{stat}) using a three-point-bending test with a span-to-depth ratio of 50 x and bulk density. Prior studies on coconut palm wood show significant effects of the span-to-depth ratio on the static MOE [3]. Thus, fundamental test results exhibit a constant static MOE for oil palm wood starting from a span-to-depth ratio of > 40 x [4].
The adjustment of drying parameters according to high quality processing requires a pre-grading of large size specimens in green condition. Thus, a comparison between green and dry measurements on oil palm lumber with ultrasonic velocity and natural frequency up to the 3rd order vibration was carried out.

2 MATERIAL AND METHODS

Oil palm lumber sawn from logs with origin in Kluang (small-sized specimens) and Kulai (Peninsular) (large sized specimen) area (Malaysia) was used:

- 112 large-sized specimens with a length of 1950 mm, width 130 – 300 mm, thickness 23 mm and 60 mm (imported as logs).
- 120 small-sized specimens ($1{,}150 \times 22 \times 22\ mm^3$) (dry imports).

The imported logs were sawn in a sawmill into seamed side cuts and square-edged main cuts (large sized timber). This involves taking raw material in green state from 13 trunks at different stem heights (49 specimens from section 0.5 – 3.25 m; 34 from section 3.25 – 6.0 m; 20 from section 6.0 – 8.75 m; 3 from section 8.75 – 11.5 m). Ultrasonic time-of-flight and natural frequency measurements were first carried out on this wet oil palm wood. The material was further kiln dried in a laboratory kiln at the University of Hamburg, where general investigations on the drying process of oil palm wood were examined [5]. On the dry oil palm wood ultrasonic

time-of-flight and natural frequency measurements were carried out again to compare the wet and dry measurements.
To examine the influence of different span-to-depth ratios in the three-point-bending test (with a span-to-depth ratio up to 50x thickness), the small-sized specimens were prepared using preferably even cross-sectional bulk density distribution. The dynamic MOE was determined by ultrasound and natural frequency and a destructive three-point-bending test provided static MOE and MOR values.
Due to the anatomic structure of oil palm wood, larger specimens showed a more distinct bulk density gradient over the cross section compared to the small-sized specimens. Figure 1 illustrates the appearance and the anatomic structure of oil palm wood.

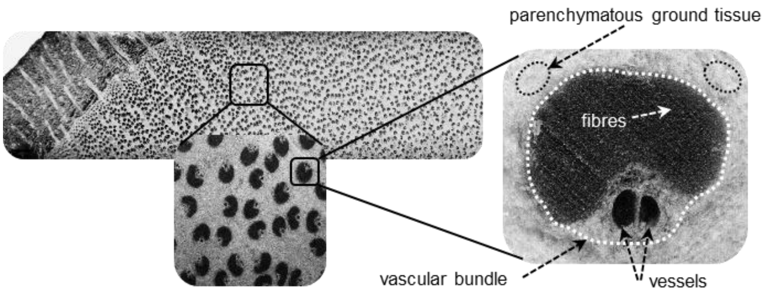

Figure 1: Cross section of an oil palm board with bulk density differences (left) and illustration of the anatomic structure (right).

Bulk density of the small-sized test specimens ranged from 170 kg/m³ to 525 kg/m³. All samples were categorized in bulk density classes. Prior to all measurements, all samples were conditioned to constant weight at 20°C and 65% relative humidity (according to DIN 50014:1985 [6]).
For all test specimens, ultrasonic time-of-flight and natural frequency were measured with subsequent dynamic modulus of elasticity (MOE_{dyn}) computation. Ultrasonic time-of-flight measurements in longitudinal direction were carried out using the ultrasonic device STEINKAMP BP 5, Bremen, Germany, with plane and conical probes for longitudinal waves (50 kHz). Coupling was performed directly without a coupling agent. On the large-sized specimens, the wet and dry measurements were performed at one marked measuring point within the cross section, because the measurement values may differ over the cross section, resulting in a substantial bulk density gradient. For the time-of-flight measurement on these boards the plane probes were handheld on both faces of the test specimen. Important for the comparison of the wet and dry values is to measure the time-of-flight at the same measuring points. In green condition,

the board is marked to ensure the compliance for the determination of the dry boards.
For the measurement of the small-sized specimens, the samples were fixed free-floating between spring-loaded conical probes in order to keep testing conditions (especially contact pressure) constant. MOE computation was done by the equation according to Steiger [7].
Natural frequency of longitudinal and flexural vibrations were determined using GrindoSonic MK5, J.W. Lemmens N.V., Leuven, Belgium ($MOE_{NF, long}$ and $MOE_{NF, flex}$). Longitudinal vibrations were used to compare the ultrasound results (MOE_{US}). Flexural vibrations were determined to illustrate the differences between respective vibration modes and for the comparison with the three-point bending test. During vibration measurements, the test specimens were supported on rectangular foam stripes in the region of the nodal points. Impulse was initiated by a small impact hammer. Dynamic MOE for flexural and longitudinal vibrations were calculated using the equations according to Görlacher [8]. Because of higher frequencies, the flexural vibrations on large-sized test specimens were determined by the 3rd order vibration. The low frequencies resulting from the large dimensions of the boards of the 1st order vibrations could not be detected by the testing device.
Three-point-bending tests (according to DIN 52186:1987 [9] using a support span of 50 × thickness) were carried out on the small-sized test specimens for comparative purposes.

3 RESULTS

The following results were determined on the small-sized specimens, except the investigations for the comparison between wet and dry measurements in Figure 8.
A compilation of measurement results and evaluated material properties is presented in Table 1 with mean values representing respective bulk density classes. Subject to the bulk density,

- Static MOE ranges between 613…10,500 N/mm²,
- MOR ranges between 3…50 N/mm²,
- Dynamic MOE from longitudinal vibration (GrindoSonic) between 800…12,360 N/mm²,
- Dynamic MOE from flexural vibration (GrindoSonic) between 767…9,570 N/mm², and
- Dynamic MOE from ultrasonic velocity (STEINKAMP) between 774…12,173 N/mm².

According to Table 1, both dynamic MOEs (MOE_{US} and $MOE_{NF, long}$) show higher values compared to the static MOE (MOE_{stat}). MOE determined by ultrasonic measurement (MOE_{US}) is 20% higher than MOE of longitudinal vibration measurement ($MOE_{NF, long}$) and 46% above MOE_{stat}, where

$MOE_{NF, long}$ is 22% higher than the MOE_{stat}. The computed MOE values from longitudinal vibration ($MOE_{NF, long}$) are around 16% higher compared to those from flexural vibration ($MOE_{NF, flex}$).

Table 1: Results (mean values) according to bulk density.

bulk density class [kg/m³]	*MOR [N/mm²]*	*MOE_{NF}* [N/mm²]		*MOE_{stat}* 50 h [N/mm²]	*MOE_{US}* [N/mm²]	natural frequency [Hz]		sound velocity [m/s]
		long	flex 3rd order			long	flex 3rd order	
170-258	6.3	1,618	1,390	1,273	1,834	1,144	227	2,814
258-324	9.8	2,638	2,280	2,155	3,199	1,283	254	3,263
324-391	14.9	4,498	3,778	3,594	5,385	1,524	297	3,844
391-458	22.0	6,858	5,764	5,661	7,956	1,728	337	4,288
458-525	29.9	8,472	7,344	7,324	9,439	1,792	356	4,367

Figure 2 shows the relation between MOR and MOE_{stat}, respectively the relation between MOR and bulk density. Determined using a span-to-depth ratio l/h=50, the coefficient of determination for the correlation between the MOR and the MOE_{stat} is R^2 = 0.9. Likewise, a strong correlation (R^2 = 0.6) between the MOR and the bulk density is given.

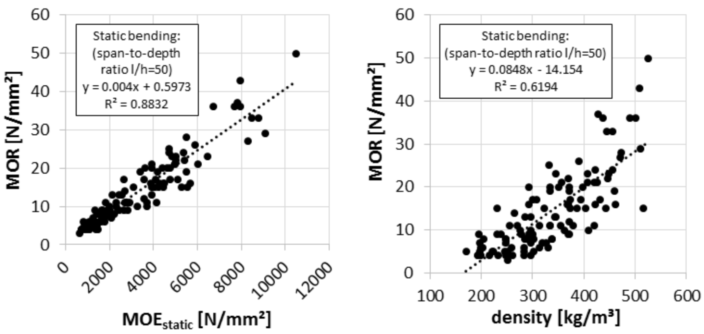

Figure 2: Relation between MOR and MOE from bending test (left) and MOR and bulk density (right).

Figure 3 shows a strong correlation between the ultrasonic velocity and MOR (R^2 = 0.7) and the frequency from longitudinal/ flexural vibration and the MOR (R^2 = 0.8/ R^2 = 0.7).

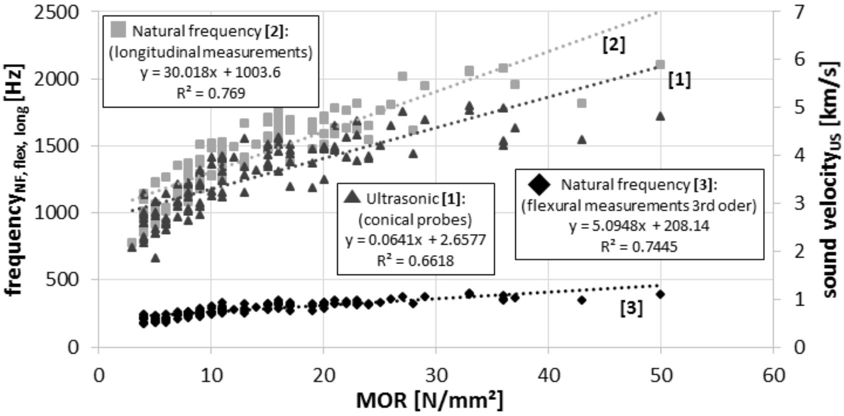

Figure 3: Relation between ultrasonic velocity respectively natural frequency from longitudinal/flexural vibration and MOR.

Ultrasonic velocity and natural frequency are the basis for calculating the dynamic MOE. To evaluate ultrasonic velocity and natural frequency as an own grading criteria, their relation to bulk density is analyzed in Figure 4. Both dynamic methods show a strong correlation with $R^2 = 0.6$ (ultrasonic velocity / natural frequency with longitudinal vibration) and a moderate correlation with $R^2 = 0.5$ for natural frequency with flexural vibration (3rd order).

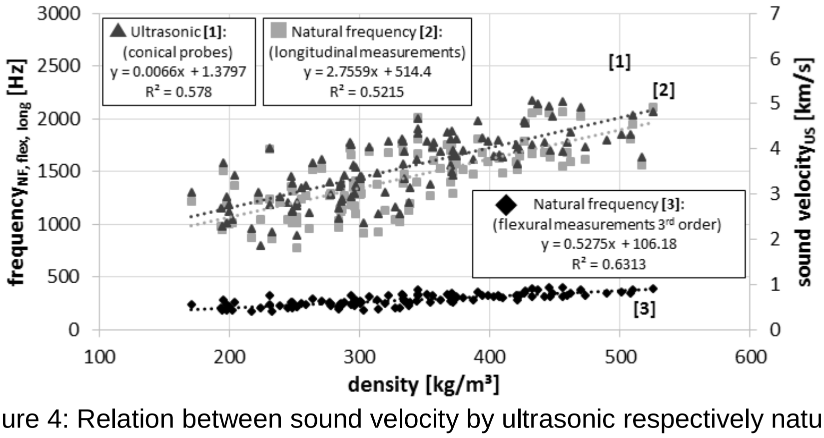

Figure 4: Relation between sound velocity by ultrasonic respectively natural frequency with longitudinal/flexural vibration and bulk density.

Divergence of absolute dynamic and static MOE values with increasing bulk density becomes obvious in Figure 5. Furthermore, a strong correlation between all dynamic MOEs, respectively the static MOE and the density, is shown.

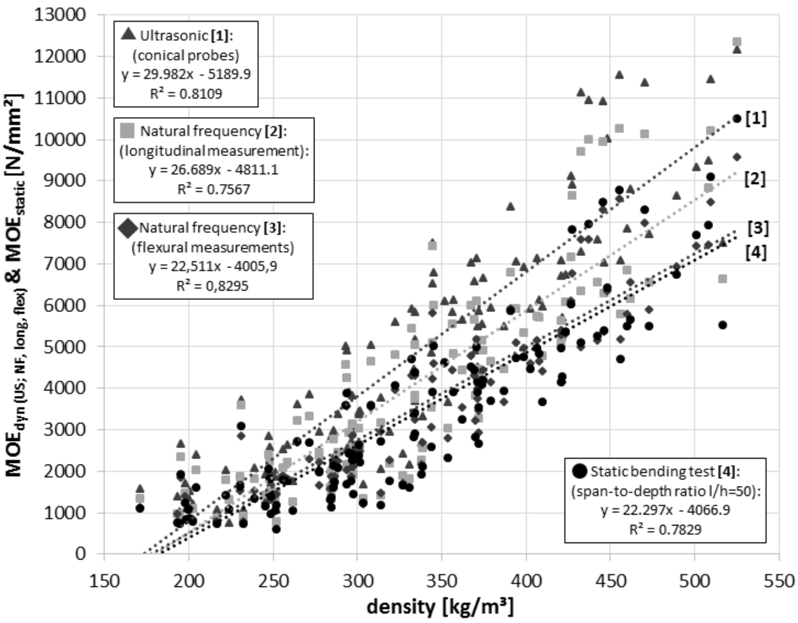

Figure 5: Relation between dynamic MOEs by ultrasonic respectively natural frequency with longitudinal vibration and static MOE by bending test.

The close linear relation between both dynamic MOE and static MOE is apparent in Figure 6: The coefficients of determination are given as $R^2 = 0.96$ for ultrasonic, $R^2 = 0.99$ for natural frequency measurement with longitudinal vibration and $R^2 = 0.98$ for natural frequency measurement with flexural vibration.

Given the strong correlation between the MOR and MOE from bending test (Figure 2) and the strong correlation between dynamic MOEs and static MOE (Figure 6), the correlation in Figure 7 can be explained. Based on these linkages, the correlation for the relation between dynamic MOEs by ultrasonic, respectively natural frequency with longitudinal and flexural vibration, and MOR by bending test are strong as well.

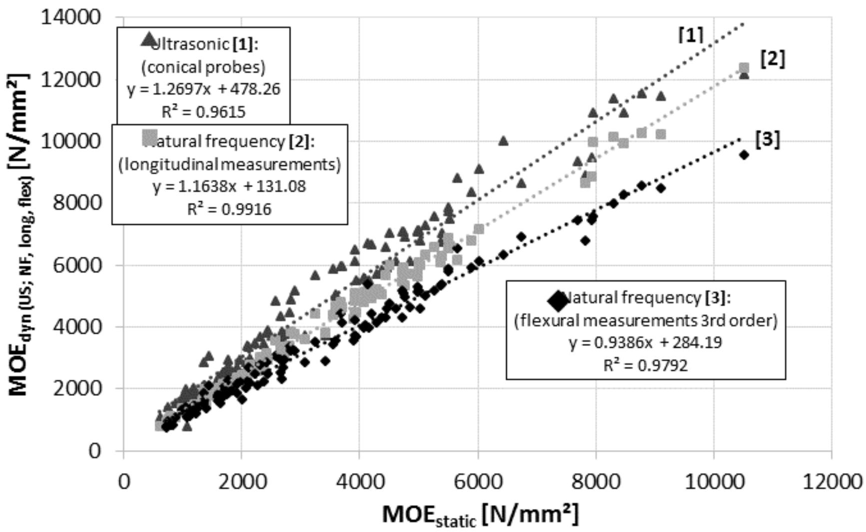

Figure 6: Relation between dynamic MOEs by ultrasonic respectively natural frequency with longitudinal/flexural vibration and static MOE.

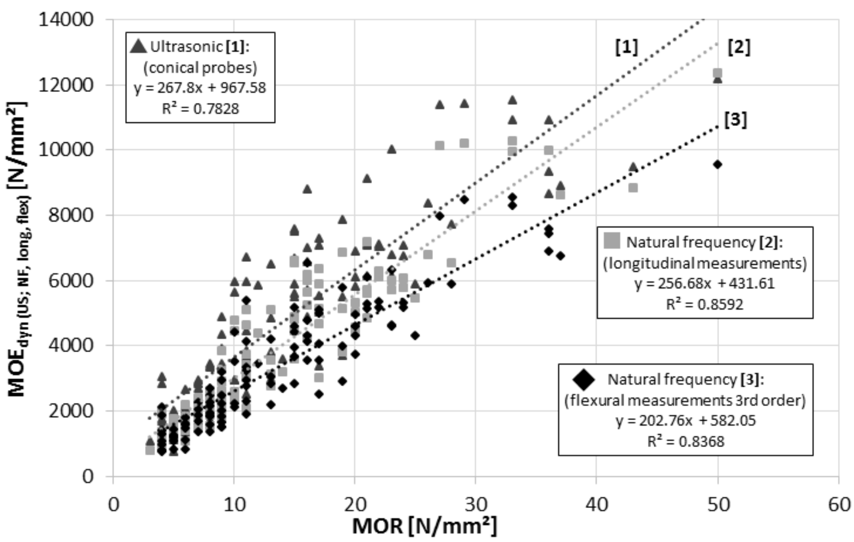

Figure 7: Relation between dynamic MOEs by ultrasonic respectively natural frequency with longitudinal/flexural vibration and MOR.

The comparison between the measurements of the wet and dry large-sized test specimens in Figure 8 shows a strong correlation with $R^2 = 0.91$.
For some of the very wet boards with a high moisture content of about 300 % and a very low density, an ultrasonic velocity below 1000 m/s is determined. Furthermore, the first impulse, measured using the ultrasonic device, cannot be metered precisely. If these low and not precisely measured values (marked in Figure 8 with a circle) are not considered, the coefficient of determination increases to $R^2 = 0.94$.
Longitudinal vibrations and 1st order flexural vibrations are not possible to measure for wet palm wood. 3rd order vibrations deliver results, but only for the high bulk density or low moisture content with a weak correlation to the dry values. Possible reasons are described in chapter 4.

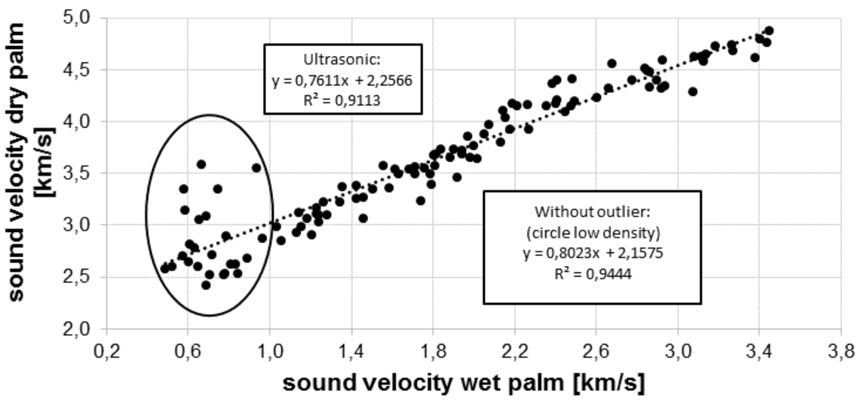

Figure 8: Relation between sound velocity from dry and wet palm wood.

4 DISCUSSION

In general, the ultrasonic velocity of wet and dry palm wood showed a strong correlation, so ultrasonic pre-grading of green palm wood seems to be possible. In this respect, the non-reproducible results for full size boards (large-sized specimens) with very low densities and high moisture content has to be considered. This can be explained with scattering effects. In dry material sound travels mainly through the fibres of the vascular bundles. In wet conditions the free bounded water in the vessels of the vascular bundles results in higher damping. The transmission of the impulse through water causes lower sound velocities.
Furthermore, investigations with 3rd order flexural vibrations were carried out on wet and dry boards. Because the width of the seamed side cut boards, were difficult to measure, average values were assumed.

This inaccuracy is associated with a larger potential error since the width is included to the third power in the equation used to calculate the dynamic MOE. Prior measurements on dry large-sized coconut palm lumber have shown that results from boards with precise dimensions are accurate [3]. It was not feasible to measure longitudinal vibration on wet large-sized specimens because the impact and the resulting vibration are not strong enough to deliver a consistent signal. The end cross section of the boards with low density and high moisture content is sometimes destroyed by the impact itself.

The dynamic MOEs are higher than the static MOE. This is accounted for the longer load duration during the static bending test compared to the dynamic tests. The longer the force is applied, the lower the MOE. Another factor influencing the difference between the dynamic MOEs and the static MOE could be the ratio of E/G and G itself that is neglected in the calculation of the MOEs. It is assumed that oil palm wood features lower shear modulus compared to dicotyledonous wood species with similar bulk densities caused by the anatomic structure. At the time of compiling this report, no studies were available on the correlation of shear modulus. Assuming that the shear modulus correlates with the shear strength and [10], [11] observed a low shear strength of oil palm wood, differences between MOE_{dyn} and MOE_{stat} may be explained. With an expected lower shear modulus for oil palm wood in relation to its MOE, according to [12] the correction factor E/G may have a significantly higher influence in the equation.

Higher values of the dynamic MOE determined with ultrasound compared to the dynamic MOE with natural frequency measurements are caused by bulk density gradients within the test specimens: according to [13] and [14], higher sound velocity can be observed in the area with the highest permeability -in case of oil palm wood the fiber caps of the vascular bundles. Because of the bulk density gradient within the boards, it is necessary to determine values from different measurement points over the cross section. Further studies are necessary to develop a mathematical model for determining the correct mean value for the MOE under consideration of the location in the steam height and cross section. In contrast, the anatomical structure affects only marginally the natural frequencies because the specimen vibrates through its entire dimensions.

The dynamic MOEs show a higher correlation to the MOR (R^2 = 0.78…0.86, cf. Figure 7) than density (R^2 = 0.62, cf. Figure 2) or frequency (R^2 = 0.74 or R^2 = 0.77, cf. Figure 3) or sound velocity (R^2 = 0.66, cf. Figure 3). So the dynamic MOE can be used as strength grading criteria.

5 CONCLUSION

In general, both ultrasonic and natural frequency measurements in longitudinal and flexural vibration are suitable for expanding the strength grading of dry oil palm lumber. Flexural 3rd order vibration measurements are appropriate especially for tests conducted under laboratory conditions with a large length to thickness ratio. To archive reliable data for large-sized timber, the boards must be square-edged. Longitudinal vibrations seem to be well suited to determine the dynamic MOE of dry large-sized specimens in component dimensions in an industrial production environment. For an industrial application, the in-line implementation of natural frequency measurements is less complicated than for ultrasonic devices. A high speed in-line system for industrial applications needs to be developed.

In cases involving small-sized specimens and an investigated influence of coupling with conical ultrasonic probes on either ground tissue or vascular bundles, ultrasonic coupling can be difficult [3]. Therefore, flat probes, especially for large-sized lumber, have to be examined further in an industrial context.

For green oil palm lumber in construction dimension with a high moisture content and low density, natural frequency measurements are not suitable. For this reason, the measurement of the ultrasonic velocity provides significantly better results. It is advisable to omit specimens with very low density and or very high moisture content for the wet grading process because of the non-reproducible results.

Considering MOE determination via static bending test, the influence of the shear modulus seems to be higher for oil palm wood compared to dicotyledonous wood species because of its anatomic structure with (high density) vascular bundles embedded in (low density) parenchymatous ground tissue. Therefore, the shear modulus for oil palm wood should be determined to analyze the accuracy of the calculation of the static and dynamic MOE.

ACKNOWLEDGMENTS

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SESSION E
Wood Processing Technologies and Furniture Production 2

EXTERIOR INFLUENCE ON THE PROPERTIES OF FINISHED SURFACES

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Abstract
This paper focuses on factors, which have an impact on the properties of pigmented finished surfaces of different kinds of wood (Oak, Pine, Larch, Spruce, Beech and Acacia). It aims to identify the impact of different shades of the same kind of finishing during long time testing and to identify influences of the different kinds of wood used. The work investigates one type of the pigmented water borne alkyd paint in the different colors (white, red, green, blue and white). The experimental part focuses on the assessment of effects applied to different kinds of wood, on the quality of coated surfaces, on the determination of the influence of different colors on the changes of gloss and the hardness of the finished surfaces. The conclusion of the work contains statistical evaluation of the impact of the finished surfaces color and the used kinds of wood on the quality of coated surfaces.

Keywords:
Lightfastness, Paints, Colors, Gloss, Acacia, Oak, Pine,

1 INTRODUCTION

Natural wood of outdoor furniture made from solid woods is exposed to many environmental agents. Especially the solar radiation causes rapid color changes, breakdown of wood polymers and coatings materials in the surface layer [1, 3]. The combined effects of the solar radiation with other environmental agents such as water in the different phases and temperature severely affect the life of wood under exterior applications. The color stability of natural wood exposed to light is low. The color changes of the finished surfaces have great impact on the aesthetic impression and properties of furniture. A common failure mechanism of organic coatings is photo degradation due to UV exposure. Adding a surface photo-stabilization significantly extends the service life of coated wooden products placed in outdoor situations [4]. And so the decreasing of the wood and coating materials photo degradation increases the aging of wooden products and so it has been studied extensively [2]. One way to ensure a long life of wooden outdoor furniture is usually coating with various decorative and protective finishes such as transparent and pigmented finishes. But the transparent

coating systems, that allow the natural features of wood (i.e. grain, colour, texture), have short life span under outdoor exposure. Due to UV light transparency of the clear coats and extreme sensitivity of wood components, particularly lignin, to UV light, degradation occurs underneath clear finishes, which results in coating failures. In order to minimize such failures, coatings are formulated with transparent UV-absorbing molecules which change the UV energy into less harmful energy, e.g. heat energy, before reaching the substrate. This heat energy is radiated into the surrounding of the wood products. The UV absorber must also be photo stable by itself. Organic phenolic molecules, such as benzophenone and their derivatives have been extensively tried and used as an organic UV absorber. However, due to their relatively low molecular weight, these additives can migrate out of applied coatings, either to the coating surfaces or into the substrates [5] and therefore have limitations in providing the long-term protection.
Those coatings are exposed to outdoor conditions, which result in stress weathering factors such as solar radiation, humidity, temperature, oxygen, bacterial and fungus attacks, dirt and others chemical factors due to the pollution. The durability of exterior wood coatings refers to loss of strength, discoloration, loss of adhesion, chalking and loss of gloss [1]. It is still problematic for outdoor coatings to fulfill the guarantee periods expected by the users.
Well-known, inorganic and organic UV absorbers that increase the polymer stability are often used in coatings formulation. Inorganic UV absorbers for exterior applications offer the most effective UV protection in the long-term because they do not decompose and do not migrate into the coatings during weathering [2].
The second way to improve the durability of outdoor furniture and wooden based products is to use pigmented coating materials in different colors for coating solid kinds of wood of outdoor furniture.

1.1 Goal of research

This contribution focuses on the influences of different kinds of colors on the durability or on the aging of the pigmented finished surfaces. These factors have a great effect on the lightfastness of finished surfaces, the durability of outdoor furniture made from different kind of wood and finished by different colors of the paints based on the same alkyd. The research work aims also to identify the impact of different colors on the important quality factors for example the lightfastness and durability of outdoor furniture and other wooden products during their outdoor exposition. The second aim is to determine the impact of different color on the quality of the finished surfaces particularly on the loss of gloss and color changes.
The assessments of the tested surfaces were evaluated by comparing the color changes between the exposed and non-exposed parts of the tested surfaces.

2 MATERIALS AND METHODS

2.1 Used appliances

- **Spectro-quide 45/0 gloss** portable spectrophotometer, based on the measurement of special reflectance within the visible spectrum of the spectrum of wavelengths from 400 -700 nm with white standard in the CIE Lab.
  Changes of colors were defined on the basis of colorimeter measurements of color coordinates (L, a, b) and carried out by using BYK-Gardner spectrophotometer spectro-quide 45/0 gloss. The change of color in the CIE Lab system was calculated according to ISO 7724-3: Colorimetry – part 3 Calculation of color differences
  $$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$
  Where: ΔE refers to color difference, L to achromatic color coordinate (lightness), a, b to chromatic color coordinates (a – green/red axis, b blue/yellow axis)
- **Buchholz assessment** of surface resistance against hardness going into coated films by micro-hardness tester according ČSN 607 3074
- **Byk gloss meter** assessment of surface gloss according to the standard ČSN ISO 2813 (67 3066) and the comparison to the grey scale (5-steps according to ČSN 80 0121 Grey scale pro determining the surface light-resistance).

2.2 Tested samples

The tested samples were prepared from **six kinds of wood:** oak beech, acacia, spruce, larch and pine finished by pigmented paints. The dimensions of the tested samples were 200 mm x 100 mm x 18 mm. Eight samples were prepared for each color and each kind of wood, together 240 samples were measured.

The tested samples were finished by

1. ADLER Acryl-Tauchgrund 40950 ff, waterborne acrylic paint, the first coat.
2. The coated surfaces drying, conditions: room humidity 25% r.h., temperature of indoor air 24.9°C.
3. ADLER Varicolor 41201 waterborne alkyd cover paint in the colors black RAL 9005, white RAL 9010, red RAL 3024, blue 5015, green 6017, surface coated 2 times by this paint.

Table 4: Assessments of tested color on glass.

	RAL	***ØL****	***Øa****	***Øb****
Black	RAL 9010	11.38	0.09	0.42
White	RAL 9005	94.00	1.29	10.76
Red	RAL 6017	43.54	60.45	48.27
Green	RAL 5015	47.05	-24.94	30.59
Blue	RAL 3024	47.17	-14.61	-34.90

2.3 Exposure of tested samples

One sample from each kind was stored in a dark space for comparing with the seven tested samples exposed to outdoor conditions in the region of south Moravia. The specimens were faced to the south. The properties of the tested finished surfaces were measured before their outdoor exposition and after their outdoor exposition. The outdoor exposition started on March 15, 2015 and were finished on October 20, 2015.

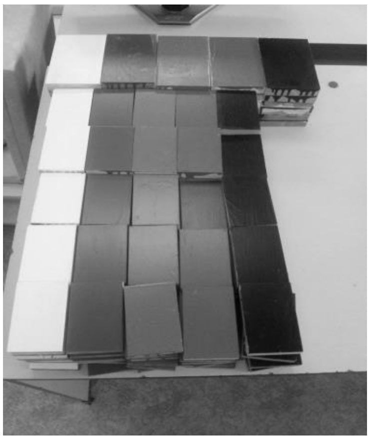

Figure 1**:** Different colors of tested samples.

Figure 2: Outdoor exposition of the tested samples in South Moravia.

3 MEASUREMENT RESULTS AND DISCUSSION OF RESULTS

The results of the tested samples are published in Table 1, 2 and Figure 3. The results are expressed in the percentage of color changes.

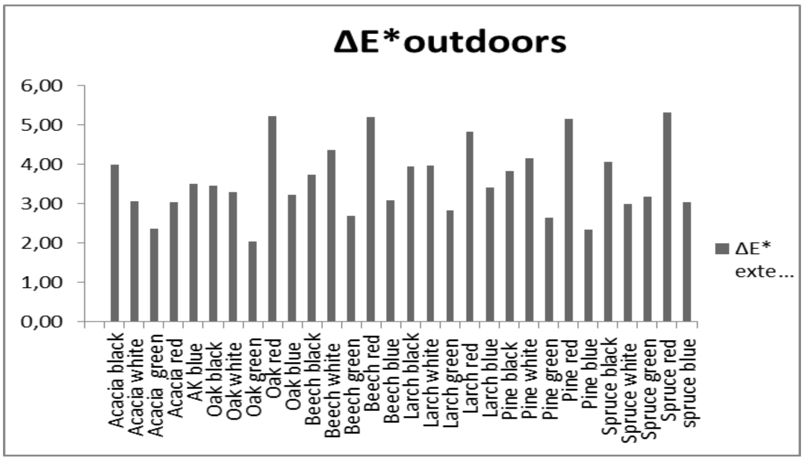

Figure 3: Lightfastness of tested samples after their outdoor exposition.

Table 1: Assessment of color changes after outdoor exposition soft kinds of wood.

Paints	*Before*			*After*			***Changes during exposition***			
	ØL*	Øa*	Øb*	ØL*	Øa*	Øb*	ΔL*	Δa*	Δb*	ΔE*
Larch black	-11.0	0..01	0.27	14.1	0.15	0.35	3.93	0.01	-0.43	3.95
Larch white	94.15	0.30	10.90	90.32	1.30	10.67	-3.83	1.00	-0.23	3.97
Larch red	43.53	61.74	48.86	44.67	59.87	44.55	1.14	-1.9	-4.31	4.83
Larch green	47.01	-25.1	30.8	46.7	-23.5	28.56	-0.30	1.67	-2.26	2.83
Larch blue	43.7	-14.1	-35.8	46.9	-14.0	-32.4	-0.5	0.1	3.36	3.40
Pine black	10.56	0.15	0.39	14.37	0.15	0.00	3.81	0.0	-0.39	3.83
Pine white	94.16	0.18	10.71	90.10	1.02	10.34	-4.06	0.8	-0.37	4.16
Pine red	43.84	61.8	48.46	44.73	59.2	44.09	0.89	-2.6	-4.37	5.15
Pine green	47.10	-25.0	30.51	46.77	-23.2	28.58	-0.33	1.8	-1.93	2.65
Pine blue	47.13	-14.3	-36.1	46.40	-14.2	-33.9	-0.73	0.1	2.22	2.34
Spruce black	11.29	0.07	0.64	15.34	0.10	0.42	4.05	0.0	-0.22	4.06
Spruce white	94.19	12.8	10.52	91.32	13.1	9.78	-2.87	0.5	-0.74	2.98
Spruce red	43.88	50.2	49.28	42.26	46.6	45.71	-1.62	-3.6	-3.57	5.32
Spruce green	47.21	24.9	-30.4	46.32	-21.8	30.15	-0.89	3.1	-0.22	3.18
Spruce black	47.41	13.9	-36.3	46.87	-13.2	-33.4	-0.54	0.8	2.90	3.04

Table 2: Assessment of color changes after outdoor exposition hard kinds of wood.

Assessment of color changes of coated films										
Coated materials	Before			After			Differences			
	ØL*	Øa*	Øb*	ØL*	Øa*	Øb*	∆L*	∆a*	∆b*	∆E*
Acacia black	11.0	0.10	0.27	15	0.0	0.15	4.0	-0.1	-0.1	4.0
Acacia white	93.4	0.44	11.54	90.6	0.9	10.3	-2.8	0.5	-1.2	3.1
Acacia red	42.9	60.2	47.17	44.0	59.	44.5	1.2	-0.7	-2.7	3.04
Acacia green	46.69	-24.77	30.62	46.8	-23.2	28.82	0.08	1.55	-1.8	2.38
Acacia blue	46.64	-16.44	-30.89	47.1	-14.1	-33.5	0.50	2.34	-2.6	3.51
Oak black	11.78	0.20	0.35	15.2	0.23	0.11	3.45	0.03	-0.2	3.46
Oak white	94.13	0.23	10.74	91.0	1.22	10.21	-3.1	0.99	-0.5	3.30
Oak red	43.31	60.72	47.62	44.5	57.7	43.56	1.22	-3.1	-4.1	5.23
Oak green	46.91	-24.64	30.20	45.7	-23.0	30.02	-1.2	1.67	-0.2	2.04
Oak blue	46.96	-14.52	-34.87	46.0	-14.3	-31.8	-0.9	0.22	3.09	3.23
Beech black	10.79	0.07	0.45	14.5	0.09	0.22	3.73	0.02	-0.2	3.74
Beech white	94.09	0.41	10.86	89.9	1.42	10.52	-4.2	1.01	-0.3	4.36
Beech red	43.75	62.24	48.90	42.8	60.9	43.97	-1.0	-1.4	-4.9	5.21
Beech green	47.12	-25.08	30.71	46.6	-23.4	28.64	-0.5	1.66	-2.1	2.69
Beech blue	47.29	-14.07	-35.95	46.4	-13.8	-33.0	-0.9	0.25	2.96	3.09

The results of the investigation of the effects of outdoor exhibitions on the hardness of finished surfaces are summarized in Table 3. In Table 3 there is also published the impact of the used wood and different colors and the impact of the wood fiber direction on the hardness of the surfaces. The impact of the outdoor exhibition on the change of the surface hardness is expressed as the percentage of the changes. The decrease of the hardness values is rendered as minus values and the increase of the hardness values is expressed as plus values.

Table 3: Change of the surface hardness in % by Bucholz measured along and across the wooden fiber after outdoor exposition.

Coated materials	Change of surface hardness along the wooden fiber %	Change of surface hardness across the wooden fiber %
Acacia black	-21	-3.48
Acacia white	-51.68	-54.44
Acacia red	-9.14	-37.73
Acacia green	2.12	-18
Acacia blue	-10.79	-32.45
Oak black	-70.52	-67.09
Oak white	-65.42	-64.86
Oak red	-68.67	-61.73
Oak green	-55.38	-48.7
Oak blue	-70.25	-74.48
Beech black	47.55	1.81
Beech white	-8.18	-41.54
Beech red	52.14	-41.02
Beech green	-17.22	-34.33
Beech blue	84.71	34.94
Larch black	19.16	-41.26
Larch white	15.61	-47.59
Larch red	155.7	-36.15
Larch green	36.84	-38.89
Larch blue	157.33	-12.32
Pine black	117.29	-62.66
Pine white	61.43	-54.94
Pine red	133.05	-51.25
Pine green	1.03	-58.65
Pine blue	248.92	-55.5
Spruce black	6.3	-35.23
Spruce white	-89.6267	-53.59
Spruce red	21.41	-41.37
Spruce green	36.79	-16.17
Spruce blue	96.74	-19.86

The results of the impact of the outdoor exhibition on the loss of the gloss are published in Table 4 and Figure 4. The impact of the outdoor exhibition on the loss of gloss is expressed as the percentage of the changes. The decreasing of the gloss values is put into the graph as minus values and the increasing the gloss is expressed as plus values.

Table 4: Decrease of loss of gloss in the percentage of GU - measured across the wood fibers after outdoor exposition.

	Decrease of the gloss across the wood fibers after the outdoor exposition
	%
Acacia white	-13.54
Acacia red	-16.55
Acacia blue	-12.34
Acacia green	-13.63
Acacia black	-19.85
Oak white	-18.90
Oak red	-28.71
Oak blue	-24.51
Oak green	-24.79
Oak black	-30.25
Beech white	-22.41
Beech red	-32.83
Beech blue	-27.68
Beech green	-36.45
Beech black	-32.63
Larch white	-6.37
Larch red	-25.49
Larch blue	-24.04
Larch green	-28.97
Larch black	-24.79
Pine white	-16.10
Pine red	-29.59
Pine blue	-19.50
Pine green	-26.10
Pine black	5.19
Spruce white	-18.35
Spruce red	-26.77
Spruce blue	-21.99
Spruce green	-23.99
Spruce black	-27.82

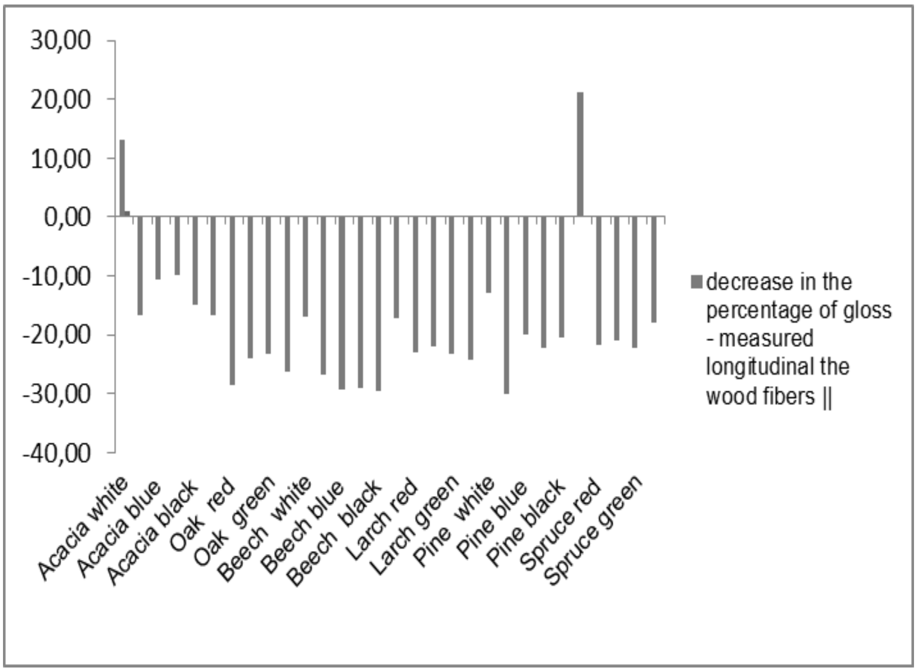

Figure 4: Declines of gloss in the percentage of gloss - measured longitudinal wood fibers after the outdoor exposition.

4 RESULT DISCUSSION

On evaluation of issued results in this article it is possible to state the following.

Lightfastness of the samples
The effect of light exposure on finished surfaces is shown in Figure 1 and 2. The best results were reached by the finished surfaces of different kinds of wood finished with green color followed by the samples coated with blue color. The finished surface coated with red color is indicated as the samples with the worst results of lightfastness followed by black color.
The results of the gloss decreasing measurements are shown in the Figure 4 and Table 4, which show the impact of applied colors and kinds of wood. The used colors have a great impact on the hardness of the finished surfaces, as shown by the tested samples. From the point of the surfaces hardness, the red shadow of the paint is a very important color because the red color increases the hardness of the surfaces during outdoor exhibition especially in the direction across of wooden fibers. From the view of the

assessment of the tested samples´ surface hardness, great differences were found between the directions of measurements.
From the point of the different colors the best results in hardness of the surface were reached by the finished surfaces coated by red and green color, followed by black color.
The average of the loss of gloss for the samples placed in the exterior along the grain is 14,08%. We can see the greatest decline of gloss loss reached by the samples of pine finished by red color in the direction along the wooden fibres (30,00%) followed by beech finished by black color (29,93%). The smallest decrease of gloss along the wooden fibres was acchieved by the finished surfaces of acacia finished by green color followed by acacia finished by blue color.

5 CONCLUSION

From the point of the measured results in this contribution, it is possible to state that it is not possible to transfer the results of tested surfaces without respect of the color of used paints. The outcome from the assessments of the surface properties stability is that it is possible to determine the most suitable color for finishing outdoor furniture and outdoor products made from massive wood, which is green followed by blue.
A very important finding of this work is also the results of the investigation of the influence of color types and types of wood and their impacts on the finished surfaces hardness after the outdoor exposition. The most important color is red which increases the hardness of finished surfaces in comparison to other colors.
Regarding the results it is possible to state that the colors of the coating materials have significant impact on the quality of the finished surfaces and their durability.
The summary of the conclusion of this contribution is:

- The tested kinds of wood have no impact on the lightfastness of the tested coated surfaces and the loss of gloss.
- The colors of the used paint for coating the surfaces have an impact on the lightfastness, the loss of gloss and the hardness of the finished surfaces.

The results of finished surfaces hardness of the tested kinds can be statistically compared regarding the tested kinds of wood. It is possible to say that only the finished surfaces of acacia have different results.

ACKNOWLEDGEMENT
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PRODUCT DEVELOPMENT OF FURNITURE: DESIGN AND TECHNOLOGIES

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Abstract
New technologies are applied in the furniture industry for a long time. Furniture production is very accurate and faster thanks to CNC technology, also allowing joint production. Furniture with joints manufactured on the CNC machine is from the point of view of structure known as ready-to-assemble (RTA) furniture. The multidisciplinarity of the product development and testing of mechanical properties of selected types of RTA furniture is presented. The manufacturing process of chair and desk design manufactured on CNC machines and subsequent testing procedures are described. For further analysis of mechanical behavior in the accredited laboratory, the standard tests for furniture employing the European Standards are used. The Digital Image Correlation (DIC) method analyzes displacement and deformation of critical construction. Predictions for the most stressed joints are made by numerical simulation. The test results of chair and desk provide specific information about the developing process and enable the optimization of strength properties. The presented work highlights the importance of furniture parametrization and application of new methods for testing of industrial products.

Keywords:
Product development, Furniture, CNC technology, Testing

1 INTRODUCTION

The use of hardware as a traditional approach of European furniture industry is one of the basic principles of furniture constructions. New holistic perspectives are brought to furniture industry by the influence of globally used technologies and processes. Dismountable furniture is usually described as a type of construction with a use of knock-down fittings. Because of its simplicity this construction method is commonly used by large volume producers as well as by small carpenters. The significant advantages are the through-feed lines, production cells or other technologies that can be used for drilling, sawing and routing. Dependence on the fittings and their influence on design, price and quality of final product are the major issues. The nesting technology had an influence on the manufacturing of joints on

CNC machines. RTA furniture development is the result of such an approach. The necessity to eliminate the multiple positioning of the part on the machine table leads to new construction and joints development related to CNC machines. A manufacturing cell is able to produce a complex furniture product, which is simple to produce and to assemble with high accuracy and without any additional material for joinery. Nevertheless, the process depends on the manufacturing technology that influences the speed, flexibility and quality. The above-mentioned principles, excluding their disadvantages and traditional construction concepts, can lead to new interesting designs. Nowadays, furniture design and technology development trends as well as modern methodologies of applied research and development of industrial products enable a faster launch of competitive furniture products. The synergic effect of this fact is a wide cooperation between research and development in university departments and the commercial sphere.
CNC machine technology has been developed in the 40s and 50s of the 20th century in the United States. The main advantages of CNC technology are automation of the manufacturing process, high accuracy and speed of processing, high reliability and versatility with low maintenance and exclusion of technology breaks for new settings. On the other hand, the main disadvantages are higher purchasing and operating costs, higher knowledge demands on the operator and lower production speed compared to large series production with various specialized machines [1]. While RTA and/or flat pack furniture has been produced for more than twenty years, experience with designing it and with its strength properties is still limited. The development of technologies, new materials and information technologies not only in production and marketing, but also in furniture design brings many methods which allow engineers and designers to adopt new work approaches. Despite the fact that standardized furniture testing is not compulsory for producers in most cases, it is commonly implemented. Numerical simulations have been applied by furniture industry in a limited way so far, e.g. Mirra Office Chair [2]. However, they are supported by research quite significantly. From a large number of works, research on the behavior of constructions of seating furniture [3] [4] [5] or box-type furniture [6] [7] can be mentioned. The DIC methodology in relation to a shape and deformation measurement is described e.g. [8].

2 METHODOLOGY AND RESULTS

2.1 Chair testing in the laboratory

The design of the chair was created by using CAD-CAM applications. It was made by a CNC machine (with a nesting table) out of plywood (12mm), with integrated dovetail not-glued joints. Similar principles of constructing furniture based on rapid manufacturing were described e.g. by [9]. The construction of the chair was assembled out of six parts while no glue was used. It was designed as a self-locking construction (Figure 1).

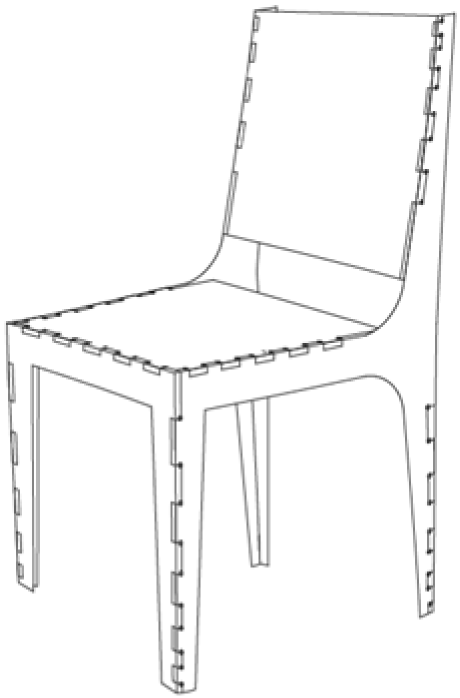

Figure 1: Chair design based on RTA principles.

The construction was mechanically examined in an accredited furniture testing laboratory according to the Czech standard CSN EN 1728 [10], article no. 6.4. An experimental optical measurement was carried out by the digital single lens reflex (SLR) camera (Nikon D5100) which was set perpendicularly to the examined surface, in this case the side part. To achieve a constant intensity of the recorded surface image, it was necessary to keep stable lighting conditions within image acquisition. For this purpose the examined surface of the chair construction was lightened by diffuse lights. The frequency of recording was set up to 1 fps, the bit depth of images was 8-bit. An open-source tethering software, connected to the camera using the USB port, was used to transfer data to a mobile PC station. In the Vic-2D software, correlation computation of displacement and strain fields was carried out.

The goal of the work was to compute displacement fields on the chair side surface using the DIC method. The DIC computation brought reliable results which are based both on quantitative (standard deviation was lower than 0.05) and qualitative evaluation (displacement contours follow mechanical behavior assumptions resulting from a loading mode). For the horizontal displacement, the highest absolute value was experienced at the top of backrest (u = 3.9 mm) and the highest absolute value of vertical displacement was experienced at the front leg (v = 1.2 mm). In a next step of the analyses, strain fields computed from displacements were evaluated. The strain field in horizontal direction (εxx) is depicted in the Figure 2; the vertical strain component (εyy) is depicted in the Figure 3.

Figure 2: The strain field in horizontal direction (εxx).

Figure 3: The strain field in vertical direction (εyy).

The results show that the vertical strain is highest in the dovetail connections on top of the chair seat. Nonetheless its highest absolute strain did not exceed ~ 0.3% so that all strains occurring there can be affirmed as elastic – below the proportional limit of all possible loading modes in wood and birch plywood [11] [12]. The horizontal strain is the highest in the backrest dovetail connections and its maximal absolute value is ~1.56%.

2.2 Numerical simulation of desk

The analyzed desk construction (Fig. 4) was produced as a prototype using CNC laser cutting, precise CNC press bending (metal parts – base) and typical furniture production CNC processing (wooden composite materials – desk top). The aim of the study was to establish the probable mechanical behavior of the office desk, especially the base, in consequence of the defined static loading based on the standards. Thus, the study focuses on the analysis of the extreme response (maximum tension) points and the probable breakage points by means of static numerical analysis. These

points will be evaluated based on a proposed solution for the achievement of the optimum results.
A CAD software (Autodesk Inventor) was applied to create a three-dimensional, parametric model of the analyzed construction. The numerical strength analysis was carried out in the module Strength Analysis of the used CAD software application by means of the finite element method (FEM).

Figure 4: The desk design based on origami principles.

The model is nonlinear in its geometry and it consists of three different materials. All components were allotted with the appropriate material and its properties: physical, mechanical and constants such as density, Young´s modulus of elasticity, Poisson constant, yield points and rupture points in tension were established based on literary sources and standards. The process of ascertaining the size of the affecting force was based on the Czech standard [13], which deals with the methods for the construction stability and mechanical strength establishment. Based on paragraph 5.2 of this standard (vertical loading test), two points where a loading force of 1000 N acts on the construction were selected. The first was the center of a long apron; the second point was a corner of an apron. Analyses of the construction of the desk stand were applied with emphasis on the upper part of the leg. As the leg is made of an open profile, it was expected that it will be most sensitive to loading.
Pictures showing the progress of the measured quantity by means of color spectra present the results of the numerical simulations in a graphical form. The resulting images represent von Mises stress (Fig. 5) and the coefficient of safety (Fig. 6, 7). As the desktop of the final prototype is made from anisotropic-laminated chipboard, which would unnecessarily prolong the calculating time, it was excluded from the simulation. With respect to the

focus of the study on the analysis of the stand and the critical points in the upper part of the leg, an inclusion of a desktop would be inefficient. Therefore, when assessing the results of the analysis, it has to be taken into account that the loading force applied to the desk apron at the given point would be more homogeneously distributed over the entire construction – thanks to the desktop.

According to the analysis, the expected deformations and damage would occur at the points where the upper part of the desk leg is connected to the plate (which ensures the dismantling connection of the desk leg to the apron), specifically at the points of contact between the plate and the edges. Because of the symmetry in the leg geometry and the symmetrical progress of tension in this geometry, the leg was divided by a vertical plane in the axis of symmetry and further only results of one half of the model will be considered. In Fig. 8 we can see the lowest coefficient of safety of 0.41 in bending inside the open profile. This value shows, that the equivalent tension at this point is 504.88 MPa, which is approximately 2.5 times higher than the yield point of steel (Re 207 MPa). According to the numerical analysis, a permanent deformation of the material would appear at this point.

Figure 5: Equivalent tension (von Mises) when the apron is loaded in the corner.

Figure 6: Coefficient of safety when the apron is loaded in the corner.

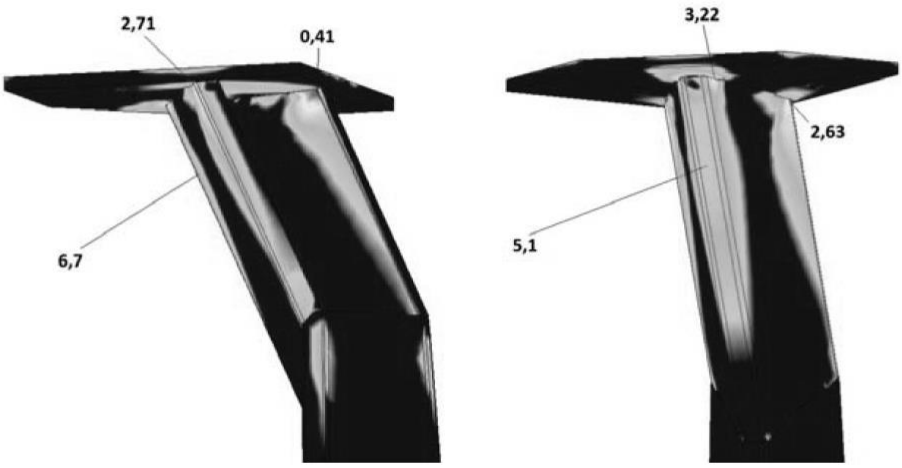

Figure 7: Coefficient of safety – detail of the upper part of desk leg.

3 CONCLUSION

The goal was to present a new concept of furniture design based on the connection of modern technologies, recent R&D advances in the field of furniture industry and parametric design. Parametric design currently represents what most industries are trying to achieve – not only does it save resources, but it also increases competitive strength and stimulates

innovation [14]. In the furniture industry and timber trade, this tendency may be observed mainly in the field of education and innovation. This is due to the fact that one of the specific features of parametric designs is usually innovative design that is not accepted by every customer. And also due to the fact that furniture, unlike other industrial products, does not have such well-developed legislation dealing with the placement of new products on the market, new products struggle to break into the market.
From the applied method point of view, it is possible to say that the DIC is easily applicable to furniture testing due to its relative simplicity and low requirements on employed devices, undemanding data procession and data assessment realized by accredited laboratories or research institutes. Development departments of furniture making companies can apply the methodology to increase their competitiveness and innovation potential. By means of deeper analysis of data it is possible to detect badly dimensioned construction connections or to optimize the construction from the shape or used materials point of view.

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THE QUALITY OF INDOOR AIR IN WOODEN BASED BUILDINGS

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Abstract
This paper focuses on factors which influence the quantitative and qualitative composition of Volatile Organic Compound emissions regarding the indoor air of wood-based buildings. It aims to identify the impact of used wooden based materials on the amount and content of VOC emitted into the indoor air. The experimental part focuses on the assessment of influence of applied wood-based materials in the wood-based buildings with focus on the quantity and quality of VOC emissions in indoor air.

Keywords:
Wooden based buildings, VOCs, TVOC, Quality of indoor air, Gas chromatography

1 INTRODUCTION

Indoor air quality is extremely variable and depends on activities of the people [1, 2, 3, 4 and 5], home furnishings [6], building materials [7] and season [8]. Current research is involved with the constantly rising amount of sources, the complexity of mixtures, and the role of outdoor air [9]. The diversity of compounds, their variable toxicity and the addressed peer group complicate the determination of guidelines for concentrations of volatile organic compounds (VOCs) in indoor environments.

The formation of VOCs in indoor environments is difficult to understand and to reconstruct (e.g. in experiments). On the one hand, compounds originate exclusively from indoor sources (a point of origin of gases or other materials, which appears constantly in a similar way). On the other hand, they are formed by mixtures of indoor and outdoor pollutants. In most cases, indoor VOC concentrations are significantly higher than outdoor levels [9]. This is influenced by the type and age of building materials [7] and personal activities, e.g. renovation processes that cause elevated levels. Increased levels occur directly after renovations and then normalize to lower concentrations [10, 11]. Seasonal variations cause higher indoor levels to accumulate due to abated ventilation in winter [12, 13]. Furthermore, local conditions, such as industry or busy roads, create emission sources that differentiate the pollution amount of homes in industrial, urban, and nonurban regions [14]. This high variety of possible sources in indoor and ambient air poses a big challenge for scientists to assign different compounds to their point of origin.

Building materials are major contributors to indoor emission sources of volatile organic compounds (VOCs). Some VOCs are of particular concern due to their potential health impact on human [15] e.g. formaldehyde and benzene are some of the most studied pollutants since they are classified in Group 1 of human carcinogens by the International Agency for Research on Cancer [16, 17, 14 and 18]. In an INDEX project the existing knowledge worldwide has been assessed in terms of type and levels of chemicals in indoor air, as well as, the available toxicological informatik [19]. It was concluded that VOCs such as benzene, formaldehyde, acetaldehyde, toluene and xylenes have to be considered as priority pollutants with respect to their health effects [19]. Many studies have shown significant VOC sources indoors. For example, the main sources of aldehydes and BTEX indoors may include building materials (BMs), such as hardwood, plywood, laminate floorings, adhesives, paints and varnishes [20, 21, 22, 23, 24, 25 and 26], adhesives and decoration materials. In addition to these primary emissions, numerous past researches also indicated that ozone reactions with BMs result in secondary emissions of aliphatic aldehydes, secondary organic aerosols and other products that are more important [27, 28, 24, 29].

Although Green Building Material (GBM) is intended to have low toxicity and minimal chemical emission, measurement of primary emissions alone may not be sufficient since secondary emissions due to ozone reactions may affect the perceived air quality in the long run demonstrated that natural wood material with low formaldehyde emission after being exposed to ambient ozone produced secondary pollutants, including formaldehyde, acetaldehyde, cyklohexanone and benzaldehyde.

For many of these chemicals, the risk on human health and comfort is almost unknown and difficult to be predicted because of the lack of toxicological data. In the frame of the INDEX project [19] the existing knowledge worldwide has been assessed in terms of type and levels of chemicals in indoor air, as well as, the available toxicological information. It was concluded that VOCs such as benzene, formaldehyde, acetaldehyde, toluene and xylenes have to be considered as priority pollutants with respect to their health effects. On the other hand, chemicals such as limonene and α-pinene require further research with regard to human exposure or dose response and effects.

Combined indoor/outdoor air quality measurements have shown that there exist significant VOC sources indoors. For example the aldehyde concentrations are usually 2-10 times higher than outdoors. It has been pointed out that in renovated or completely new buildings, the VOCs concentration levels are often several orders of magnitude higher. The main sources of aldehydes in homes include building materials, hardwood, plywood, laminate floorings, adhesives, paints and varnishes and in some cases they are products of ozone-initiated reactions. For example, interior coatings can increase indoor air pollution due to VOC emissions. Some of

the major VOCs emitted from an oil-based varnish were ethylbenzene, m,p-Xylene, o-Xylene and formaldehyde.
The contribution of building materials and furnishing to indoor air pollution has been demonstrated by a study of VOC emissions in newly built, unoccupied houses at BRE. The sampling of VOCs in indoor air has shown that the contribution of building material emissions was significant during the first six months.
Although, numerous studies have investigated the levels of indoor air pollutants and emission measurements in laboratories, research on systematic in-field studies, linking the VOC concentrations to their indoor sources is rather limited. So the primary aim of the present work is to characterize the influence of the building materials added into wooden based buildings during their construction on indoor VOC emission.

1.1 Goal of research

The primary aim of the paper is to characterize the emissions of volatile organic compounds (VOC) in the indoor air of wood-based buildings in the Krkonoše Mts. region in relation to:

- Engineering composition of building materials.
- Emissions of pentanal and hexanal.

2 MATERIALS AND METHODS

2.1 Characteristics of the assessed buildings

The quantitative and qualitative structure of VOC emissions in indoor air was measured in free wood-based buildings in the foothills of the Krkonoše Mts., two of which are situated on a ridge at 1000 – 1030 m above sea level and the other in a valley at 476 – 527 m. The monitored detached buildings differ from one another in terms of their age, the material composition of their walls and their use.

Meassured place:
Family house in Horní Maršov
The family house in Horní Maršov was built in 2006 at an altitude of 527 m, close to a forest and with low traffic load. The windows are south-west facing. The house is heated by a solid-fuel stove.

Office in Mladé Buky
A ground floor building in the centre of Mladé Buky was built in 2000 at an altitude of 476 m with a medium traffic load. The entire area of walls is covered by tongue and groove panels. The room has a double-hung euro window with double glazing. The office is heated by an electric storage heater.

Log house in Velké Tippeltovy Boudy

This detached log house dating from the 17th century was built at an altitude of 1030 m on a forest clearing. It is heated by a tiled stove. The floor is made of solid wood boards joined by butt joints.

2.2 Methods of air sampling in the monitored wood-based buildings

The concentration of volatile organic compounds in indoor air is determined using the adsorption method. The air samples are drawn by a pump through a Tenax TA thermal desorption defined flow rate.

- The air samplers were placed in the centre of the rooms, a minimum of 1 m from walls and at the height of 1 – 1.5 m above the floor.
- Concurrently with the indoor air quality measurements, control samples were taken outside the buildings (not less than 1 m and no further than 100 m from the building), at the floor height of the building corresponding to the monitored room[1].

Sampling procedure

1. Airing of the monitored room
2. Placing the pump with a sorbent tube in the room and in the exterior.
   - Launching the VOC emission sampling; the time duration of a single sampling was 3 hours. Upon reaching this limit, the pump was stopped and the steel sampling tube was exchanged.
   - The set time duration of outdoor air sampling was 1 hour.
3. The VOC concentration in the indoor and outdoor air was determined using sampling pump Gilian LFS-113 DC. The air flow rate in the interior was 12 l/h and 6 l/h in the exterior. The sampling of VOC was done using steel tubes filled with Tenax TA.
4. By using a gas chromatograph with a mass spectrometer and a thermal desorption the VOC emission structure was determined along with the amount of individual emitted compounds trapped in the steel sampling tube. The conducted analyses provide qualitative and quantitative data on the concentrations of selected VOC and the total volatile organic compounds (TVOC) in µg.m^{-3}.

[1] **Methodological instructions** for the measurements and determination of chemical, physical and biological indicators of indoor environment quality according to Regulation No. 6/2003 Coll.

3 RESULTS

a) Family house in Horní Maršov

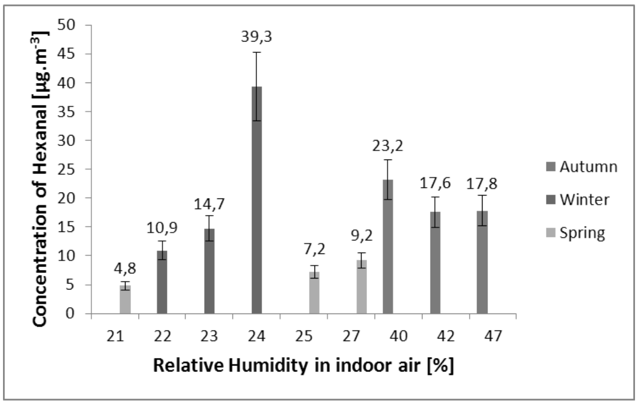

Figure 1: Pentanal fromliving room in family house in Horní Maršov.

Figure 1 shows the influence of relative moisture content on the quality of indoor air, especially of Pentanal emissions in the indoor air of the wooden base building (Horní Maršov) in dependence on a season. The amount of concentration of Pentanal is growing in winter time compared with the other seasons. The highest concentration of Pentanal was found at conditions 24% of relative humidity in winter time, conversely the lowest concentration of the compounds was measured at conditions 21% of relative humidity in spring.

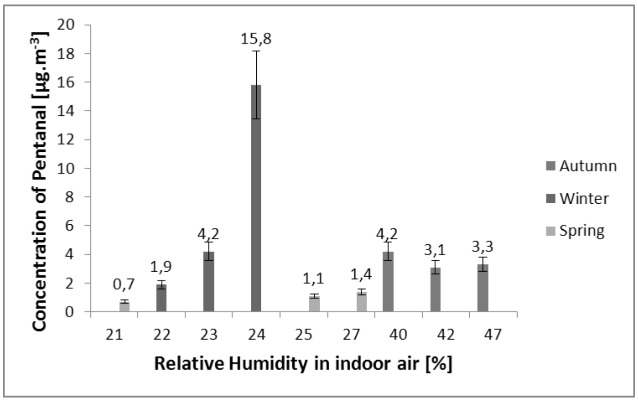

Figure 2: Hexanal from living room in family house in Horní Maršov.

In Figure 2 the influence of the relative moisture content from living room on an amount of emissions of Hexanal in family house in Horní Maršov is shown. The highest concentration of Hexanal was measured at conditions 24% of relative moisture content (39.3 µg.m^{-3}) in winter. An higher amount of Hexanal was found at conditions 40% until 47% of relative humidity in autumn.

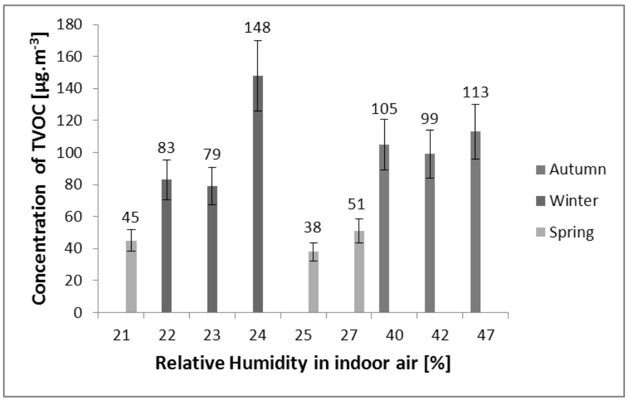

Figure 3: TVOC from living room in family house in Horní Maršov.

Figure 3 presents data of TVOC (Total Volatile Organic Compounds) from the living room in the family house in Horní Maršov. The TVOC parameter describe the total content of Volatile Organic Compounds emitted into indoor air from the living room in wooden base buildings. The amount of TVOC is growing in winter and in autumn compared to the emissions in spring season. The highest amount of TVOC was measured at conditions 24% relative moisture content (148 µg.m^{-3}) in winter.

b) An office in Mladé Buky

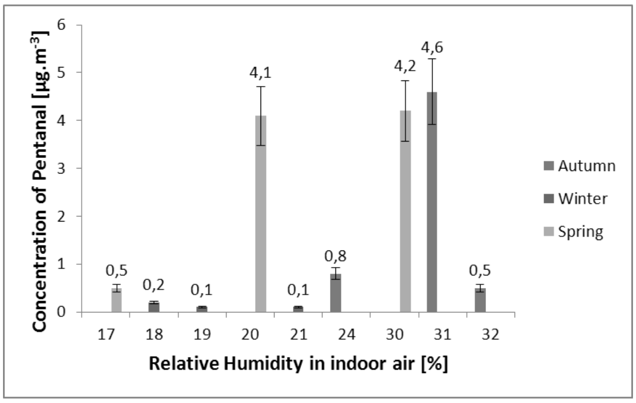

Figure 4: Pentanal from the office in Mladé Buky.

Figure 4 presents the influence of relative moisture content on a quality of indoor air, especially of emissions of Pentanal, from the office in wooden base building (Mladé Buky) in dependence on a season. The highest concentration was measured at conditions 31% of relative moisture content (4.6 $\mu g.m^{-3}$) in autumn, followed by conditions 20% to 30% of relative moisture content (4.1 and 4.2 $\mu g.m^{-3}$) in spring season. The lower concentrations of Pentanal were found in winter time (0.1 until 0.2 $\mu g.m^{-3}$).

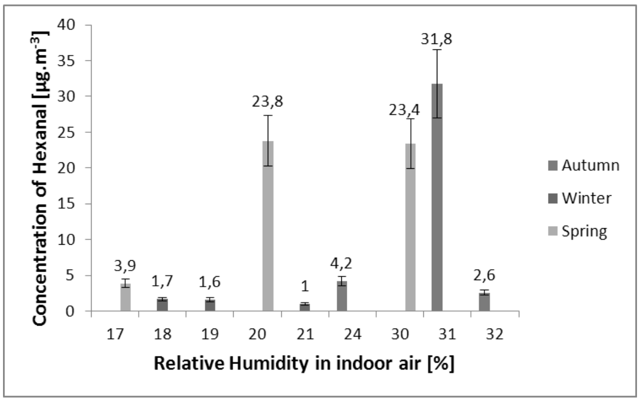

Figure 5: Hexanal from the office in Mladé Buky.

Figure 5 shows the influence of relative moisture content on concentration of Hexanal from the office in wooden base building in Mladé Buky. The highest concentration of Hexanal was measured at conditions 31% of relative moisture content (31.8 µg.m-3) in autumn, followed by values of concentrations in spring season at conditions 20% to 30 % of relative moisture content (23.8 and 23.4 µg.m-3).

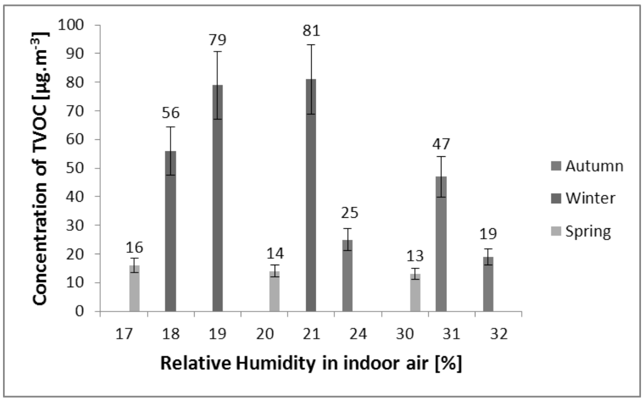

Figure 6: TVOC from the office in Mladé Buky.

Figure 6 shows the influence of relative humidity on an amount of parameter TVOC emitted by indoor air from office in wooden base building in Mladé Buky. The highest values of TVOC were measured at conditions about 20% in winter, followed by values of concentrations TVOC, which were detected in the autumn. The lower concentrations of parameter TVOC were found during spring season.

c) Log house Velké Tippeltovy Boudy

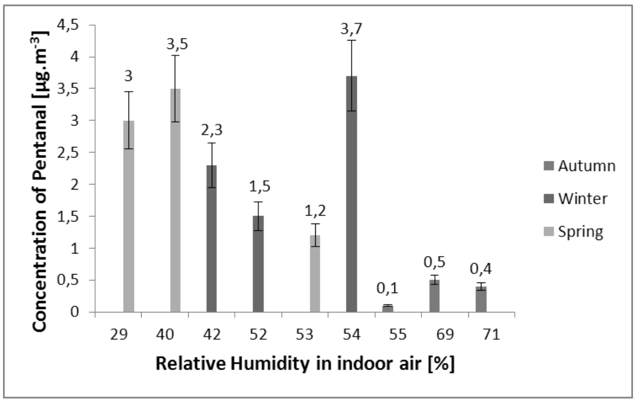

Figure 7: Pentanal from the room, log house Vellké Tippeltovy Boudy.

In Figure 7 the influence of relative humidity from the room on the quality of inddor air, especially the concentration of Pentanal in the wooden base building in Velké Tippeltovy Boudy is presented. The highest concentration of Pentanal was measured at conditions 54% of relative moisture content in winter time (3.7 µg.m^{-3}), followed values of concentration of these components that were measured in spring.

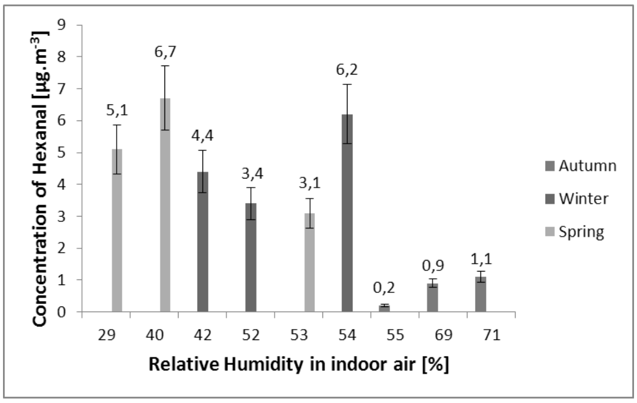

Figure 8*:* Hexanal from the room in log house Vellké Tippeltovy Boudy.

Figure 8 shows the influence of relative moisture content from the room on concentration of Hexanal in the wooden base building. The highest concentration of Hexanal was measured at conditions 40% of relative moisture content in spring season and followed by the measured value at a condition of 54% of relative moisture content during winter time. The lower values of Hexanal concentration were found in autumn.

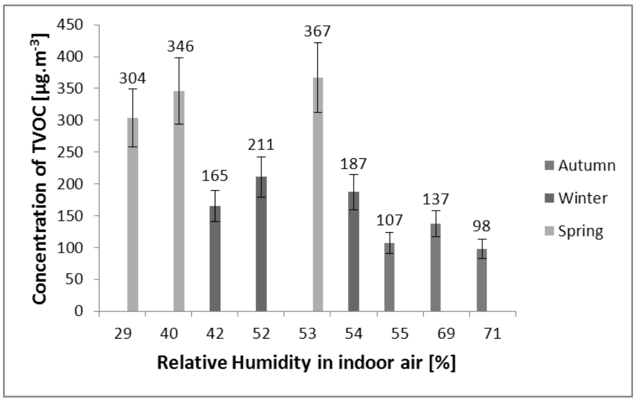

Figure 9*:* TVOC from the room in log house Vellké Tippeltovy Boudy.

Figure 9 presents data of parameter TVOC, emitted by indoor air from the room in the wood based building in Velké Tippeltovy Boudy. The parameter of TVOC describes the total content of Volatile Organic Compounds emitted to indoor air by the room in the wood based building. The amount of TVOC is rising in spring season and winter time compared to autumn. The highest amount of TVOC was measured at 53% humidity in spring (367 $\mu g.m^{-3}$).

4 DISCUSSION

Based on the results listed in this paper we can assess the indoor air quality in individual wood-based buildings.

4.1 Family house in Horní Maršov

Results of VOC emission measurements are shown in Fig. 5 - 6 which show the impact of relative air humidity on the amount of emitted volatile organic compounds, particularly aldehydes – namely Pentanal and Hexanal, over the period of three seasons of the year. The presented results reveal a dependence of the emitted Pentanal and Hexanal concentrations on relative air humidity in winter and spring. The concentration of emitted compounds

decreases with decreasing humidity. The highest concentration was measured in winter, which is related to the onset of heating season.
The measured data reveal a minimum impact of relative air humidity on the concentration of BTEX. Concentration of the said VOC was very low, which means that their amount was below the level of quantification (LOQ).
Owing to the fact that the assessed buildings were wood-based, the monitored substances included terpenoid compounds as accompanying characteristic wood product emissions from the perspective of wood-based building interior emission load. However, only the concentration of emitted 3-D-Limonen was dependent on relative air humidity in all the three monitored seasons. As an exception, the concentration of emitted Limonen increased during the last measurement in winter. This increase can be accounted for the use of an air freshener and detergents.
The values of the so-called total volatile organic compounds (TVOC) are among the key monitored parameters. TVOC represent the total amount of VOC emitted in the indoor air of the assessed wood-based building. Figure 7 demonstrates the impact of relative air humidity on the total amount of emitted VOC in relation to the season. Based on the presented results, the dependence of TVOC concentration on relative air humidity cannot be determined. The highest TVOC value, 192 µg/m^3, which borders on the recommended maximum limit of 200 µg/m^3, was measured in winter.

4.2 An office in Mladé Buky

The highest Pentanal and Hexanal concentrations in the indoor air of this building were measured in autumn. The obtained data did not reveal any dependence of the said concentrations on relative air humidity.
Based on the conducted measurements of indoor air quality of this wood-based building it can be stated that concentrations of the monitored aromatic VOC compounds (Benzene, Toluene, Ethylbenzene and Xylenes) are dependent on relative air humidity, as was demonstrated in measurements conducted in winter and spring. With decreasing relative humidity the concentrations of emitted compounds decrease as well. Only the measurement conducted in autumn revealed a sharp rise in concentrations of the said compounds. This phenomenon might have been strongly affected by heating in the monitored building (onset of the heating season).
The obtained measurement data also reveal a dependence of monitored terpenes, or terpenoid compounds, on relative air humidity, particularly in measurements conducted in winter and spring. A similar trend as that in aromatic compounds can thus be observed, upon which concentrations of emitted compounds decrease with decreasing relative air humidity. Autumn is an exception again, as concentrations of the monitored substances increase sharply. This rise may be accounted for by the onset of the heating season.
The total amount of emitted VOC in the indoor air of the monitored wood-based building, or the TVOC parameter, is dependent on relative air

humidity particularly in winter, which is illustrated by the fact the decreasing relative humidity is accompanied by decreasing TVOC concentrations.

4.3 Log house in Velké Tippeltovy Boudy

Based on the conducted measurements of indoor air quality of this wood-based building it can be stated that dependence of concentrations of the monitored aldehyde emissions (Pentanal and Hexanal) on relative air humidity in winter and spring was not established. On the other hand, the dependence was established in autumn measurements.

Based on the measured data it can also be observed that dependence of concentrations of the monitored aromatic compound emissions (Benzene, Toluene, Ethylbenzene and Xylenes) on relative air humidity was established. This phenomenon is apparent particularly in measurements conducted in autumn and spring. Measurements conducted in winter did not prove such dependence.

With respect to total emission load, or the TVOC parameter, dependence of TVOC concentration on relative air humidity was not established in the results obtained, particularly in autumn and winter measurements. However, it needs to be stressed that the TVOC values measured in winter range from 215 to 274[2] µg/m^3, i.e. they exceed the recommended limit of 200 µg/m^3.

It can also be observed that in spring measurements dependence of TVOC concentration on relative air humidity was established. However, the measured high TVOC concentrations need to be taken into account. In spring the TVOC values ranged from 394 to 481 µg/m^3, which exceeds the recommended limit twice. Heating of the building by a tile stove can probably be accounted for this fact.

5 CONCLUSIONS

The primary aim of this paper was to determine the impact of relative humidity of indoor air in wood-based buildings on the quality of their internal environment. Based on the obtained measurement results it can be stated that concentrations of VOC emissions in the indoor air of wood-based buildings in the Krkonoše Mts. region are influenced not only by air humidity and the given season but by other factors as well, including the age of the building, material composition of walls, furnishings and type of heating.

Based on the results obtained in the experimental part of this paper we can conclude the following:

1. The highest concentrations of monitored VOC were measured in the log house Velké Tippeltovy Boudy. This is probably due to the fact that a tile stove is situated directly in the monitored room. Heating releases waste gasses and consequently increases temperature in the monitored room,

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[2] the TVOC value is given including measurement uncertainty

which results in releasing of a higher amount of VOC (or higher VOC concentrations). The conducted measurements did not validate the commonly published assertion that the higher the age of a building, the lower concentrations of emitted harmful substances. The highest values of the TVOC parameter were measured in a building which is over 200 years old.

2. Results of the experimental part reveal that relative air humidity affects the VOC concentrations as well as the TVOC values. The dependence of VOC emissions on relative air humidity was established in almost all the selected representatives of volatile organic compounds.

ACKNOWLEDGEMENTS

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SESSION F
Wood Processing Technologies and Furniture Production 3

IT-INTEGRATION AND MACHINE CONCEPTS FOR COMPLEX PROCESS CHAINS – FOCUS: PROFILE WRAPPING

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Abstract
The integration of information technology (IT) into production has been carried out for many years by universities, research institutes and companies – in cooperation as well as individually. However, the objective target was and still is to automatize production processes and to achieve a better quality, to simplify the machine operation and to increase the efficiency. The difficulties to automatize production processes increase with the complexity of the process and its interaction with previous and subsequent processes in a production chain. Production chains are the universal part of industry, as almost all products need more than one process step to be produced. The process chain of profiling in the wood working industry has high interdependencies among the processes. The result of one process in the chain is the input for the subsequent one and this process has to be adapted to the characteristics of the product in this production stage. Also the processes themselves are characterized by a high complexity which has so far – in general – led to a small integration of IT in the process chain. The process design and setup is done manually, based on the experience of the operator. Especially the profile wrapping in this chain is a complex process with a difficult process design and setup. The manual setup of the pressure rollers for a certain profile can last up to several hours and requires skilled operators. To solve these problems and to integrate IT into the process chain of profiling, an advanced CAD/CAM system has been developed at Ostwestfalen-Lippe University of Applied Sciences. The system is able to generate the correct process data for the individual processes in the chain. The Düspohl Maschinenbau GmbH developed a special profile wrapping machine using robots to carry out the machine setup and to position the pressure rollers as well as an advanced CAD/CAM system to control the machine. Both developments show in detail a methodology to integrate IT into a production chain with complex processes. The result is a high degree of automatization and an increased efficiency in the processes.

Keywords:
Profile wrapping, CAD/CAM, IT-Integration, Complex process chains, Industry 4.0

1 INTRODUCTION

Profile wrapping is defined as a manufacturing method in which a coating material, with the aid of a hot melt adhesive or of a related liquid adhesive, is jointed, using pressure elements, in a continuous process with a profiled workpiece material in part or over the entire circumference [1]. A schematic illustration of the profile wrapping process together with profile geometries and products respectively is shown in Fig. 1.

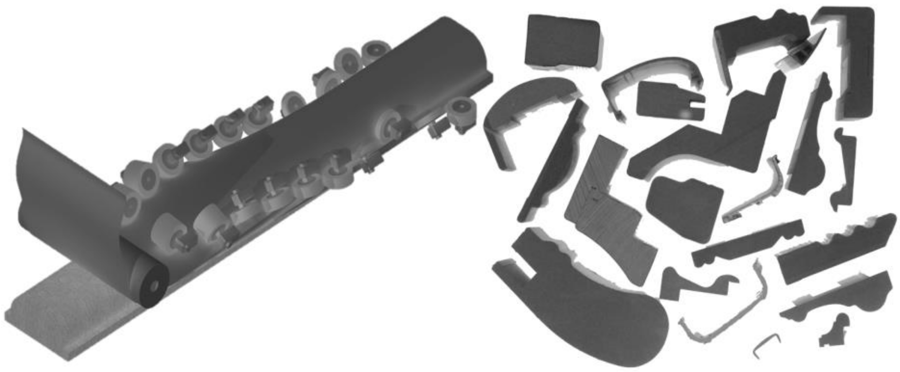

Figure 1: Profile wrapping process and typical products.

The workpiece material ranges from wood and wood based materials to plastic and aluminium. The coating material ranges from veneer, paper and plastic foils to laminates and aluminium. Different kinds of adhesives are used depending on the workpiece/coating material combination and on the requirements, which are related to the purpose and use of the product. In general, physical-setting hot melts are applied. With higher requirements on the bonding strength and on the durability of the joint, also “reactive” (chemical-setting) hot melts are used. Already the applied adhesive system creates difficulties for the process design and setup in terms of processing temperatures, pressure element configuration etc. [2]

However, the profile geometry has a major impact on the process design and setup in terms of the number, shape and position of the pressure elements, which leads to difficult and long-term setup process in a manual operation [3].

To automatize this process and especially the process setup, it is essential to analyse the input profile geometry for this process by means of a CAD/CAM system and to generate automatically the process design and the connected data for the setup [4]. It is therefore important to analyse the real input geometry, which is not similar to the target geometry, for example of the customer order. Because of the interdependencies in the process chain, previous processes of the profile wrapping corrupt the profile geometry due to the individual systematic and stochastic errors of these processes. For this reason, the entire process chain must be taken into consideration for a successful integration of IT.

2 PROCESS CHAIN OF PROFILING

The production chain for profiled products consists of many different processes in different sequences. In the woodworking sector, a basic chain includes a profile milling and a profile wrapping process. This – a chain with one shaping and one coating process – is comparable to the coated PVC window profile production with an extruder and with a profile wrapping machine. However, the configuration might also include sanding and additional milling and coating operations as shown in Figure 2. [5]

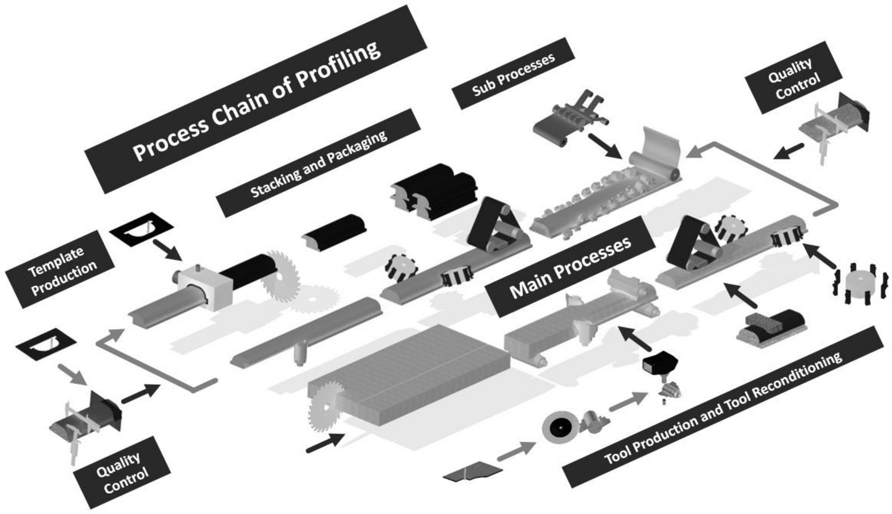

Figure 2: Sample configuration of a process chain for profiled products.

Already with one shaping and coating process, many different influences might change the profile geometry since not only the main processes but also sub processes have an impact on the geometry corruption (see Fig. 2). For example, the resulting geometry of a milling process depends not only on the capability of the milling machine (e.g. position accuracy, vibrations behaviour), but also on the capability of the machine and process for the tool production. Any systematic and stochastic error of a sub process is inherited to the main process and from there to the subsequent processes and in this way along the whole process chain.

One basis for the integration of IT into this process chain is the computation of the real profile geometry in each production step so that CAD/CAM systems for the individual processes get correct input values for the process data generation. Therefore the geometry corruption of the individual sub and main processes have been analysed and a methodology has been developed to consider the systematic and stochastic errors (Fig. 3).

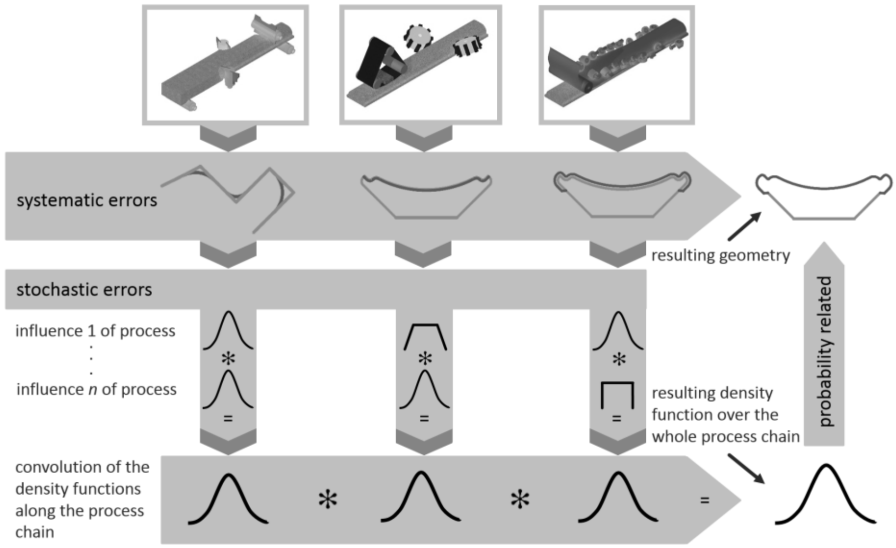

Figure 3: Methodology for consideration of systematic and stochastic errors.

In this methodology, the systematic errors are represented by means of parametrical mathematical rules according to analytical and empirical investigations of the processes. For example, a tool grinding process creates round internal corners with the radius of the grinding wheel on the cutter knife and inherits this to the corresponding external corners on the workpiece.

The key factor for considering the stochastic errors (e.g. the manufacturing tolerances and the process capability respectively) is to consider the whole probability density function of the real stochastic behaviour of the specific part of the process. With this methodology, the individual influences of the

profile geometry are considered and combined by means of statistical methods [6]. By convoluting the correlating density functions, the influences of a single process step or of the whole process chain are merged together and the result is a probability related resulting profile geometry (see Fig. 3.).
This methodology represents a system of quality models for the processes of the chain and enables the integration of IT and simulations engineering, since it is possible to calculate the output of a process and to provide this resulting profile geometry for the process data generation of the subsequent process before the real production.
With a similar approach as the presented methodology of the system of quality models, the processes of the chain have been analysed and different process models for the process data generation have been developed or already existing model form literature have been adapted to build the basis for networked CAD/CAM systems [4]. A System for the profile wrapping is presented in the following chapter 3.

3 PROFILE WRAPPING

The major task in the process design and setup of a profile wrapping process is the setting of the number, shape and position of the pressure rollers. This depends on the shape of the profile geometry and has been analysed in detail by Strauß [1] and Horstmann [2]. Figure 4 shows the correlation between the profile geometry and the number of pressure roller, used for the setup of the pictured profiles.

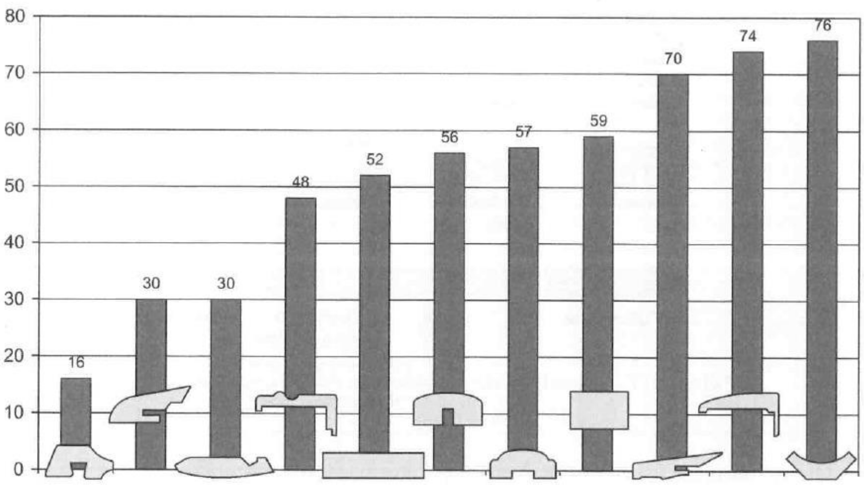

Figure 4: Number of pressure rollers for different profiles [2].

The setup procedure for a profile with a maximum number of pressure rollers (see Fig. 4) can last up to several hours. Thus, the automatization of the setup procedure holds a great rationalization potential. In the first step, the whole process of profile wrapping has been analysed at Ostwestfalen-Lippe University of Applied Sciences and at TU Braunschweig. A CAD/CAM system, i.a. based on parametric rules, to generate the process design and setup data [2] and an external setup station for the pressure rollers to enable SMED (Single Minute Exchange of Die) and to automatize the setup procedure [1] have been developed.
However, the Düspohl Maschinenbau GmbH have developed in the next step a new profile wrapping machine, based on their developed and patented machine concept [7] [8]. The whole setup procedure in this machine (Type “Düspohl RoborWrap”) is carried out with robots. In detail, the robots are able to execute the following setup tasks:

- Positioning of the robot on a linear axis along the feed direction.
- Positioning of transport wheels on each driving axis
- Automatic take-up of pressure rollers from a tool changer.
- Positioning of the pressure rollers in individual positions.
- Individual pressure regulation for each pressure roller.

The number of robots depends on the product range, on the required number of pressure rollers (see Fig. 4) and on the required degree of automatization. A set profile wrapping machine with robots is presented in Figure 5. [9]

Figure 5: Automatically set profile-wrapping machine “RoboWrap” [9].

To control the machine an advanced CAD/CAM and a machine control system have been developed. The input data for this system is the profile geometry in this production step (Section 2).
In the first step of the operation, the alignment of the profile in the machine and the position of the transport rollers is set. In the next step the correct shape, the position and the pressure of the rollers are calculated. A basis for this operation is a database with the available pressure rollers in the tool changers of the machine with the real geometry and diameter data of the rollers. Therefore a laser measuring device is integrated in the tool changer and determines geometry and diameter of each roller before or after a wrapping process. This avoids systemic errors due to tolerances in the shaping process of the rollers and the wear of the rollers in wrapping process.
With this presented machine and concept for the profile wrapping it is possible to cut down the time for the setup procedure to only a couple of minutes. [9]

4 CONCLUSION

The presented, realized concept of a new kind of profile wrapping machine shows in detail the successful integration of IT and modern technologies in a – so far – manual operating process with a difficult setup. However, to enable the full potential of IT, it is necessary to involve all processes of the production chain. Only with considering all processes and their systematic and stochastic impacts on the profile geometry during the production, it is possible to generate correct process date and benefit form simultaneous engineering. Networked process and quality models for the individual processes are the basis to build an advanced IT system for the process data generation.

ACKNOWLEDGMENTS
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SURFACE QUALITY INSPECTION

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Abstract
Quality plays a vital role for satisfying the customers and for measuring the reliability of the product. Looking at high gloss surfaces gives an idea of the difficulties in quality inspection. While common measurement techniques like gloss or color measurement are widely used in industry for quality assessment of furniture high gloss surfaces, they indicate only a weak correlation to the quality perceived by the customer.
Thus different methods for measurement and sensory evaluation need to be qualified for the application on high gloss surfaces. This report shows how the surface quality of high gloss coated wooden products can be evaluated by means of visual inspection. The evaluation quality is controlled by a developed topography based measuring system. It is possible to find out the reproducibility and repeatability of the operators by implementing six sigma tools such as Analysis of Variance (ANOVA) and Measurement System Analysis (MSA). This method will be highly helpful in the wooden industries since the quality cannot be totally measured. It is assessed based on required parameter and it also uses a Hedonic scale for calculating the results, which are quite simpler and faster compared to other methods.

Keywords:
Sensory quality assessment, ANOVA, Repeatability, Reproducibility

1 INTRODUCTION

Since industrial produced furniture entered ordinary living with a more or less uniform look, the importance of surfaces rises. Decorative surfaces became an essential connection, like the first impression between customers and objects [1]. The perceived quality, depending on the visual and haptic appearance, is assigned as a basic and performance feature by Kano. This quality has to meet the expectations of the customers. At this point mistakes are hardly ever forgiven by the customer, postulated by Buck and Obst.
Coating processes are in general time and cost consuming and cannot be reduced to lacquer costs. Instead, holistic solutions are necessary by looking at the whole process chain and the associated costs. Calculating costs per square meter, which include applying efficiency, is suitable [2]. Additionally, product costs as well as mistakes are cumulated over the

whole value-chain. Therefor the occurrence of process anomalies has to be avoided in order to minimize the reparation costs, leading to a highly effective process. [3]
To obtain the effectivity in terms of process management, a controlled production process is required [4]. This implies a wide knowledge of all process inputs, like machine parameters, process values and incoming preprocessed products, respectively product qualities. It is also necessary to gauge their influence as well as interactions, which is the basis to build up a quality control loop. Beside machine settings and production conditions already existing surface attributes need to be fixed into quality thresholds. [5] give an overview of the different steps of coating processes and their interdependence. With the five-step model of Kleinesorg in [4] they pointed out that the reproducibility and repeatability of the quality control at each production step are very important.
Common measuring systems in wooden industry range from single manual devices up to fully automated "inline" quality control systems. By the means of high-tech cameras, image analysis and pattern recognition systems only flat, uniform colored surfaces or those with a well-known pattern can be controlled. For this purpose actual product data concerning color, gloss, image pattern and marks are deposited with included variance ranges of each attribute, and especially exact defined thresholds. High gloss surfaces are uncommon in large mass productions, which are represented by that part of inline quality control [6].
Offline quality control is done with the use of handheld units. Concerning the appearance of high gloss surfaces focus remains on color and gloss. These detections work very precise with high repeatability and reproducibility. But more evident documentations or tradeable agreements about distances of single deviations in CIELab are missing, as Prill explained. With the regard to visual color perception of customers in CIELab, distances between color differences result in unequal color impressions, which are not respected by ΔE-value [7]. The same applies to gloss measurements, which are divided into two visual principles. Pointer et.al. describe that some observers tend to judge gloss with the reference to the total amount of light reflected from surfaces, while others judge gloss according to the sharpness of images in lacquered surfaces. It is found, that visually scaled samples do not correlate with measured gloss data. The authors pointed out that a cubic function better fits and explains the strong relations between visual scaled and measured reflection of haze at samples. [8]
The identification of errors or a unique topographic element currently is done by visual inspection. Otherwise extensive surface structures can be analyzed line-by-line [9]. Based on grey scaled Histograms and Fast-Fourier Transformation deviations at light-dark transition of a projected pattern can be evaluated. Previous researches of [10, 11] have shown that based on deflectometry, which works with a grey scaled projection, quite good correlations to visual inspections of topography were achieved. In this case without an allocation of a specific topographic character.

All measuring systems work very precisely, but either without a correlation to visual perception or without an allocation of attributes. To obtain a controlled coating process inspections close to customer's perceptions are necessary. Besides this, a functional assessor panel should be the basis for measurement improvement. That is why repeatability and reproducibility of sensory quality assessment is discussed in this paper.

2 MATERIAL AND METHODS

2.1 Sample preparation

The samples were prepared at one production area as a lot size of twenty pieces and with a dimension of 500 mm by 500 mm. Afterwards they were cut into four pieces, each with a size of 250 mm by 250 mm. All the samples did extremely look alike since the assessors will be visualizing material from different angles or under test conditions. It is highly impossible to check whether the material is good or bad by naked eye.

This selection of materials is done using OPTIMAP measurement device for evaluating surface quality, which is quite largely used in automotive industry for inspecting the bodies. It is provided with the software ONDULO which gives a clear idea if the surface has a crack or some other flaws. ONDULO shows the range for each and every sample, thus giving a perspective how much a material is affected. The test figured out five samples which have variants from very good to very bad only according to lacquer shrinking.

Essential appearance characteristics of high gloss surfaces

Herzberg et al. show that buying decisions of customers correlate with geometric-topographic attributes [12]. Further Hunter charted the effect on color and gloss due to the size of topographic appearance.

The guideline VDI 3414-1 collected and clustered all-known attributes into the four categories geometric-topographical attributes, structural characters, optical attributes and chemical physical attributes [13]. Within them, single characteristics are divided into regular and irregular occurrence. In case of lacquer shrinking a regular occurrence over the time is expected. Because of this, accurately defined as well as precisely described characteristics of these attributes are necessary in order to build a quality control loop. In opposite to real errors, which are irregular attributes like scratches and can be evaluated analog to DIN EN ISO 4628-1 in quantity and size of errors, regular attributes need a scaling or ranking [14]. Usually common measuring systems cannot rank or scale that easily without complex self-teaching tools or because of unspecific thresholds. That is why the focus of this analysis is related, according to the guideline VDI 3414-1, to the category of geometric-topographical attributes [13], which includes attributes like waviness or roughness. For this experiment it is especially fixed with lacquer shrinking.

2.2 Measuring device

A number of technologies for direct or indirect measuring of surface topography are available, but due to the special properties of high gloss surfaces some techniques are difficult to apply. In test measurements the Phase Stepped Deflectometry was identified as a suitable technology for capturing the topography of furniture high gloss surfaces. A LCD display projects a periodic grid on the reflective surface and a camera sensor captures the reflection of the projected pattern. Each source point is reflected in a certain position of the surface and will appear at a corresponding pixel of the sensor. Every distortion of the ideal surface will lead to a variation of the ray path and results in a displacement of the point´s position on the sensor. Based on this position the perpendicular to the real surface can be calculated in each point and thus the slope of the surface in this point is detected [15]. To get a complete image of the surface a phase of the pattern is shifted, which will move the reflection of the source point to a new point on the surface and the calculation is repeated. This measurement is repeated with a pattern in x- and y direction and results in a matrix containing the complete data of surface slope. By applying mathematic operation like differentiating and integrating on this data, also the curvature and the three-dimensional topography of the surface can be calculated [10]. This three-dimensional data is saved in a 3D matrix and used for further processing.
Based on the two-dimensional *Motif* [16] morphologic properties like areal expanse, form, height or slope can be used to determine the different characteristics and their intensity. To receive a comprehensive image analogue to the *Motif*, a value was created that considers the ratio of the height of a hill to its areal expanse. The value is calculated from the three-dimensional surface data by first applying an areal robust Gaussian filter. In a next step local maxima and their surrounding valleys are identified. These valleys are used to define the projected base area of the hill. The difference between the mean z-value of the valleys and the z-value of the maximum allows to calculate the height of the single hill. The ratio of hill height to area is used for evaluating the surface quality and also for comparison to the assessor's evaluation.

2.3 Operators

The assessors were recruited among the students of the master study program “Production Engineering and Management”. Eight students, four male and four female, with a similar age between twenty-five and thirty years and a normal good acuity were found. Their previous knowledge concerning production flows and quality control are advanced. According to the at hand kind of sensory tests and surface quality of high gloss surfaces, all students have more or less basic information. All operators were instructed about the research aim, test procedure, dos and don'ts while testing and the attribute itself. For a deep understanding of this attribute and the specific characteristics, the operators were trained. They studied the range of characteristic occurrence as well as the initial status.

2.4 Experimental design

Operators

Before an operator was authorized to participate in the experiments, all training tests had to be passed as a kind of operator quality control, which means a defined setting by hypothesis test of sequential analysis of Wald [17].

In detail:

- H_0 = an operator is suitable, if more than 90% of tests are passed. (p_0 = 0.1)
- H_1 = an operator is not suitable, if more than 40% of tests failed. (p_1 = 0.4)
- Type I error = 0.02
- Type II error = 0.03

The training was done by the use of triangle test with samples of the same part family, described above [18].

One difficult task of this visual inspection of surface quality is that the set vision depends on the person´s daily mood. Thus to check the repeatability of the operator and also whether the results can be considered, the person fills in a daily form, which will help an organization to sort out this kind of issues. The daily form is determined by two scalable questions about the self-perceived fitness to perform the tests and about an event that emotionally affected the assessor. Extreme results for this value lead to a rejection of that day´s tests. The second process before experiment is a concentration test. This test allows to check whether an operator is highly concentrating on the work or not. An interesting fact about this test is that operators will be highly engaged because it will be like a fun game. This plays a vital role in evaluating the operator and his or her reliability.

Test methods

The total experimental set up and test conditions are prepared strictly to the settings in [19]. Light with a pattern of black and white stripes hits the sample from the top with the help of a desktop monitor. Once it is done the operators are given five different samples, in this case (702, 416, 381, 263, 252) and asked to evaluate these, based on the ranking first. Then they are allowed to add the values to the form provided (Table 1). Further the operators were asked to give a feedback for each sample. This is given in order to understand their reason for decision and to ensure whether it can be altered in order to make a sample better. In this experiment three trials were carried out with eight operators each. The test design in combination with the following statistical analysis was evolved in analogy to [20, 21, 22, 23 and 24].

Table 1: Hedonic scale and feedback form.

Ranks	Points	Satisfaction	Samples
	9	*Like Extremely*	
	8	*Like Very much*	
	7	*Like Moderately*	
	6	*Like Slightly*	
	5	*Neither Like nor Dislike*	
	4	*Dislike Slightly*	
	3	*Dislike Moderately*	
	2	*Dislike Very much*	
	1	*Dislike Extremely*	

Statistic analysis

Basic statistics as mean and standard deviation were used for a first undistorted impression of measured and evaluated results. In context of global measurement analysis concerning the ability, a deeper knowledge is essential. Especially in case of unknown interactions, which have to be taken into account for sensory quality assessment, further statistical analysis are useful. The Range & Average Method computes the Total Measurement System Variability, and allows the Total Measurement System Variability to be separated into repeatability, reproducibility, and part variation. ANOVA method is highly recommended for finding out repeatability and reproducibility values because of its accuracy and more precise value [20, 25]. Effects on product, operators or their interactions can be observed as well as conclusions can be drawn to errors [25, 26].

The formulas used for evaluating the table are listed below [22, 26].

$$\mathrm{SSA} = \sum_{i=1}^{a} \frac{(Yi)^2}{bn} - \frac{Y^2}{N} \tag{1}$$

$$\mathrm{SSB} = \sum_{j=1}^{b} \frac{(Yj)^2}{an} - \frac{Y^2}{N} \tag{2}$$

$$\mathrm{SSAB} = \sum_{i=1}^{a} \sum_{j=1}^{b} \frac{(Yij)^2}{n} - \frac{Y^2}{N} - SSA - SSB \tag{3}$$

$$\mathrm{TSS} = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} \frac{(Yijk)^2}{1} - \frac{Y^2}{N} \tag{4}$$

$$\mathrm{SSE} = \mathrm{TSS} - \mathrm{SSA} - \mathrm{SSB} - \mathrm{SSAB} \tag{5}$$

a=number of appraisers $\quad$ b=number of parts

n=number of trials $\quad$ N=total number of readings

$$\text{Repeatability RPT} = 5.15\sqrt{MSE} \tag{6}$$

$$\text{Reproducibility RPD} = 5.15\sqrt{\frac{MSA-MSAB}{bn}} \tag{7}$$

$$\text{Interaction between appraisers I} = 5.15\sqrt{\frac{MSAB-MSE}{n}} \tag{8}$$

$$\text{R}\ \&\ R = \sqrt{RPT^2 + RPD^2 + I^2} \tag{9}$$

$$\text{Part variation VP} = 5.15\sqrt{\frac{MSB-MSAB}{an}} \tag{10}$$

$$\text{R}\ \&\ R = \sqrt{R\&R^2 + VP^2} \tag{11}$$

Table 2: Two way ANOVA table.

Source of Variation	*Sum of Squares*	*Degree of Freedom*	*Mean Square*	*F Statistic*
Appraiser	*SSA*	*a-1*	$MSA = \frac{SSA}{a-1}$	$F = \frac{MSA}{MSE}$
Parts	*SSB*	*b-1*	$MSB = \frac{SSB}{b-1}$	$F = \frac{MSB}{MSE}$
Interaction (Appraiser, Parts)	*SSAB*	*(a-1)(b-1)*	$MSAB = \frac{SSAB}{(a-1)(b-1)}$	$F = \frac{MSAB}{MSE}$
Gage (Error)	*SSE*	*ab(n-1)*	$MSE = \frac{SSE}{ab(n-1)}$	
Total	*TSS*	*N-1*		

3 RESULTS AND DISCUSSION

3.1 Measuring results

Because of the large measuring area of the described measuring device, captured information comprise almost the total sample area, when measuring four times.

A small ratio of hill height/area represents a smooth surface. The surface appearance becomes more homogenous with decreasing standard deviation of this value. The results of the five samples show a moderate increase of the mean of this ratio, which over all samples has a range from 0.036 to 0.046 [mm/mm²], shown as circles in Figure 1. Thus, a ranking in analogy to the order in Fig.1 is identified. Two standard deviations stand out among the results of the ratio: The sample 416 has the highest ratio and a standard deviation of 0.001, which is by far the the smalles. The sample 252 has the second to last ranking and the highest standard deviation of 0.004.

The second value examined is the mean of peak to peak distance, which implies a smoother surface with an increasing number. The mean values of the results are presented by rhombs in Figure 1. The largest distance is found for 263. The sample ranked second (381) has a similar mean value but with the smallest standard deviation. Based on the peak to peak distance, the sample 252 is again ranked second to last, while at the same time it shows the highest standard deviation. The shortest peak to peak distance is detected for the sample 416. Concerning the value ratio hill height/area the sample 252 has an insignificant better mean value than 263. Because of the large standard deviation and the smaller mean of the peak to peak distance, the sample 252 was ranked second to last.

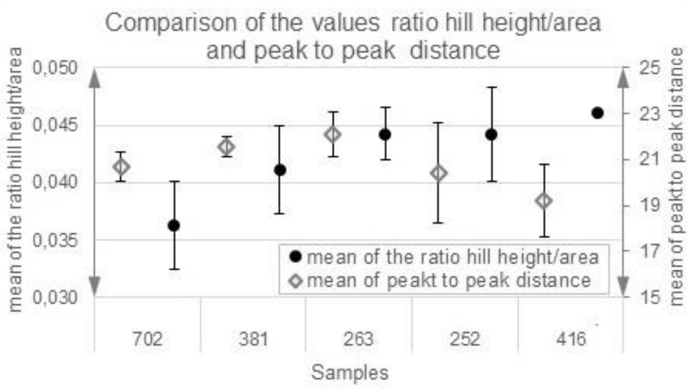

Figure 1: Comparison of the measuring results of the two values ratio hill height/area and peak to peak distance.

3.2 Sensory test

First of all, it has to be mentioned that the ranking differed within one single sample from the measurement results. The new rank of the sample 416 is assigned as the second best rank.
Figure 2 shows that sample 702 is significantly evaluated on the first rank. Compared to the others this is ensured as the best sample.
Ranks two and three have the same calculated median. But beside this, the results of sample 416 are more scattered in comparison to 381, which were evaluated highly consistent. It is found that no operator rated this sample below five. Furthermore, the boxplot in figure 2 shows that the rating of sample 416 varies from worst to best score. Also the mean value indicates whether it can be accepted or not (cf. table 3).

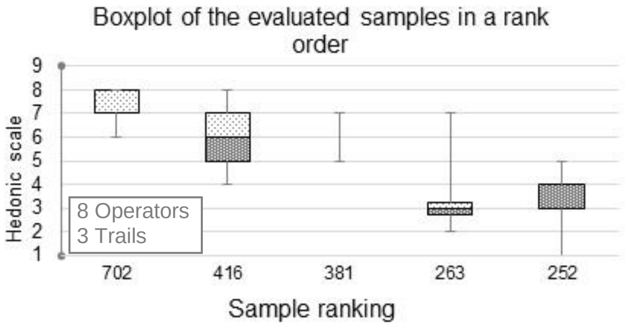

Figure 2: Characterization of the response behavior of the operators organized in a boxplot and a rank order.

Table 3: Mean and standard deviations of the evaluated results.

Sample	*Mean*	*Standard deviation*
702	7.208	0.721
416	5.916	1.412
381	5.875	0.537
263	3.208	1.215
252	3.541	1.021

Considering the measured results of the samples 263 and 252 the wide-spread evaluation results are expectable. More unvarying results are found for sample 263, located ranks range up to seven. Sample 252 is evaluated down to one. Including the mean and the standard deviation regarding these two sample, the differences in evaluation between these samples are slightly more obvious, table 3.

3.3 ANOVA

Table 4 shows the summarized report of all values and degrees of freedom, which are explained by their formula 1 - 5 above. With an Fc-value (α=0.01) no significant difference within the operators is found [27]. But very high significant differences between the samples were detected by the operators. In addition to that, table 5 presents the results of ANOVA. The values regarding reproducibility and interaction were neglected or such less that they produce zero. For this reason, the R&R value is equal to the value repeatability and it is seen that part variation is dominant.

Table 4: Summarized report of ANOVA.

Source	*Sum of means*	*DOF*	*Mean square/DOF*	*F*	*Fc (α=0.01)*
Appraisers	9.03333333	7	1.29047619	2.49769585	2.87
Parts	280.966667	4	70.2416667	135.951613	3.56
Interaction	71.9666667	28	2.5702381	4.97465438	1.976
Gage	41.3333333	80	0.51666667		
Total	403.3	119			

Table 5: Results of ANOVA.

Repeatability	3.70179574	*Part Variation*	8.64777299
Reproducibility	#NUM!	*Total Variation*	9.40676721
Interaction	#NUM!		
R&R	3.70179574		

3.4 Discussion

A scattering of the measurement values is caused by the inhomogeneous sample quality. This is also represented by the operators´ assessment. The improved ranking of sample 416 might be explained by Stevens' power law. According to this the perceived quality of a homogenous appearance is better than the one of an inhomogeneous appearance. Inhomogeneity in this case is conterminous to the perception of a failure, as the spectator is more aware of small deviations on a largely good surface.

The operators´ assessment characteristics are widely uniform, which is also represented by very weak interaction. This indicates an acceptable testing process. The relatively high F value is disadvantageous.

4 CONCLUSION

A measurement system analysis is required for a more comprehensive evaluation of the testing system. For this, the results from table 5 need to be related to a predefined reference value. Typical reference values, like tolerance or the sextuple process variation, are not defined for characteristics of surface appearance. Thus, part variation can be taken into consideration. The ratio of scattering caused by the operator to part variation implies a testing process with limited suitability, according to [25].
All the samples for this test were chosen from the high quality area, while the complete lot included parts with significantly worse characteristics. Regarding the choice of samples, the testing process can be judged as suitable for the overall process. The results for the interdependency show that a deterioration of the scattering caused by the operator will probably not be caused by the part variation.

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SESSION G
Innovation Techniques and Methodologies

ELEVEN POTENTIALS FOR MECHATRONIC V-MODEL

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Abstract
The development of modern products of the 21st century requires the interaction of various disciplines. Thereby, in addition to the technological and the product complexity, the complexity and the amount of communication at the organizational level increases. The guideline VDI 2206 provides an approach of the year 2004, which deals with these challenges. The ongoing increase in complexity, the development progress in the involved disciplines and the necessity of multidisciplinary development requires a revision of the guideline VDI 2206. In addition, the former term understanding of mechatronic products did not yet contain aspects which emerge in connection with the idea of Industry 4.0 and Cyber-Physical Systems. Further, the interdisciplinary mechatronic development should not be limited to the classical disciplines of mechanic, electronic and information technology. In this contribution, eleven potentials to enhance the mechatronic V-model are outlined as proposals for the revision of the guideline VDI 2206 and especially the mechatronic V-model. The potentials describe aspects referring to content as well as structure and illustration of the V-model.

Keywords:
V-Model, Interdisciplinary product creation, CPS, Mechatronic development

1 INTRODUCTION

Increasing global competition forces companies to constantly reduce the time-to-market of their products with innovative ideas, high quality and low prices, etc. In the past decades, these requirements were satisfied by mechatronic systems, which enable the synergetic integration of mechanical engineering with electronics and intelligent computer control [1]. The close integration of multiple domains permits new solutions and technologies which considerably improve the cost/benefit ratio and stimuli novel products [2]. These mechatronic products like the adaptive automatic transmission, the automatically focusing camera and the mechatronic brake can perfectly interpret the value of mechatronic systems for life, industry and economy. Despite mechatronic offers lots of benefits, it imposes at the same time special requirements on the development process [3]. Mechatronic systems entail the complex collaboration among the coupled elements, which are realized in different technical disciplines (heterogeneity) [4]. Therefore, the development of mechatronic systems requires cross-domain communication and cooperation between the involved domains. Besides, in order to make precise decisions in the later developing phases with effective and efficient manner, the integrated combination of various domains should be taken into account in the early development phase. However, the development has mostly taken place separately in the individual domains by their specific methods and appropriate way of thinking with limited exchange of information. A cross-domain development of mechatronic systems was urgently needed and the guideline VDI 2206 was therefore developed in 2004.

In recent years the life cycles of new mechatronic systems have constantly decreased whereas the mechatronics complexity has simultaneously been rising exponentially. Traditional mechatronic systems development methodology VDI 2206 cannot achieve this rising complexity and regard the mechatronics development as an interdisciplinary development consisting of merely three classical engineering domains (mechanic, electronic and software engineering). For example, a symbiosis between engineering and aesthetic domains is the prerequisite to create an efficient design of a mechatronic system. Furthermore, it is necessary to divide these domains into deepened fields, e.g. mechanical engineering into hydraulics, thermionics and aerodynamics, etc. Additionally, the boom of new technologies, e.g. “Industry 4.0”, “Cyber-Physical Systems (CPS)”, necessitate emergently pragmatic development methodology [5]. As both of them relate intimately to mechatronic systems, it is conceivable to modify VDI 2206 serving as the development approach as well. Eventually, on the one hand, the development of interdisciplinary systems faces the growing complexity because of the tight collaboration of more disciplines than aforementioned. On the other hand an applicable development process is required to handle these challenges.

This paper aims to expand the VDI 2206 for the current development of mechatronic, CPS as well as Industry 4.0 systems.

The contribution is structured as follows: Based on the introduction to V-model (the central component of VDI 2206) and CPS in chapter 2, the potential improvements in V-model are analyzed (chapter 3). In chapter 4 corresponding strategies, which base on the drafted improvement potentials, are listed up.

2 STATE OF THE ART

2.1 Mechatronic Systems

In 1969, the Japanese president of YASKAWA Electronic Corporation, Ko Kikuchi, presented firstly the term mechatronics [1, 2]. This manufacturer of automated technical products, such as servo drives and robots, made the understanding of mechatronics as the electronic function expansion of mechanical components. The term consist of mechanisms (later mechanics, or generally mechanical engineering) and electronics (or general electrical engineering) and was protected in the period from 1971 to 1982 as a trade name [2]. After that, a constant development of the term in line with technological enhancement can be observed. With the fast growing technologies of microelectronics and in particular the microprocessor technology, the mechatronics covered also the information engineering. In 1996, Harashima, Tomizuka and Fukuda [1, 2] formed the definition of mechatronics as follows: “Mechatronics is … the synergetic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacturing of industrial products and processes”. In view of the rapid development a firm definition of mechatronics is neither possible nor desired. Otherwise, it would only limit this technical development dynamics. Mechatronic systems are characterized by the functional and spatial integration of sensors, actuators, information processing and a basic system. The performance of mechatronic systems is in appreciation of the synergetic effect of interdisciplinary technologies. It is necessary to use a systematic development procedure, to bring the individual disciplinary development together and establish an overall approach.

2.2 VDI 2206

VDI 2206 is intended to contribute a guideline for the target group “practical developers” of mechatronic systems. It aims to gather the separate development in different domains. This guideline provides a flexible procedure model, mainly featured by three viewpoints problem-solving cycle on the micro-level, V-model on the macro-level and predefined process modules for handling recurrent working steps in the development of mechatronic systems [2]. Goal of V-model, representing the macro-cycle, is to support the user in understanding the complexity of the development process and its phases [2]. V-model, which is illustrated in Fig. 1, is divided into three phases. After completing the “system design” the development continues to the bottom of V-model, which is named “domain-specific design”. This is the second main phase. An elaboration of V-model is presented in this section.

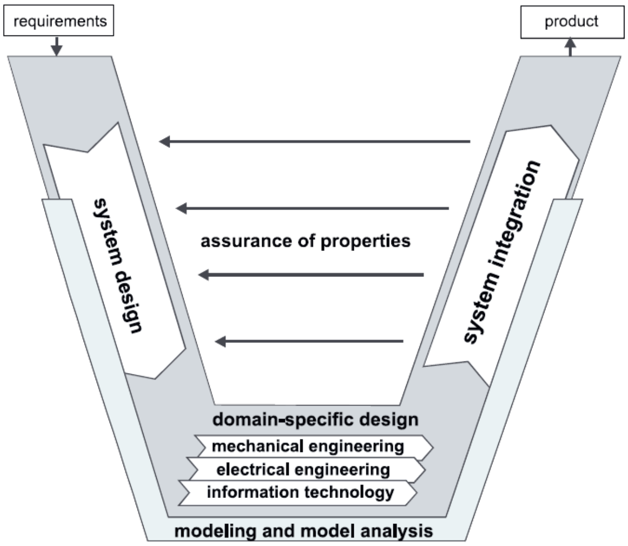

Figure 1: V-model on the macro-level in VDI 2206.

Requirements are defined as input for V-model. The explicit as well as the implicit requests of all stakeholders involved will be formed as verifiable requirements. It serves not only as the development framework but also as the measures for the assurance and assessment of the developed products.
System design aims to establish a cross-domain solution concept with the main characteristics of the future product. First of all, the system functions should be divided into main sub-functions. The corresponding operating principles and solution elements will be solved and tested if they meet the required functions.
Domain-specific design concretizes the solution concept separately in the involved domains. By their individual domain-specified ways and methods, accurate explorations, calculations and interpretations are implemented. The required product and its performance will be improved and ensured, respectively.
System integration establishes an integrated system with all the developed components and the suitable connections. The interaction between the involved domains are able to be realized.
Assurance of properties takes place during the system integration to ensure that not only a correct but also a right product is developed [VDI 2206]. In another words, product properties will be verified and validated. Making sure that stakeholder requirements are satisfied and arising problems during the development process are solved.

Modeling and model analysis draws on the aid of models and computer-aided tools to simulate system properties. On account of the complex structure and cross-domain character, mechatronic systems should be supported by models and simulations.
The outcome of a continuous macro-cycle is an increasing mature “product”, such as the laboratory specimen, the functional specimen, the pilot-run product, etc. [2]

2.3 Cyber-Physical Systems
In 2008, Edward A. Lee coined CPS in [6] as follows: “CPS are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa”.
The project in ACATECH “integrated research agenda CPS” from 2010 to 2012 defined CPS in [7] as follows: CPS are characterized by interdisciplinary and global interconnection with world-wide services and software-intensive systems. As a consequence, they offer diverse potentials in development and application.
As of today, there is not one generally accepted common definition for CPS. Probably, such a definition will be never given but leave always place for new keywords. However, the characteristics of CPS are still an urgent question to get a clarification. CPS are systems comprised of physical entities such as mechanisms controlled or monitored by computer-based algorithms in an open global network. CPS involve interdisciplinary approaches, merging theory of cybernetics, mechatronic design, and design and process science [6, 7]. Obviously, the similarity between CPS and mechatronic systems focuses on the keyword “interdisciplinary”. It is therefore a challenge for the development of CPS, how to combine the various engineering disciplines involved during the system development. Engineers from all disciplines need to be able to work collaboratively, allocate the responsibilities and analyze tradeoffs between them [8].
The rapid development in information and microsystem technologies enable more efficient software-intensive embedded systems and integrated application, which is the premise of development CPS. In a CPS, these embedded systems are able to intertwine and communicate with each other using data and services in an open global network [7]. The communication in a global network makes the distinction between CPS and mechatronic systems. The tiny difference can realize a more intelligent system. Mechatronic systems can only get data from the system and environment. In a CPS, except the aforementioned data, the information from other CPS components can also be captured. The data exchange among the CPS components can make a more accuracy and intelligent monitoring and controlling. However, it entails a more difficult modeling and simulation to gather all the interactions in a CPS than in a mechatronic system.
Until now, there is no development procedure for CPS that gathers all the involved disciplines and challenges. Referring the relations between CPS

and mechatronic systems, it is conceivable to analyze and expand the VDI 2206 to achieve a development procedure for CPS.

3 ANALYSIS OF THE POTENTIALS FOR THE V-MODEL

V-model should be updated to adapt the development of present mechatronic systems and CPS. Firstly, eleven improvement potentials of V-model are analyzed in this chapter.

Potential 1: Target product: First of all, the transition of the target product in VDI 2206 should be taken into consideration. V-model covers only three classical engineering disciplines: mechanical, electrical and software engineering. However, the development direction of mechatronic systems turns to comprise more disciplines beside these three classical engineering domains. The application of mechatronics in health aspect like aforementioned instance "cardiac pacemaker" shows the significance of "biology" in the development of mechatronic systems. The discipline "aesthetic" supports an appealing and innovative outlook, which is becoming a more and more important factor to attract consumers. In view of this point, the interdisciplinary systems like CPS should also be added to the target product group of VDI 2206.

Potential 2: Target group: So far the intended audience of VDI 2206 are mechatronic developers. Concerning the transition of the target product within the VDI 2206, it is necessary to extend the range of the target group to all involved developers and coordinators or project managers for the development of mechatronic systems and CPS.

Potential 3: Starting point "requirements": Typically, current complex mechatronic systems and CPS are comprised of multiple independent subsystems and components. At best, the capability needs of the whole system are met by the requirements of the different subsystems and components. However, in many cases, the whole mechatronic systems or CPS might not be consistent with the requirements for the constituent systems at every point of the development process. Therefore, the requirements definition is both iterative and recursive [9]. In these cases, requirements engineering is necessary to handle the identification of stakeholders and their needs, document these in a form that is amenable to analysis and maintain e.g. requirements while the whole product development process.

Potential 4: V-Model: V-Model focuses on the stage development, not on the whole product life cycle. A system life cycle can be defined as the series of stages that usually contains planning, development, production, utilization and retirement. The purpose in defining the system life cycle is to establish a framework to meet the stakeholders' requirements in an orderly and efficient manner for the whole life cycle [9].

Potential 5: Modeling and model analysis: The bracket "Modeling and model analysis" in V-model encompasses the V at the lower level. This activity can lead to misunderstandings, because there is no annotation when to begin or end the modeling and the model analysis. On account of the complex structure and interdisciplinary characters, not only the individual systems and related components but also the other parts in V-model like "requirements" should be modeled. On the one hand, models provide clear structures to deal with the complexity, on the other hand, models are a simple understandable language for all involved engineers and managers.

Potential 6: Domain specific development: The phase "domain specific development" in Fig. 1 shows a rigorous parallelism among the pre-stated three classical engineering disciplines. First, a strict parallel development among the disciplines is an idealized case scenario. Typically, the development among the involved disciplines needs a tradeoff to get a developing basic structure such as a mechanical structure in first instance. Therefore, parallel development is possible but it should not be forced to start at the same time. The second potential has already mentioned in potential 1 "target group". Today, the development of a successful system either a mechatronic system or a CPS needs more disciplinary allocation than before.

Potential 7: Assurance of properties: The leftwards arrows on the right wing of V-model, showed in Fig. 1, represent a late assurance of properties. Verification and validation (V&V) process is implemented to keep selected solution variants and assess their properties on the basis of the requirements [9]. Performing property assurance at the end of V-model can cause inefficient iterations.

Potential 8: Decision gates: V-model aims a flexible systematic development procedure model for mechatronic systems. However, to reach this goal it is unavoidable to implement "decision gates" in the development project. Decision gates should be drafted in V-model as approval events, sufficiently important to be defined and included in the schedule by coordinators or project managers. Entry and exit criteria are established for each gate as a development results measurement and management baseline. As a result, decision gates support on the one hand efficient development in combination with verification and validation, on the other hand a consistent management. Proceeding beyond the decision gate is able to entail risks [9].

Potential 9: Segmentation in the phase "system design": "Function structures, operating principles, solution elements and a cross-domain solution concept and more other missions are sequentially executed in this phase. To deal with the set of tasks of system design, organizing an orderly development progress is necessary. Additionally, architecture definition should be covered in the VDI 2206. Architecture is defined as a fundamental organization of a system, embodied in its components, their relationships to each other and the environment, concepts and characteristics of systems [9]. The purpose of the architecture definition is to frame stakeholder concern and meet system requirements and to express this in a set of consistent views [9]. The ambiguous using of “design” and “development” is able to confuse the developers.

Potential 10: Results of V-Model: The outcome of V-model is defined as different “products” in terms of different developing degree, like laboratory specimen, functional specimen, etc. This description about outcomes of V-model is disputable. These outcomes are actually the results of the phase “system integration”. Hence, there is no outcome but rather the next development phase, for example the phase “production”, which belongs to system life cycle, or “variants determination” and “production preparation”, which cause are start of V-model.

Potential 11: Integrative development of product and production system: Increasing global competition forces to constantly reduce the time-to-market of products. This involves not only the reduction of the product development time itself, but also the reduction of production system development effort. Therefore, the development of product and production system has to be developed both parallel and in a close interdependency. The parallel product and production system development should replace the sequential development in V-model.

4 STRATEGIES

Strategies to improve the eleven potentials

The eleven potentials to improve the guideline VDI 2206, in particular V-model are introduced. In the following chapter the practical strategies are presented in accordance to the listed potentials.

Strategy 1: Expansion target product: It is proposed to expand the target product from classical mechatronic systems to multidisciplinary systems, such as CPS and the current mechatronic systems, which need more than three classical disciplines for development. All disciplines should be considered into the communicative framework using an understandable language. A specific challenge in CPS is the development of interfaces, which contribute for communication with other CPS-components in a global network. The implicated disciplines for the interface development have to be regarded.

Strategy 2: A wider range of target group: Referring to the development of mechatronic systems and CPS, not only the developers but also the coordinators or project managers should be treated as target group in the VDI 2206. Coping with the complex development project, coordinator and project managers are as decisive as the professional developers. They have to direct and organize the whole development task or even a development project, planning an adequate schedule, being aware of the problems in a development project and making precise decisions.

Strategy 3: Requirements engineering instead of requirements: There are a lot of inherent difficulties to implement requirements engineering in V-model. Stakeholders are often numerous and distributed. Their goals may vary, conflict and might be explicit and difficult to articulate. Dividing requirements engineering in three key activities allows to make this complex process more systematic and easier to implement. First, “Identification of stakeholders” should be emphasized as a phase fixed in the system life cycle, while it is the prerequisite for the whole requirements engineering process. Second, requirements should be identified based on the stakeholder needs phrased in an overall understandable language. Using requirements management the requirements, which are also regarded as assessment measures, are able to be constantly traced, analyzed, prioritized and documented through the whole V-model.

Strategy 4: V-Model covers a whole life cycle: V-model should cover a whole life cycle from planning, to identification of stakeholders, development, production, utilization and retirement. It provides an entire system life cycle to support the system thinking. Additionally, defining life cycle stages and using decision gates is useful for scheduling the development task. Requirements are able to be completely detected and defined in all the stages of a system life cycle. Experts from all these stages are able to communicate, to trade-off analyses, to support decision making, and to end up with a balanced solution. As a result, a comprehensive Vision of the whole development task can be formed through the system life cycle, which also provide an interdisciplinary communication platform. [10]

Strategy 5: A broader bracket for Modeling and model analysis: Using models at the beginning of the system development is suggested. Many different types of models and simulations may be needed to aid the phase “modeling and model analysis” [11]. A key activity is to facilitate the integration of models and communication across multiple domains and disciplines. As an example, system models can be used to specify the elements of the system. The logical model of the system architecture may be used to identify and partition the elements of the systems and define their interconnection or other relationships among the elements [9]. Function models may be used to define and represent the target function of the behavior of systems. Different models must be sufficiently integrated to ensure a cohesive system solution. Note for CPS, while the interaction structures between the CPS systems are not allowed to be taken into account completely, a right way of modeling and model analysis is quite important.

Strategy 6: Drawing with more domains into domain-specific development: The specific domains should be loosely coupled instead of the strict parallelism and more disciplines like biology or chemistry are possibly included. Note, only the significant disciplines are allowed to join in the domain specific development, since superfluous disciplines are involved, the more complicated the development task is.

Strategy 7: Assurance of properties in advance: The properties are expected early to verify and validate with support from modeling and model analysis. Every crucial step in the system development should be merged with verification and validation (V&V). Furthermore, requirements provide measures to support this V&V process. Additionally, the cooperation between “Assurance of properties” and “decision gates” can deliver a more systematic and efficient development.

Strategy 8: Launch decision gates: Decision gates are often named as “milestones” or “reviews”. Defining entry and exit criteria supports to plan and to implement an efficient development schedule. Decision gates ensure that new activities are not pursued until the previously scheduled activities, on which new activities depend, are satisfactorily completed and placed under configuration control [9, 12]. There are at least two decision gates in any project: authority to proceed and acceptance to delivery. The other decision gates should be decided in terms of their beneficial purposes.

Strategy 9: Segmentation in the phase “system design”: System design begins with identification of requirements to fetch essential statements and solution-neutral formulation of problems. Sequentially, function structures including the overall and sub-functions are set up. On the basis of these functions, operating principles and solution elements are acquired as a solution concept by the next step. At the end, a cross-functional concept and systems architecture should be determined as an overview to show a clear interrelation between the system components. Defining a system architecture is sufficient useful for complex CPS and mechatronic systems to contribute a model environment for all involved developers and coordinators.

Strategy 10: Results of V-Model: Referring to different V-model cycles, appropriate results can be physical objects as well as virtual processes, concepts, etc. In terms of the maturity degree, these results are determined as an input for the next life cycle stage or a starting point of the next V-cycle.

Strategy 11: Integrative development of product and production system: The product concept is highly determined by the available or considered manufacturing technologies since many properties regarding material, surface or shape can only be realized with certain manufacturing technologies. It is therefore necessary to proceed a close product and production development from the beginning to avoid cost and time intensive iteration loops during the development phase. A number of approaches such as Model Based Systems Engineering help to cope with the resulting complexity by structuring the specific models of the different engineering domains in an interrelated hierarchy [13, 14, 15].

5 CONCLUSION AND OUTLOOK

In this contribution, the classical development methodology of mechatronic systems "VDI 2206" is introduced. After explicating the advancement of mechatronic systems in the last decade, eleven improvement potentials are analyzed and represented to extend its applicable range, for example CPS. It enables a development of mechatronic systems, which is not restricted to the three classical domains. Based on the eleven improvement potentials, the corresponding strategies are demonstrated and implemented in V-model. These strategies fatten V-model to adapt the development of more complicated and complex systems. The expanded V-model is embedded in an entire life cycle and controlled by continuous "requirements engineering" with consideration of all stakeholders needs. Production systems can be developed in parallel with product development, which leads to a significant reduction of time and costs. Analysis and development of product and according production system not just shorten development cycle time but also avoid unnecessary iterative loops indeed. The continuous modeling and model analysis is based on simulation tools to establish a communicative framework for all stakeholders involved.

The next step of improvement VDI 2206 is to define the sub-steps which keep recurring in accordance with the adaptive V-model. Every step in system design, domain specific development, system integration, assurance of properties and requirements engineering should be explained in the form of partly process modules. Using process modules enables to further reduce development cycle time. The predefined process modules is an immense strategy to reduce the rising complexity of system development, which arises from the pressure of market. Additionally, the appropriate approaches and aided tools for corresponding systems (CPS or mechatronic systems) should be specified and documented. Using the modified V-model, engineers are able to focus on their essential work with arising efficiency. Controlling complexity is another potential aspect to improve the development efficiency. Hence, it is necessary to develop effective strategies of analyzing, reducing and controlling the increasing complexity of mechatronic systems.

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EXPERT KNOWLEDGE SYSTEMS TO ENSURE QUALITY AND RELIABILITY IN DIRECT DIGITAL MANUFACTURING ENVIROMENTS

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Abstract
In the context of Industrie 4.0 respectively direct digital manufacturing, seamless process chains are an important factor. The objective is to shorten the time between quoting for individually designed products and their production and delivery. Therefore, reliable automated and fast evaluation procedures are needed to ensure the quality of the individually designed products in terms of product safety and reliability. This paper aims to demonstrate how a metamodel, generated on simulated data, adapts to the type of product and delivers the required quality and evaluation procedure. The metamodel guarantees the requested characteristics of the final product without the consultation of human expert knowledge. As proof of concept, a simple, well-documented task from the field of construction has been chosen. The estimation from of the metamodel will meet all safety requirements, is based on the individual input variables and is confirmed without expert interaction. Fast, reliable prediction models deriving from complex simulation models are indispensable conditions for direct digital manufacturing. Using metamodels in automation contexts will be a foundation of manufacturing in future.

Keywords:
Simulation, Metamodel, Computer experiment, Design of experiments

1 INTRODUCTION

In future, manufacturing processes will have to be highly flexible and dynamic. Manufacturing companies are involved in networks that require agile collaboration between partners [1]. Therefore direct digital manufacturing needs digital data from the product and the manufacturing process. IT tools are needed and global networks are useful. Designers will use engineering tools (CAD, FEM etc.) for product design and optimization [2]. The product design is also part of direct digital manufacturing. So everyone involved in the design process will be part of this digital revolution. Soon the prosumer will be a part of the design group. Prosumers are persons who combine the economic roles of producer and consumer. Usually prosumers have no expert knowledge. Therefore, reliable automated and fast evaluation procedures are needed to ensure the quality of the individually designed products in terms of product safety and product reliability. Fast and easy-to-use engineering tools could be one solution here.

Additionally customer needs and requirements are getting increasingly diverse while individual customer requirements become more and more important. The old concept of a consumer not being involved in the manufacturing process will change to the concept of prosumers who will play an active part in direct digital manufacturing [3]. Therefore suitable prosumer concepts and easy-to-use tools should be developed for direct digital manufacturing.

Today, human experts check, based on their experience, whether the consumer (client) desired product parameters are valid to create a product that meets the required safety level. If necessary, the expert adapts the product parameters after client consultation in order to fulfill the safety requirements. Depending on the specific application the review of the parameters is done with special and often complex simulation tools. In most cases a human expert is needed to run the simulation, which is often very time-consuming. An alternative approach is the use of metamodels. Metamodels are “simplified models from a model” where the results come from algebraic equations. They are normally used to replace time-consuming complex simulations. The metamodel technique can also provide the algorithm for simple engineering tools, which require only a small amount of knowledge. Statistical tools are also well known for building metamodels. The metamodel approach can be used with a new data stream [4] or a constant data base.

A metamodel that has these characteristics should only run on the client given parameters and information of the demanded characteristics or usages of the future product. In the description below, these parameters are called input variables. Parameters based on expert knowledge should be covered by the metamodel itself and not be influenced by client requirements.

2 METHODS

2.1 Metamodel of complex simulations as a fast expert knowledge system

Metamodels in the context of IT represent a simplified model of a complex computer analysis which is based on statistical methods. The aim of the metamodel is to predict the future behavior of a process without doing the complex computer analysis. The results of the metamodel are an approximation of the output variables defined by a functional relation based on statistics. Therefore the calculated results of the metamodel normally have an error or residual left over [5]. The metamodel will not be used to

predict exact values, but helps to make decisions, e.g. whether the product design fulfills the safety requirements or not.
In order to use statistical methods to find relations between the input variables and the output variables, data sets are necessary. The quality of the statistical model depends to the number of given data sets and the distribution of the input variables [6]. The fastest way to achieve a reliable and valuable metamodel is to use a minimum number of complex computer analyses. Here the complexity and the nonlinearity between the input variables and the response have to be taken into account. The well-known methods to design computer experiments can be used.

2.2 Design of computer experiments

The design of experiments requires a method on how to do physical test systematically. Computer experiments differ from physical experiments in the way, that repeated computer simulations with an identical set of input variables result in identical output variables. That means, that a single observation on a given set of inputs provides perfect information about the final result. With this advantage in mind, the design strategy for computer experiments should fulfill two principles [7]:

1. Design should not take more than one observation at any set of inputs [7].
2. The design should provide information about all portions of the experimental region [7].

The space-filling design fulfills the two above mentioned principles. It includes different design methods such as Latin Hypercube, Maximum Entropy, Uniform, Fast, Flexible Filling and more. The method that will be used depends heavily on the application [8].

2.3 Statistical modeling

After selecting an appropriate experimental design and finishing the necessary computer runs, the next step is to launch the model fitting process.
Many alternative models and methods exist here. Most prevalent in the literature are the response surface, neural networks, including learning and kriging [9]. In this case the response surface method was chosen, because it is widely used and implemented in common statistical tools in order to keep the mythologies as simple as possible.
In computer experiments the response vector y is influenced by a vector of independent factors x (y=f(x)). There are no random errors. Since the true response surface function f(x) is usually unknown, a response surface g(x) is created to approximate f(x). Frequently used response surface approximation functions are low-order polynomials [9].
The parameters of the polynomials are usually determined by least square regression analysis by fitting the response surface approximations to

existing data sets [9]. The validation of the simplified prediction model is a crucial success factor.

3 CASE STUDY

The aim of the paper is to show how the theoretical framework discussed above can be used in the context of construction. In this case a very simple, well-researched area of construction is chosen, because it is easier to obtain real and proven validation data and to compare the results with others [10]. As proof of concept the task of vision panels in facades or doors from the field of construction was chosen. The main research concentrated on the resistance of the glass to soft body impact and its safety properties after fracture. The test scenario is generally determined by an impact test, for example as defined in the European standard EN 12600 [10]. In the last 10 years calculation methods using transient, implicit or explicit finite-element methods have been developed. They simulate the experimental results very well. These methods now form a part of the design method according to the German standard DIN 18008-4 'Glass in building – design and construction rules – part 4 [11]: additional requirements for barrier glazing'. To use this calculation method, complex software tools and detailed expert knowledge is required. The expert must have knowledge about the program, the material parameters, element size, drop height and so on. The use of expert knowledge leads to an increase in time and costs. It also does not improve the process when used in automated actions.
To get a rough idea of whether the chosen vision panel might fulfill the required safety standards apart from physical trails, two simulation methods are normally suggested: the more reliable calculation using the finite element method. The second method uses analytical equations and substitute input values taken from charts. To combine the advantages of both methods, i.e. being reliable, fast and capable of being used without expert knowledge, would represent a third possibility.
The main question here is: is it possible to find a metamodel which allows to take a decision on whether vision glass panels are resistant to a soft body impact? The second question addresses the issue if this decision should be rather made by the human mind with very little expert knowledge, as in the case of sales people, or automatically proofen in an automated ordering process via the Internet.

3.1 Metamodel development

Beginning with the input parameters, it is important to consider the geometry of the vision panel, i.e. the height, the width and the thickness of the glass. The strength of the glass is also a very important parameter. There are three different glass types with different strengths – see Table 1.

Table 1: Allowable stress (DIN 18008) [12] for soft impact.

GLASS TYPE	*ALLOWABLE STRESS*
Float	81 MPa
HST (heat-strengthened glass)	119 MPa
FT (ESG) (fully toughened glass)	168 MPa

Due to the fact that the user of the metamodel needs only little expert knowledge, the common known glass type should replace the input for the glass strength.
The main input parameters which represent the minimum level of knowledge for designing the glass are:

Table 2: Used parameters.

PARAMETER	*SYMBOL*	*VALUE*	*TYPE*
Glass height	h	500 mm – 3000 mm	Continuous
Glass width	b	500 mm – 2500 mm	Continuous
Inclination	α	0°-90°	Continuous
Glass thickness	d	6 mm -24 mm	Continuous
Glass type	gt	Float, HST, FT	Categorical

The output results should answer the question whether the clear four-sided glass panel is able to resist the soft impact (as ruled in – DIN 18008) or not.
After the input parameters are set, the design of experiment is created with the space-filling design and in detail with the fast filling function. This function is chosen because it allows the use of categorical input variables. In this case no additional rules for the parameter are taken into account. For example, the glass thickness is available on the market in steps only, i.e. not every thickness is available. Due to the fact that the metamodel is built from data sets which are derived from the computer simulation, this is not important.
Figure 1 shows the distribution of the input variables in the design space. It can be clearly seen that all input variables are spread out as far as possible over the design space.

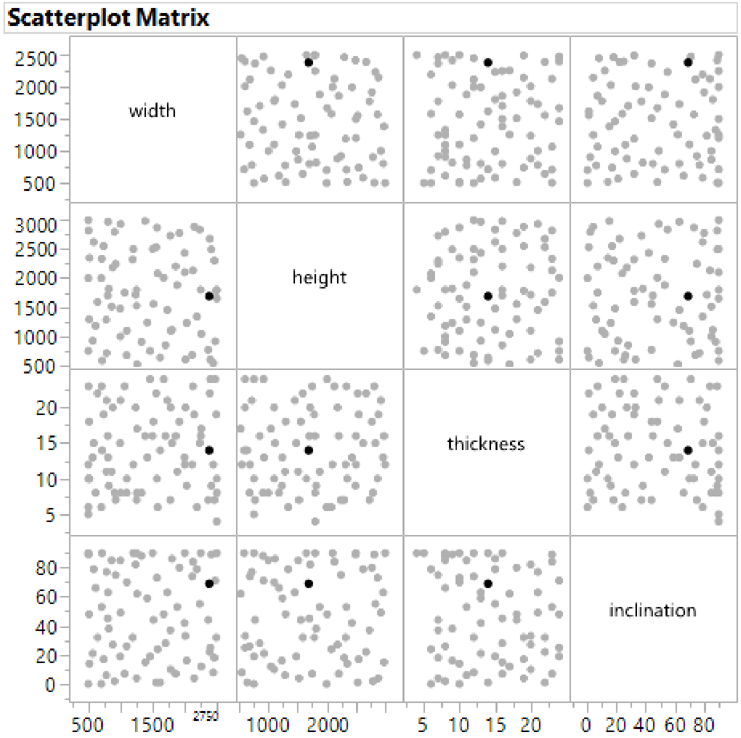


Figure 1: Scatterplot of space-filling design.

As a computer program for the simulation of the transient soft impact SJ-Mepla [13] is used, an expert explores how to do the simulation. The results from the complex simulation are verified by testing [14]. The stresses calculated with this program for all input parameters are the results from the computer simulation. To determine whether the vision glass panel restrains the load from the soft body impact, we have to build an output value of a yes / no event. Therefore, the outcoming resistance factor which is the relation between the stresses occurring in the glass form the calculation, and the allowable stresses of the glass type can be used.

$$F_R = \frac{\sigma_{Ed}}{\sigma_{Rd}} \tag{1}$$

F_R resistance factor

σ_{Ed} first principal stress to occur

σ_{Rd} allowable stress

If the resistance factor is $F_R \leq 1$, the design is resistant against soft impact. If F_R is > 1, the occurred stresses in glass are higher than the allowable stresses, that means the glass is likely to break and a safety issue might occur.
Bringing all input parameters and output results from the simulation completed with the resistance factor in one data sheet, makes it possible to build a statistical model. First steps are: a screening analysis. The results are shown in the half normal plot (Fig. 2). The glass type and the glass thickness, especially the glass type Float, have a major impact on the result.

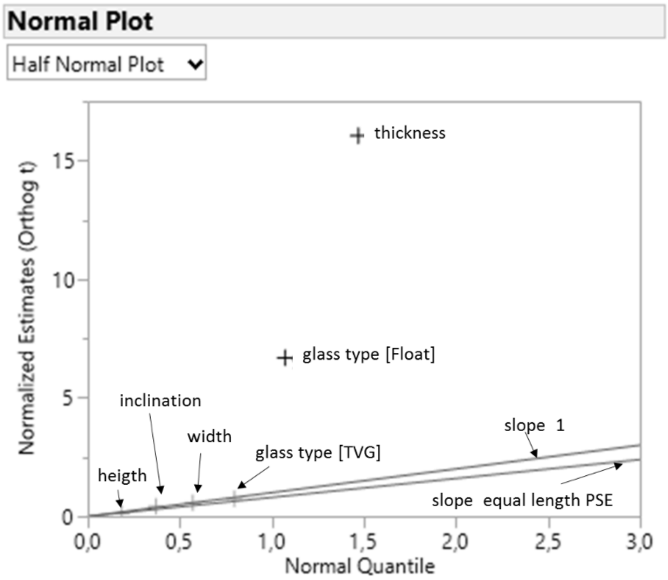


Figure 2: Half normal plot of a screening.

As mentioned in chapter 2, the response surface method is used to build the model. The statistical evaluation is done with the software tool JMP pro.
Figure 3 shows the distribution of the residual. The residual average is near zero and median is slightly larger (0.002). This is a good indicator of the model quality. The belonging confidence interval indicates as well that the residues are likely to be small.

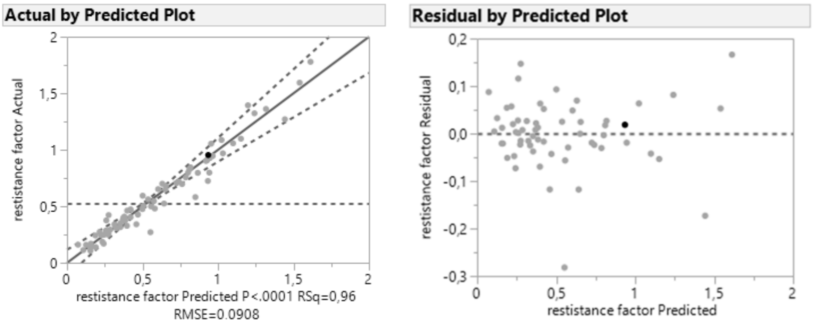
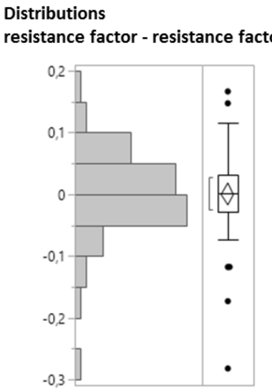


Figure 3: Predicted resistance factor / calculated resistance factor.



Quantiles

100.0%	maximum	0,1662913444
99.5%		0,1662913444
97.5%		0,1562385302
90.0%		0,0803602082
75.0%	quartile	0,0313271697
50.0%	median	0,0021889508
25.0%	quartile	-0,028194557
10.0%		-0,068311244
2.5%		-0,224727226
0.5%		-0,281913531
0.0%	minimum	-0,281913531

Summary Statistics

Mean	1,036e-16
Std Dev	0,0699126
Std Err Mean	0,0090257
Upper 95% Mean	0,0180603
Lower 95% Mean	-0,01806
N	60

Figure 4: Residual by predicted resistance factor.

The metamodel is supposed to deliver an early and robust estimation. Therefore it seems to be sensible to follow a very conservative approach to define the threshold when a vision glass panel is seen as safe. This indicates to put a greater security layer around the prediction. The standard deviation of 0.069 was chosen.

$predicted\_F_R < 1 - 0.0069$	The vision glass panel is predicted to be safe.
$1 - 0.069 < predicted\_F_R < 1 + 0.0069$	The vision glass panel needs detailed simulation by experts.
$1 + 0.069 < predicted\_F_R$	The vision glass panel is predicted to be not safe. Changing the glass thickness or glazing type might be a solution.

To validate the results, additional data that is not part of modeling is necessary.

3.3 Validation of the model

To prove the validity of the metamodel, additional simulation runs are performed to create data sets that were not part of the model generation. The data set from DIN18008 is used for validation as well.
In the predicted plot (Fig. 5), the resistance factor, which is calculated with the finite element model, is plotted over the predicted resistance factor. The data marked with a cross (VAL) is the data used for validation. These data sets are randomly chosen values. The data marked with a dot (DIN) is validation data from the German standard, table B.1 [11]. In table b1 of the German standard, the vision glass panels are listed with a minimum and a maximum amount for the width and height. For the validation of the metamodel only the maximum possible values for the glass panel dimension are taken. The resistance factors of these data sets are in the area of 1 (see Fig. 5). Therefore, the predicted resistance factor should also be near 1 in the area of uncertainty. The metamodel is able to identify these sets.
The dots (DOE, marked with a circle) are the datasets which are used to build the statistical model.

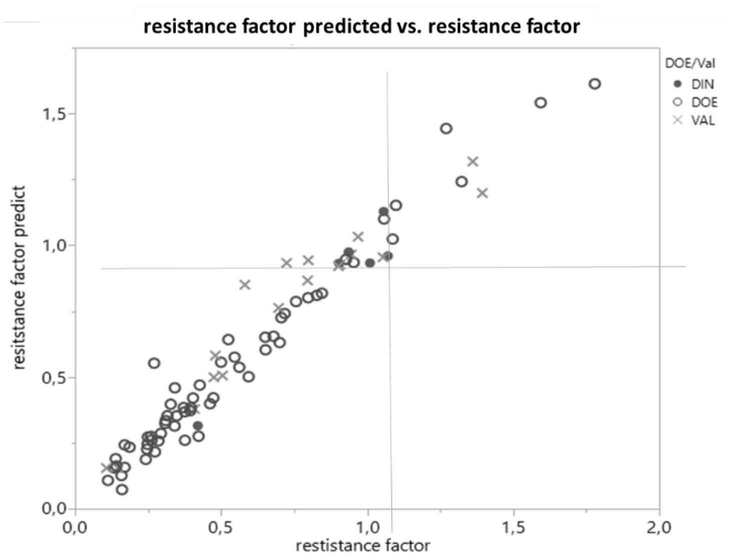


Figure 5: Predicted resistance factor over calculated resistance factor with validation.

Using the forecast rules (item 3.1) two visual glazing from the validation data set (VAL) fail to pass (see table 3).

Table 3: Comparison of results.

	REAL			*PREDICTED*		
	Failed	Detailed investigation necessary	Fulfill requirements	Failed	Detailed investigation necessary	Fulfill requirements
DOE	7	0	53	6	3	51
VAL	3	0	15	2	5	11
DIN	3	0	3	1	4	1

In those cases the customer has to choose a greater glass thickness or a different glass type. For seven data sets the forecast is not clear, i.e. detailed investigation has to be carried out, or the customer has to choose a greater glass thickness. If detailed simulation is performed, the result shows that for some data sets the design fulfills the requirement, and for some it does not (see table 3, column REAL). Nine glazing panels are safe. Looking in detail at the data set from the German standard (DIN), detailed investigation of the four data sets is required, as elaborated before. Data sets taken from the German standard have a close resistance factor. After a detailed investigation two data sets of the four will have results that failed, while the other two data sets fulfill the safety requirements.

From 84 data sets the metamodel identifies 63 items that fulfill the requirements and 9 vision glazing that would fail. For 12 data sets detailed investigation is necessary, something that will usually be performed by an expert.

The advantage offered by the metamodel is obvious. Instead of testing or calculating a complex 84 vision panels, it is only necessary to perform a more detailed calculation for 12 models. Alternatively, these 12 will be provided with a new parameter setup such as increasing glass thickness to meet the criteria. This will reduce time and cost. This also means that architects and sales representatives are able to determine at a very early stage of the project which setup will suit the plans for the project.

3.4 Outcomes

The case study shows that those complex simulation models, which need a lot of expert knowledge can be transferred into metamodels. These metamodels use input parameter which represent the minimum knowledge for designing the glass. The results are not exact values for example the stresses in the glass. The result is the decision if the required safety is fulfilled or not. The found algorithm can be used to build a fast and easy to use engineering tool which work in the background during a client makes the order for visual glazing. During the order process the customer gets a direct information if his desired design fulfills the required safety standards.
The implementation of the model is fast and easy to use engineering tools might generate a great economic impact. With such simple tools architects or facade planners can check in an early stage of a project if the glazing they like to use fulfills the requirements. Also sales people use such tools for a fast forecast during a sales discussion.
Predictive modelling can be used to reduce complexity to support decision making. Even in highly regulated industries the predictive analytics can be used to reduce time needed to run complicated analyses. It also enables non-experts or even customers to make reliable decisions themselves.
The statistical model is essentially an approximation however the accuracy and precision can be improved by increasing the size and complexity of the experimental design. The statistical model can also be a signal when to revert to the more precise, time-consuming and complex top of the range analysis.

4 OUTLOOK

The results above show that metamodels can be used to obtain a first impression of the suitability of the material and design of the product. This enables the industry to take decisions at an early stage of complex construction products. In future projects the metamodel can be spread to complex problems in the field of construction. It will be proved that, with different loads such as climatic loads, wind loads and different shapes, the metamodel will provide a reliable estimation so that the industry might use them as a forecast planning method more generally.
In summary, building a metamodel shortens the simulation time with only a small loss of information and without expert knowledge.
Finally it can be said that using metamodel instead of complex and time consuming simulation tools is at the beginning of the direct digital manufacturing a way to give the prosumer the possibility to do the design responsibly.

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PROJECT COST ESTIMATOR – A PARAMETER-BASED TOOL TO PREDICT PRODUCT REALIZATION COSTS AT A VERY EARLY STAGE

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Abstract
Due to steadily increased demand for customized products, as well as their enhanced complexity and shorter product lifecycles, companies in all industries require a reliable prediction of the expected product development costs from the very start of product realization. Incorrectly estimated project costs may lead to serious consequences in the course of a development project. For example, offers are most often based on such early cost estimations and consequently, a major safety margin has to be added, which may result in the refusal of an order. A too low estimation of the costs of a product development project, on the other hand, may result in a loss for the project.
In this paper, a software tool is presented for the prediction of product development costs which offers the user the ability to create a more accurate prediction of project costs on the basis of a minimum of retrograde project information. By combining a parametric cost model and cost result with stochastic character, based on the Monte Carlo method, in one software system, it is possible to significantly improve project cost estimations.

Keywords:
Cost prediction, Product realization projects, Monte Carlo method, Parametric cost model, Software tool

1 INTRODUCTION

A serious problem for the costing of product development projects, especially in the early stages, is the need for information based on completed projects (retrograde project information). The lack of information in the early stages of product development projects greatly affects the quality of the cost calculation results. Another major drawback of current project cost estimates is the result evaluation based on deterministic values. This refers to the cost forecast based on an exact value but without proper consideration of the risks and uncertainties.
The aim of this study is to give the reader an insight into the implementation of a parametric cost model for the prediction of product development costs by a software tool. For this purpose, all basic concepts and mathematical functions, as well as the need for information, are explained in detail. This

includes a brief outline of the state of research. The main part covers development of the software tool itself. The applied programming language and development environment are described. In the last part, the Project Cost Estimator system is tested and qualified with an application example.

2 CHARACTERISTICS OF PRODUCT REALIZATION PROJECTS

A product realization project has the characteristics that it is limited in terms of time with a fixed start and end date and also involves a financial limitation [1]. The task of the project management is to lead the project in compliance with the success criteria: to remain on budget, on time and within scope. The product development process describes the work procedures beginning with the product idea until series production. The process is classified into three task areas:

- Strategic product planning
- Product development
- Production system development

The first phase contains the potential finding, product finding, business planning and the product design. The second phase comprises the product definition within determination of the product properties. The last phase is production system development, which is a parallel process to the product development [2]. The cost planning for a product realization is part of the business planning and contains the first phase (strategic product planning). The planning is performed before the actual product and production system development. This cost planning in the early phase of product realization differs from the product costing analysis, which is a task of financial controlling. The basis for the prediction of product realization costs are influenced by factors which can be categorized as follows [3]:

- Company-specific input
- Industry-specific input
- Anterograde project information

3 METHODS FOR COST PREDICTION OF PRODUCT REALIZATION COSTS

To increase the competitiveness of companies, it is of great importance to estimate the cost of a product realization project as accurately as possible before the beginning of the actual product development [4]. Currently, the majority of companies uses software solutions based on a spreadsheet such as Microsoft Excel, to carry out the early calculation of product costs in a development project [5].

Alternative solutions are enterprise resource planning (ERP) systems, product lifecycle management (PLM) systems, or the development of an individual solution [6]. Each of these systems has individual options of product costing. However, none of these software solutions offers a way to predict the product realization costs, particularly in the early stages of the product development process. Merely in the area of software engineering are there systems that can estimate the development costs of software development projects based on the COCOMO method [7].
There are many methods for cost prediction, such as subjective assessment procedures, relationship procedures and parametric procedures (for further information see [4]). The method which is used for the Project Cost Estimator is a linear multiple regression and contains to the parametric procedures. This parametric cost model is based on the assumption that there is a functional relationship between the anticipated costs and the project specific cost factors [3]. With the help of retrograde project information from completed projects and statistical methods it is possible to determine such a relationship empirically, as is now explained in the following chapters.

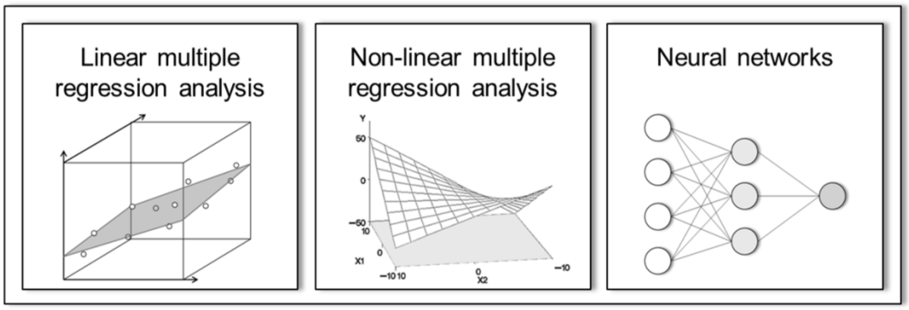

Figure 1: Analytical methods [3].

4 MODELING

Using structure-checking multivariate analysis methods, formal constraints of a cost model are shown, whereby one or more equations are set up. These equation systems consist of input variables and output variables (target) [8].The functioning of multiple linear regression analysis, which is used in the Project Cost Estimator, is explained in the following chapter. In addition, the Monte Carlo method is used to model the probability of different targets, because a fundamental problem in the result visualization of parametric cost methods, such as the simple linear or the multiple linear regression analysis, is the evaluation of results based on a deterministic result value.

4.1 Multiple regression analysis

One of the most widespread statistical analysis procedures is regression analysis, with whose help the relationship of one or more input variables $(x_1, x_2, \dots, x_i)$ on a target variable can be analyzed. To be able to predict the target variable, for example the costs or a value of a product development project which is not transferable into costs, it is necessary for the investigation to use several input variables (factors of influence) in the cost model, since the complexity of a product realization project is difficult or impossible to explain with just one factor [9]. Due to this fact, the approach of simple linear regression analysis is extended to include other independent input variables, so that the linear multiple regression analysis was implemented in the Project Cost Estimator. The general formula for the linear multiple regressing model is defined as [8]:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_j x_j + \cdots b_J x_J \qquad (1)$$

With:

y:	Target variable
b_0:	Constant term
b_j:	Regression coefficient (j = 1, 2,…, J)
x_j:	Independent input variables (j = 1, 2,…, J)
J:	Number of independent input variables

The calculation of the regression coefficients $(b_0, b_1, b_2, \dots, b_J)$ is based on the 'method of least squares'. This is an algorithm that fits the line through the given sample data with the smallest sum of squared residuals. In the case of the Project Cost Estimator, the sample data is used from completed projects. Within the Project Cost Estimator, this operation is carried out for each established regression equation with the aid of matrices, which are then solved by the following calculation rule [10]:

$$\vec{\beta} = (X^T X)^{-1} X^T \vec{y} \qquad (2)$$

With:

$\vec{\beta}$:	Vector of the regression coefficients
X:	Design matrix of the linear model
$\vec{y}$:	Vector of retrograde project data

4.2 Probability of the output variable

The result of a deterministic analytical model always delivers an exact value by using exact input variables. To provide information about the probability of a target variable, the stochastic distribution of the input variables has to be known. In this case the Monte Carlo method is used to predict the probability of the target. This method is a procedure of numerical analysis which allows a large number of random sizes to be generated.

A results presentation in the form of an exact value does not take the uncertainty and risks of a cost model into account [4]. In the case of modeling of a product realization project, especially in the early stages of the product realization process, two types of uncertainty must be distinguished.

Model uncertainty:
Due to the fact that the regression equations for each project segment are calculated based on retrograde project information, there are deviations of values around the regression line. These deviations are called residuals and represent variables which are undeclared by the regression line. The probability and the degree of deviations are defined by the standard deviation σ [8] [4].

Anterograde insecurity:
A major problem for the prediction of product realization costs, particularly in the early stages of the product realization process, is the lack of information, with the result that there is only little or inaccurate data at the beginning of the development project, and thus, the expression of the factors can be defined by the users, normally with a low level of certainty.
The uncertainty originating out of this is caused by the subjective assessment of the user while defining the influencing factors and should be referred to below as the anterograde uncertainty [4].

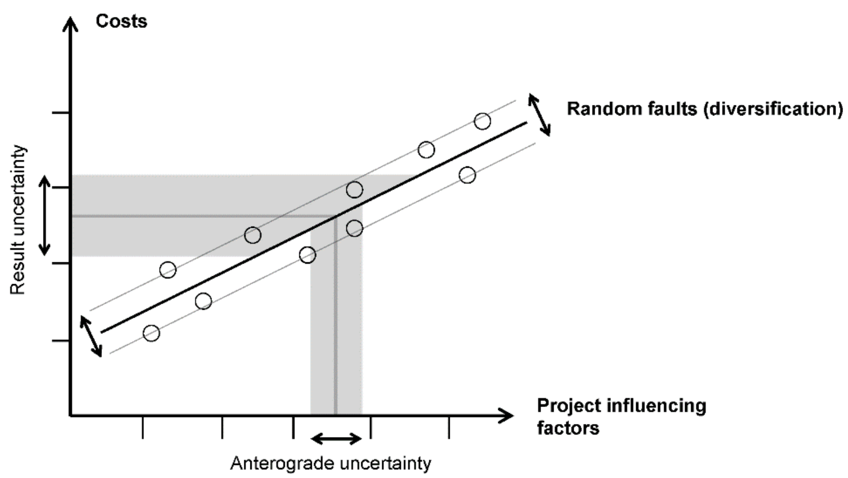

Figure 2: Uncertainty [4].

The predictive accuracy of the cost model is due to the two above described uncertainties. Together, the result uncertainty arises from it (Figure 2). In order to make users aware of the risks and uncertainties which are involved in the cost model, the result output within the Project Cost Estimator is performed in the form of a distribution function that provides information about the expected value and standard deviation of the simulation model. In detail, this means that the user can generate value combinations by entering expected values and standard deviations of the influence factors and a number of random numbers based on those, statistically evaluated by the Project Cost Estimator.

Consequently, the anterograde uncertainty for each project segment is calculated and the user gains an impression of the result expression with upper and lower probability of occurrence. With the Monte Carlo method, a large number of “random” projects can be generated to counteract the information deficit. The consequence is that the accuracy of the result increases [4]. Figure 3 shows a comparison between the deterministic and stochastic result output.

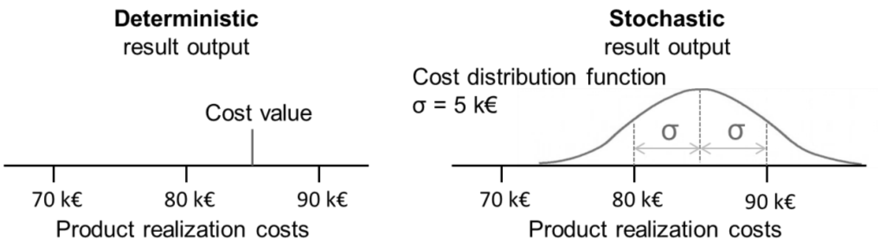

Figure 3: Deterministic vs. stochastic output [3].

5 STRUCTURING THE COST MODEL

Structuring of the cost model follows a bottom-up approach. This is to understand that a total problem is divided into several smaller detailed sub-problems and has to be resolved [11] from bottom to top. The total cost of a project will be formed by aggregation of the segments. Each project segment (dependent variables) can be determined by operation, work effort, project section or department. Thus, the significant effect on the project segments is represented by the influencing factors involved in the project (independent variables). The level of the expected total project cost is affected by a variety of internal and external influences, so that the user must define the factors involved in the project to obtain a customized, company-oriented database [4]. With an increasing number of influencing factors, the need for retrograde project information increases, as only such influencing factors can be recorded in the cost model for which information from completed projects is available [4]. For this reason, the influence factors for the description of one project segment are summarized in representative multivariables. With this, the user remains flexible in terms of modeling, and the need for completed project information is reduced. Figure 4 shows the structure of a cost model.

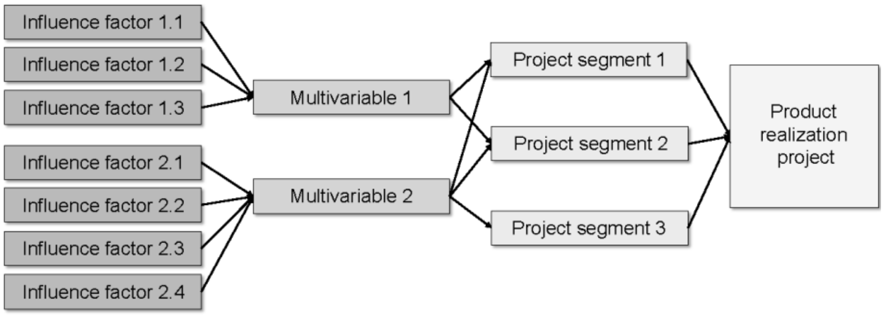

Figure 4: Cost model structuring.

6 DEVELOPMENT OF THE PROJECT COST ESTIMATOR WITH MODELICA

The object-oriented programming language Modelica is used for modeling and simulation of physical systems. Modelica is different from conventional programming languages such as C and Java in that it is not based on allocations of variables, but on equations [12]. Modelica has the major advantage that simulation models can be created graphically, using a model editor (OMEdit). Components such as influencing factors, multivariables and project segments can be easily placed via drag-and-drop from a predefined library on the simulation user interface and then be graphically linked, by which the mathematical structure of the parametric cost model is mapped [13]. Another advantage of Modelica is the use of freely configurable libraries, whereby the Project Estimator is individually adaptable to each company. It is necessary to distinguish between the actual programming language Modelica on one hand, and the development environment used on the other hand. Modelica, as an object-oriented programming language, is freely available [14] under the Modelica License 2, however, there are open source and commercial solutions in the development environments, which are all based on Modelica. In the case of the Project Cost Estimator presented, OpenModelica comes with the OpenModelica Connection Editor (Figure 5).

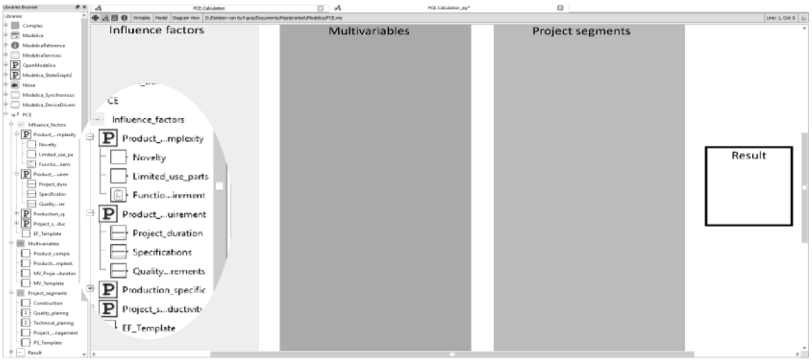

Figure 5: Simulation interface of PCE.

7 COST PLANNING WITH THE HELP OF THE PROJECT COST ESTIMATOR

The practical application of the Project Cost Estimator will be explained below in greater detail, using a case example. The creation and subsequent calculation of a cost model is divided into five phases (Figure 6), which are run through sequentially.

Figure 6: Phases of PCE.

The first phase is structuring of the cost model, in which the user defines the project items eligible from the program library. Nonexistent elements can be defined in accordance with the aid of templates to map the product development projects. The result of the first phase is a catalog of influence factors, with whose help the model is graphically created in the second phase. For this purpose, the constituting elements of the cost model are placed by drag-and-drop on the corresponding colored fields of the simulation interface. The choice of the project elements involved (influence factors, multivariables and project segments) cannot be generalized and must be adapted to the enterprises and industries [4]. After identification of the project elements which are relevant, the product realization project is completed in the first two phases, whereby in the third phase logical connections are built using graphic connections, known as connectors. For this purpose, the elements are linked to each other in sequence:

Influence factor → Multivariable → Project segment → Result

The fourth phase of the application consists of the input of anterograde project information and definition of the data for the Monte Carlo method, consisting of the expected value and standard deviation of the influence factor and the number of random numbers to be generated. The concluding fifth phase will start the actual simulation run, in which the calculations of the regression equations are carried out. For this, the Project Cost Estimator imports all required retrograde project information from the enterprise database (in form of a TXT file), forms the regression equations for every project segment and afterwards, puts the anterograde random projects in the equations to eventually calculate the average and the standard deviation of the cost model. Figure 7 shows the user interface of the PCE, filled with the example data.

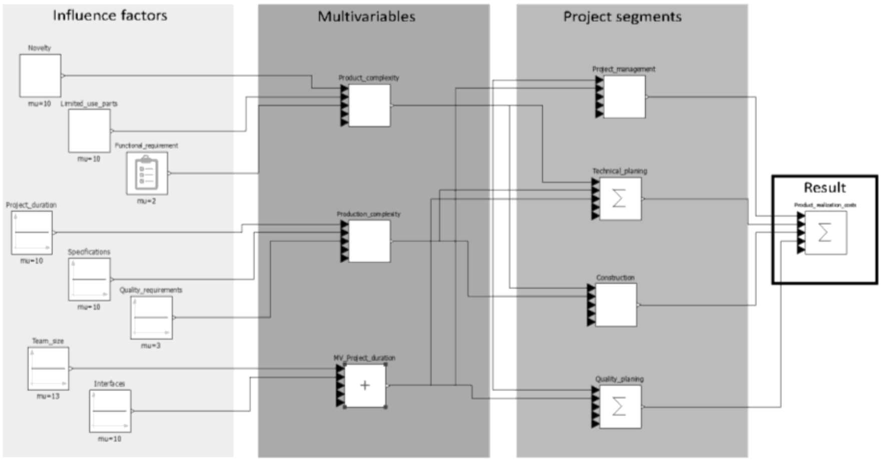

Figure 7: PCE screenshot.

The data used for this example consists of retrograde project information from 15 completed projects, four project segments (project management, technical design, construction, quality planning), 4000 random numbers and the combination of influence factors and multivariables as shown in Table 1:

Table 1: Sample data.

MULTIVARIABLES	INFLUENCE FACTOR	VALUE	
Product complexity	Novelty degree	μ = 10	σ = 0.0
	Difference items	μ = 10	σ = 0.0
	Functional requirements	μ = 2	σ = 0.0
Production complexity	Number of manufacturing processes	μ = 10	σ = 0.2
	Degree of automation	μ = 10	σ = 0.2
	Output quantity	μ = 3	σ = 0.1
Project duration	Experiential knowledge	μ = 13	σ = 0.4
	Different parts	μ =10	σ = 0.6

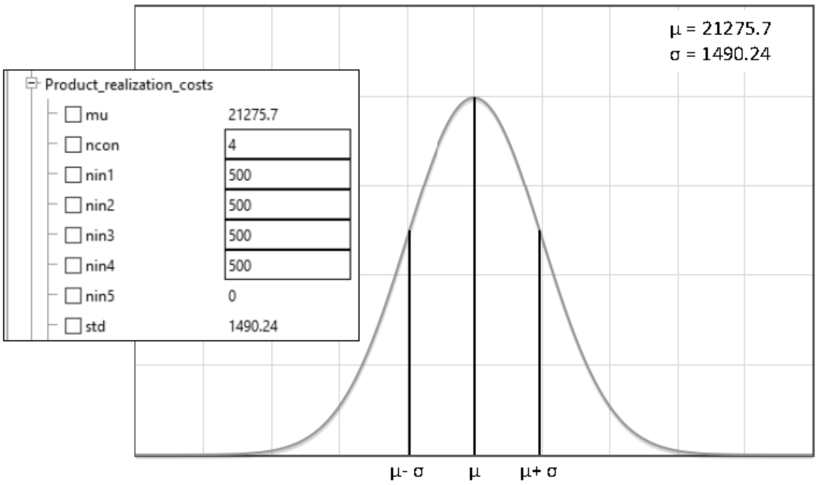

Figure 8: Simulation result.

As a result, for the sample project shown in Figure 8, an expected value of **21275.7** and a standard deviation of **1490.24** time units were calculated based on the Monte Carlo method. The regression equations of the project segments prepared by the Project Cost Estimator are broken down as follows.

Table 2: Result of regression equations.

REGRESSION EQUATION PROJECT SEGMENT	PROJECT COST ESTIMATOR
Project management	$Y_{pl} = 2300.3 + 94.1x_1 + 320.44x_2 + 48.32x_3$
Technical planning	$Y_{tp} = 1114.41 + 240.88x_2$
Engineering/Construction	$Y_{ko} = 534.25 + 258.45x_1$
Quality planning	$Y_{qp} = 268.29 + 80.22x_1 + 127.35x_2$
Result	$\mu = 21275.7; \sigma = 1490.24$

8 CONCLUSION AND OUTLOOK

The relevance of a cost forecast of product development projects is of growing importance for organizations. Especially in the early stages of product development when information is lacking, it is a challenge to predict the resulting project costs as accurately as possible. Not only large companies, but also small and medium-sized enterprises have to face this problem. The Project Cost Estimator provides an applicable software solution for project management, by which it is possible to graphically represent a product realization project and to simulate a forecast of the expected cost of the development project based on very little retrograde information. By applying the Monte Carlo method, the prediction accuracy will be greatly improved due to a stochastic presentation of results. Another key feature of the Project Cost Estimator is the flexible adaptability of a project library, whereby the software solution can be used in almost every company.

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The proceedings of the sixth International Conference on Production Engineering and Management, held between September 29 and 30, 2016 at the OWL University of Applied Sciences (Germany), collects the works carried out by professors, lecturers, researchers, graduates and students of the University of Trieste (Italy), the OWL University of Applied Sciences, Lemgo (Germany) as well as experts from other European universities and from industry. The main aim of the sixth edition of the conference has been to cover a broad range of topics and to bridge the gap between theory and practice in the field of Production Engineering and Management by offering an occasion where academia and industry could discuss practical and pressing questions. The conference therefore includes not only production technologies and management in a narrower sense, but also new aspects of direct digital manufacturing, of lean management, of innovation techniques and methodologies, along with different topics of high interest for the wood processing and furniture production and addresses sustainable and revolutionary developments in modern industry.

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